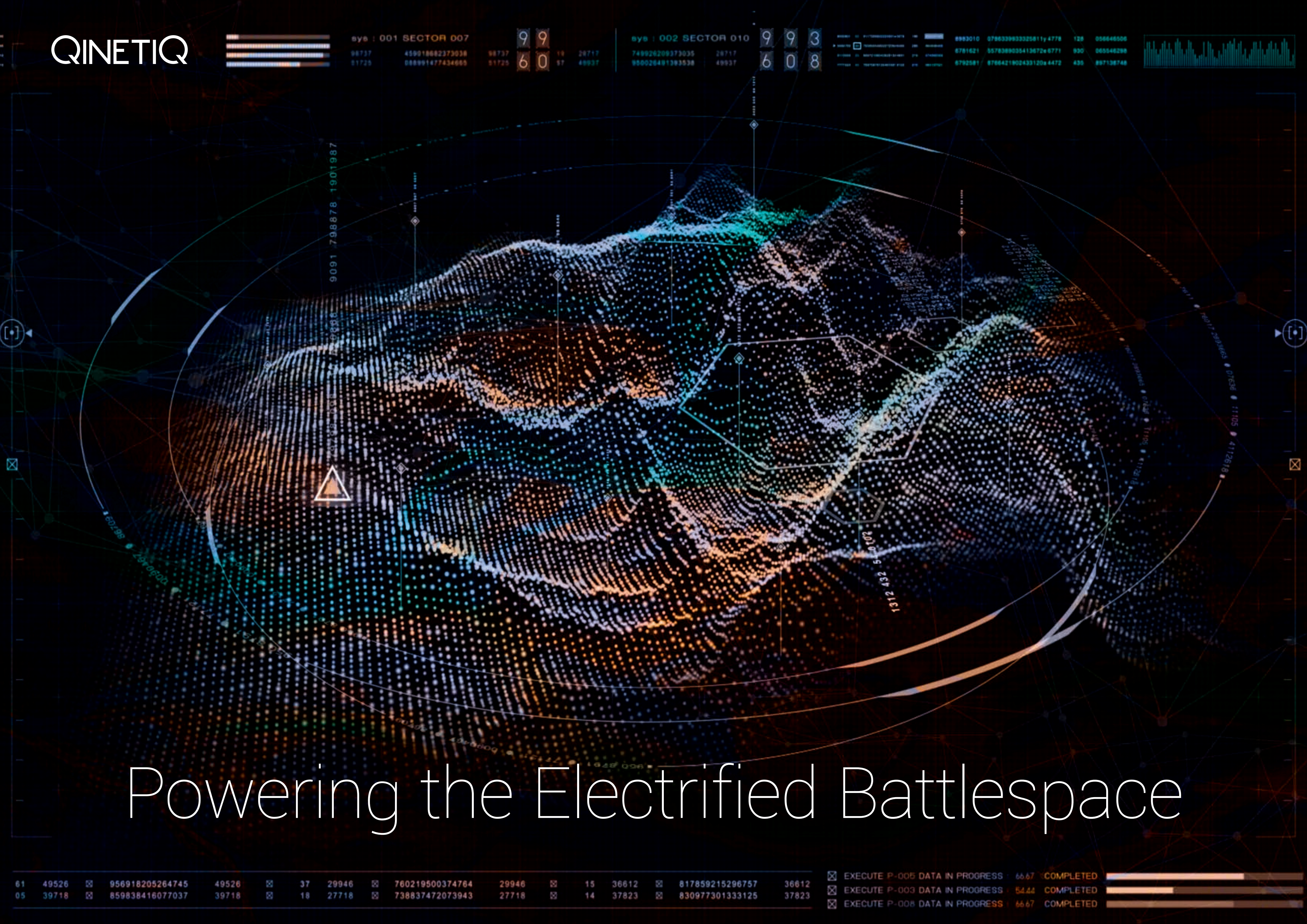


Powering the Electrified Battlespace

The fundamental enabler for all future warfare is electric power

A wave of electrically powered technologies promises to transform the way in which wars are fought. But will this electrical revolution be sabotaged by underdeveloped battlefield power infrastructure?

Historically, electrical technologies have been little more than useful additions to military capability, designed to augment the primarily mechanical equipment and human fighters at the heart of warfare. That is now changing. The growing financial, environmental and human costs of transporting and burning fossil fuels are forcing governments to seek cheaper and more sustainable energy sources that create smaller logistical and carbon footprints.

Necessity has ushered in a new era of innovation. Countermeasures, platforms and situational awareness tools are evolving at an astounding pace in response to changing threats and tactics. Directed energy weapons will soon knock out enemy communications or neutralise swarms of low-value targets at very low cost. Unmanned systems will resupply troops and deliver humanitarian aid, minimising human exposure to dangerous contested areas. Networks of smart sensors will collect and prioritise data to provide the fighter with a wide-ranging situational awareness picture, without causing cognitive overload.

However, all of these revolutionary technologies rely on electrical energy, so can only be as effective as their power sources allow. In the race to provide this power, we must not sacrifice the mobility, survivability or lethality of our troops and platforms by overburdening them with batteries.

Electrical technologies are also being shoehorned into a pre-existing infrastructure that was intended to support mechanical equipment. How do we deploy electrical weapons, platforms, or intelligence tools in a world powered by diesel?

The evolution of military capability from mechanical to electrical will only fulfil its enormous potential if the underlying power infrastructure evolves in tandem. This report explores:

- The geopolitical factors driving the electrification of the battlefield
- The emerging technologies and innovations that rely on electrical power
- The challenges of deploying these technologies in different environments
- How to resource militaries' growing electrical power demands

Our aim is to change the way we think about energy provision in defence. We must break the habit of increasing the capacity and the number of generators, then supplying more diesel to feed them. We must stop weighing down people and platforms with more and more batteries. And we must stop focusing on the power demands of individual capabilities, instead taking a macro 'system-of-systems' view to tackle the issue at an infrastructure level. This will allow us to reduce demand and variability of demand, enabling supply to be precisely matched to the load.

We hope to encourage collaboration, debate and innovation to solve this most urgent of challenges.

SECTION ONE:

Factors driving the electrification of warfare

1 The financial and human cost of the diesel supply chain

Fuel consumption in the US Army has increased from an average of one gallon per soldier per day during World War II, to 20 gallons per soldier per day during Operations Enduring Freedom and Iraqi Freedom. Supplying these fuels and moving them around conflict zones presents huge logistical challenges. Refined oil is cumbersome and volatile, making it difficult and dangerous to transport in large quantities. Fuel resupply convoys are slow-moving and conspicuous, making them easy, high-value targets for enemy forces. Over 3,000 American soldiers or contractors were killed in attacks on fuel supply convoys between 2003 and 2007 in Iraq and Afghanistan. A 2009 report by the US Army Environmental Policy Institute puts the estimate at one casualty for every 24 convoys. The logistic burden is substantial, and the loss of life resulting from it unacceptably high.

Transporting diesel is not only highly dangerous, but highly uneconomical. Field data shows that for every gallon of generator fuel used during the Afghanistan conflict, seven gallons were used in transporting it there. Consequently, the accumulated costs of delivering each of those gallons to a forward operating base can add up to hundreds of dollars. The fact that oil's cost is determined by market forces also makes it hard to accurately forecast expenditure over long periods.

Lastly, competition for oil is itself a source of conflict, as rivals fight to control reserves and refineries. As a result, the first nations to successfully develop and deploy electric combat vehicles, and to reduce their operating bases' reliance on diesel generators in favour of more sustainable power sources, will achieve an immediate battle-winning advantage.

2 Threats from rapidly evolving technologies and tactics

Russia's investment in weapons modernisation under its State Armaments Programme places new importance for the West on long-range intelligence, surveillance, target acquisition and reconnaissance (ISTAR) capability to counter the threat from hypersonic missiles. New high-precision aerial and ground-to-ground weapons will necessitate active protection systems to protect platforms and bases – all of which will generate further demand for electrical power.

Hostile states are increasingly turning to anti-access and area denial measures (sometimes abbreviated to A2/AD) to limit the West's ability to exercise its advantage. The aim of A2/AD is to prohibit intervention in a specific region by making it too risky or costly for foreign forces to enter.

Even the most advanced strike aircraft can be rendered completely ineffective if the carrier from which it operates is unable to get within range. The ability to operate at stand-off distances will be critical in overcoming these obstacles, through use of long-range smart weapons and unmanned systems – both of which will depend on integrated electrical infrastructure that provides secure communication, precise geolocation and acute situational awareness in real time.

On land, adversaries will employ A2/AD to increase the complexity, cost and lethality of moving supplies around the battlespace. UK defence has been quick to respond to this threat by exploring the use of electrical and hybrid-powered autonomous and robotic systems to deliver supplies to dangerous and inaccessible locations. During Dstl's 2018 Autonomous Last Mile Resupply challenge, unmanned land and air vehicles demonstrated the ability to co-operatively plan and navigate routes across challenging off-road terrain. In future, this type of technology will ensure critical items can reach those in need, without exposing soldiers or aid workers to heightened risk from aggressive enemy A2/AD tactics – although their success will be dependent on the introduction of suitable battlefield charging infrastructure.

The asymmetric threat continues to grow as commercial off-the-shelf (COTS) and other low-cost technologies become more sophisticated and prolific. We have witnessed how a simple quadcopter can shut down an international airport, or carry explosives with the aim of assassinating a human target, and it is likely this is just the beginning.

Greater degrees of autonomy and the ability to control multiple drones at once will enable operators to launch sophisticated, co-ordinated attacks on a small budget and with little prior training. This presents a problem for nations' armed forces, whose expensive countermeasures are intended to tackle expensive threats.

Take, for example, the well-publicised case of a US ally using a $3m Patriot missile, designed to intercept enemy aircraft and ballistic missiles, to shoot down a $200 consumer quadcopter. Defending against a single drone in this way is uneconomical, but a swarm could quickly deplete a ship's arsenal and leave it defenceless against further attacks. Electrically powered countermeasures, such as lasers and radio frequencies (RF), can be used to neutralise high volumes of low-value targets economically and decisively, but have not yet been deployed on a large scale.

3 Sustainability and environmental management

The United Nations (UN) identifies climate change as 'the defining issue of our time'. At a 2018 press conference, UN Secretary-General António Guterres called it: "the most systemic threat to humankind", warning that nations' food security, health and stability are at risk unless urgent action is taken to reduce civilisation's reliance on fossil fuels.

The defence sector is likely to be among the first to see the impact of climate change up close, as troops are deployed to manage conflict and deliver humanitarian aid in regions where food has become scarce and competition for resources threatens stability.

But here lies a dilemma: militaries are highly reliant on fossil fuels – the United States Department of Defense is estimated to be the biggest organisational consumer in the world – and as a nation's military spending increases, so does its CO2 output.

For as long as the defence sector remains a chief source of CO2 emissions, it contributes to the very problem it is charged with solving. In the short term, military deployment can be effective in managing the symptoms of climate change, but ultimately the defence sector must treat the underlying causes.

The outlook may sound bleak, but there are reasons to be hopeful. In January 2019, the United Kingdom's Ministry of Defence (UK MOD) announced that it had met its target to reduce fossil fuel use by 18% two years early. The MOD is now pursuing further efficiencies to reduce its consumption by a further 10% by 2026 – although it acknowledges this is ambitious:

> "Achieving the new target will be challenging. The MOD's fuel demand is heavily dependent on our operational activity and subsequently capability energy is and will continue to be affected by operational requirements."

Source: Sustainable MOD Annual Report 2017/18

To help meet its objectives, the UK Government has introduced a new standard concerning Environmental Management Requirements for Defence Systems (Def Stan 00-051), applicable to all products, systems and services procured by the MOD. While compliance is not mandatory, the standard will be a key consideration in all procurement decisions, making it hugely significant for the defence supply chain, as suppliers that offer sustainable solutions will be more competitive when bidding for MOD work.

But what do the sustainable solutions of the future look like? Returning to the UN press conference, Mr Guterres's speech offers a clue, citing technological progress as cause for optimism:

> "Technology is on our side. Advances continue to generate solutions. Clean, green energy is more affordable and competitive than ever."

Global investment in clean energy technology continues to rise, but public sector funding trails that of the private sector by a ratio of nearly one to three. Meanwhile, China is establishing itself as the world leader in the electric car market, as it takes decisive action to reduce its

dependency on imported oil, tackle its deadly pollution problem, and assert its dominance as an emerging superpower.

To remain globally competitive, the defence sector must similarly invest in technologies that minimise the co-dependency between operational activity and fuel demand, meaning a decision to deploy does not conflict with vital commitments to environmental management.

4 The need to secure advantage through technological superiority

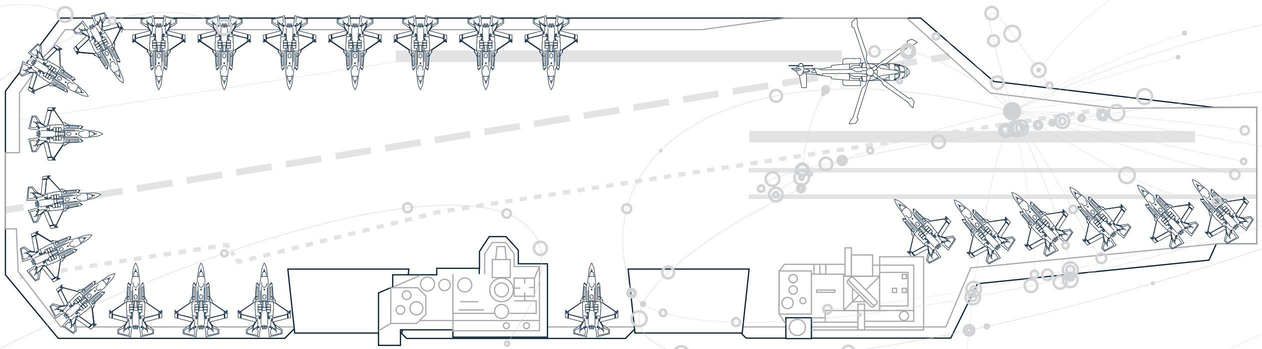
Having the biggest army and the most powerful weapons is not a guarantee of victory. Future advantage will belong to the side that is most proficient at exploiting technology to develop novel capabilities.

Faced with multiple, complex, ever-changing threats – from cutting-edge hypersonic missiles to quadcopters loaded with C-4 explosive – forces will need to respond by becoming smarter, increasingly agile, harder to detect, harder to hit, and more effective over greater distances.

All of this will rely on high-fidelity intelligence about the operating environment, which will inform highly targeted missions executed using advanced weapons that minimise collateral damage and risk to human life. Keeping people and platforms agile will depend on our ability to equip them with the technologies they need to outthink and outmanoeuvre the enemy, without overburdening them with batteries and other power sources.

Evading detection will demand greater stealth, enabling units to conduct surveillance and strike targets without giving away their position based on their thermal, acoustic or visual signatures.

The next section of this report examines some of the electrically powered technologies that will satisfy these requirements and secure that crucial advantage: directed energy systems; electrified land platforms; robotic and autonomous systems; and sensors and situational awareness. For each technology, we discuss its advantages and its impact on battlefield power demands – either as a consumer or contributor.



SECTION TWO:

Securing the electrical advantage

Technology focus: directed energy systems

The next generation of countermeasures relies on electrical energy to neutralise threats or disrupt enemy operations, by emitting laser beams to confuse sensors or ignite hardware, or radio frequencies (RF) to disable electronics and communications systems.

Large, high-powered laser systems will most commonly be deployed on ships, while lower-powered systems can be vehicle mounted or carried by infantry. Radio devices may be planted by hand or airdropped into enemy territory to block communications or shut down local electrical infrastructure.

Advantages of directed energy systems

The anti-ballistic missiles and close-in weapon systems currently in use on naval platforms were designed to counter small numbers of fast-moving, high-value targets. Faced with high numbers of low-value targets, deploying these countermeasures immediately becomes uneconomical, as the material cost of neutralising a swarm of commercial off-the-shelf drones costs thousands of times more than the attack.

The enemy can procure, manufacture and deploy improvised airborne explosive devices much faster than countermeasures can be delivered to the front line through the established defence supply chain, meaning the attacker can keep sending more devices after the defensive arsenal is exhausted.

Because the ammunition for directed energy systems is electricity, it can be produced on board the platform rather than transported from elsewhere, greatly reducing the logistical footprint and the associated risk, delay and cost. Captain Christopher Wells of the USS Ponce has claimed the cost of firing the laser weapons system on board his amphibious transport ship is less than a dollar a shot.

Removing the need for ammunition resupply gives the weapon virtually unlimited availability, meaning it can economically defend against sustained attacks from swarms of low-value targets without depleting its stock.

When fighting in densely populated urban environments, ballistic or explosive weaponry may present a disproportionate risk of collateral damage and civilian casualties. A directed energy system can achieve an objective, such as defeating a command and control node located inside a building, without damaging the structure or causing harm to human occupants.

The beam from a laser weapon is not visible to the naked eye, generates no sound, and produces only a small plume on contact with its target. RF energy is likewise invisible and leaves no tell-tale trace following engagement.

It therefore takes the enemy longer to recognise that an attack is taking place and launch a counter-offensive, giving ground troops more time to move in. The low visibility also maintains the secrecy of the weapon's location and avoids creating dramatic visuals that can be used in propaganda material.

Impact on battlefield power demands

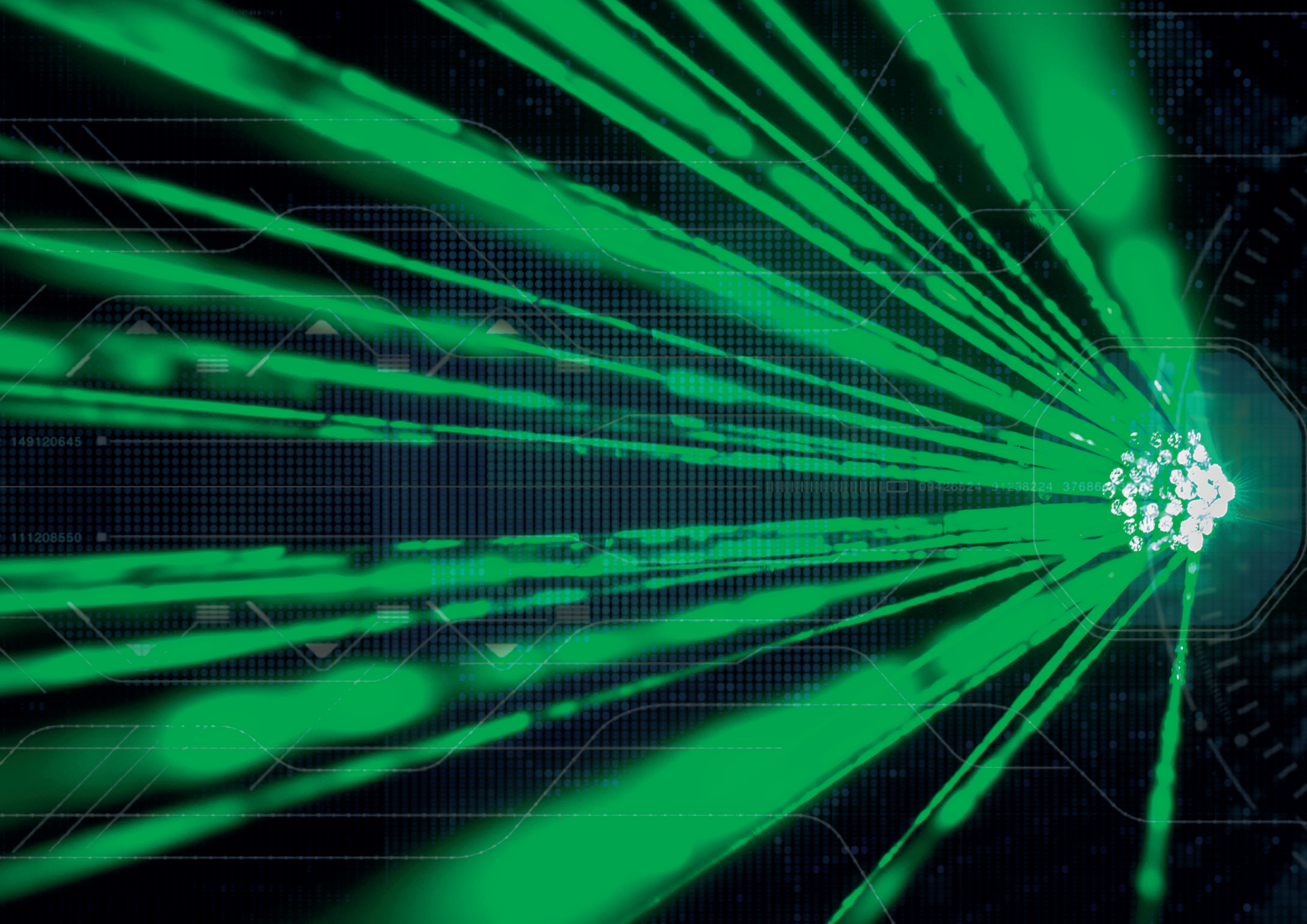
A high-powered, platform-mounted directed energy system requires more electrical energy than is currently available on a typical platform. Firing the weapon requires repeated, rapid delivery of power, which must either come from large storage cells or from a generator able to replenish the energy stores very quickly.

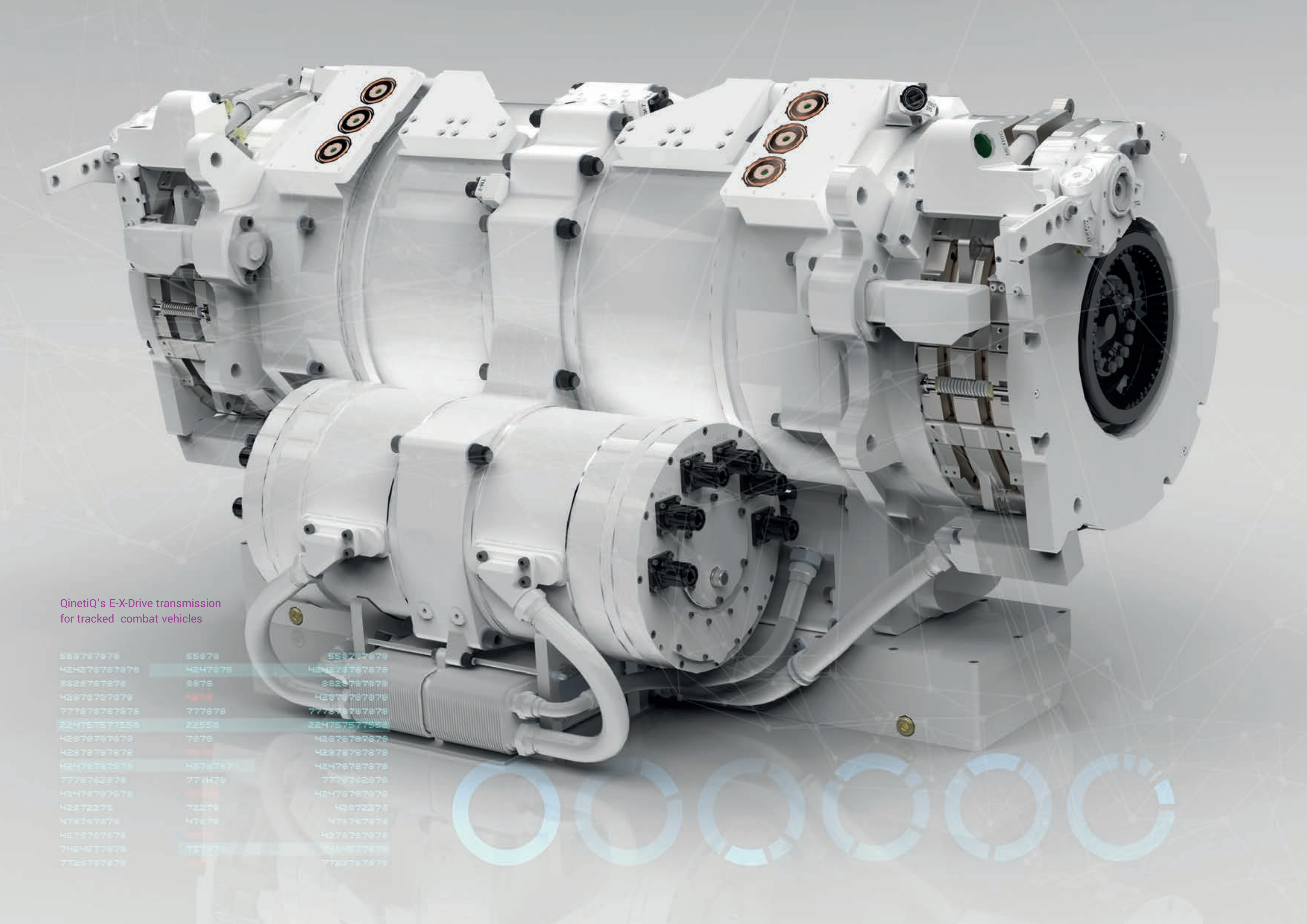
Conducting a mission using a directed energy system will require higher fidelity intelligence about the target and its surroundings. A laser beam can be attenuated and precisely aimed to neutralise the threat without applying disproportionate force that may deplete energy stores or increase the likelihood of collateral damage.

However, this relies on an understanding of the target's structural materials and configuration to identify the vulnerable areas most susceptible to attack, or, in the case of RF weapons, the frequencies of enemy transmissions.

The sensors involved in intelligence, surveillance, target acquisition and reconnaissance also consume electrical power, as do the cooling systems required by laser weapons in particular.

To service all these additional energy requirements without overburdening platforms or occupying already limited space, a directed energy weapon must be introduced in tandem with a suitable novel power system.





QinetiQ's E-X-Drive transmission
for tracked combat vehicles

Technology focus: electrified armoured fighting vehicles

The power resource on board an armoured fighting vehicle is already under enormous pressure from its command and control systems, situational awareness equipment and the data connections required to support them.

The demand for electricity is now pushing the limit of what is available on a conventional platform, and this trend will continue upward as new innovations are added incrementally in the very near future.

Forced to hedge against multiple unpredictable threats, vehicles are becoming increasingly overburdened with heavy armour. Active protection systems (APS), which sense and defeat incoming threats, are currently being explored as a way of reducing reliance on armour, but the intelligence, surveillance, target acquisition and reconnaissance (ISTAR) capability needed to locate, prioritise and defeat threats produces an additional power demand. If met using extra auxiliary power sources, this creates a different physical burden on the platform.

The mechanical vehicles that have served armies for the last century were simply not conceived with today's electrically powered technologies in mind. If our vehicles are to continue exercising their operational advantage by retaining their mobility, survivability and lethality, it is time to rethink their fundamental design principles.

Advances in hybrid electric drive systems specifically for military vehicles mean there is now a credible alternative to conventional mechanical designs, enabling technological advantage through increased design freedom and on-board power availability.

Advantages of hybrid electric drive systems

Opportunities to introduce more power to conventional vehicles are limited by the configuration of the internal combustion engine and driveline components. The driveshaft must run unimpeded along the length of the vehicle's underside, constraining the hull geometry and underbelly protection. A detonation beneath a vehicle can turn its transmission components into projectiles, blasting them through the floor and making them lethal to the occupants.

In a hybrid electric vehicle, electric motors contained within the wheels – or transmission in the case of a tracked vehicle – draw power via cables from a battery or generator, which can be placed almost anywhere in the platform. This design freedom, along with the weight reduction, enables hull geometry to be improved to increase blast resistance, make more effective use of passive armour, and locate personnel in safer parts of the vehicle, improving survivability.

Electric drive systems offer enhanced mobility by producing greater torque and faster acceleration. In-wheel motors can be controlled individually, increasing traction and agility, and can be mounted to long-arm independent suspension systems, giving them the ability to operate across more diverse and challenging terrain.

Finally, an electric drive system increases the vehicle's lethality by giving it the ability to conduct extended periods of silent watch and silent running. It minimises the vehicle's acoustic and thermal signatures by fulfilling tasks – such as rotating turrets or moving into position – without switching on the loud, hot diesel engine.

Impact on battlefield power demands

A hybrid electric drive system is not just a consumer of power, but a contributor. The on-board generator produces energy that can be stored or applied according to demand. This energy can be directed to whichever part of the platform needs it most at any given time, whether it is to a directed energy system to neutralise a threat, or to the wheels for a burst of acceleration. It can also be used to charge off-board equipment or to supply temporary power to military bases and community hubs such as hospitals or refugee camps. The generator can then replenish the vehicle's own energy reserves during periods of lower demand.

Power management in a hybrid system is more efficient and effective because all electrical automotive and integrated systems can use the same energy source. Vehicles designed with sufficient power budget from the outset can accommodate new subsystems when required or as they become available. Much of this technology can be retrofitted to extend lifespan and prevent obsolescence in legacy vehicles.

The improved fuel efficiency provided by electric powertrains extends the vehicle's operational range, increasing the mission options available to the user. The electrification of drivetrains will see transport energy produced much closer to the point of consumption, greatly lowering supply chain costs and saving lives by reducing risk.

Technology focus: autonomy and robotics

The evolution of robotics in warfare has accelerated dramatically in recent years, turning novel future concepts into practical realities in a relatively short space of time. This has been made possible thanks to swift advances in the enabling technologies, supported by an emerging culture of rapid innovation in defence and targeted investment from governments that recognise its strategic importance.

There are three factors that combine to create the optimum capability. The first is robotics, which describes physical platforms engineered to operate at standoff distances. The second is automation, which reduces or removes the role of the human in operating robotic platforms. The third is integration, which enables multiple robotic platforms to work collaboratively, either under the control of an operator or autonomously.

Advantages of robotic and autonomous systems

The advantages of robotic systems are twofold. Firstly, a robot can be deployed in scenarios that present disproportionate levels of risk to humans, such as mine clearance in the water, or bomb disposal on land. Secondly, they are able to access areas and perform tasks that would be impossible for humans, as they possess greater endurance and more acute sensing abilities.

While it is possible for an operator or several operators to control multiple robots simultaneously, to do so unaided would place a high cognitive burden on each individual, and a high communication burden on all members of a team. Automating low-level processes takes decisions out of the hands of the operator, easing the cognitive burden and reducing the complexity of communication.

Co-operation between multiple autonomous and robotic systems is the key to unlocking the technology's full potential. A team of innovators led by QinetiQ has demonstrated an integrated autonomous system capable of delivering supplies to dangerous and inaccessible locations, as part of the UK Defence Science Technology Laboratory's Autonomous Last Mile Resupply competition.

Unmanned aerial vehicles are deployed to scan the environment and relay mission data to a central command and control module. The system then plans the optimum route for air and ground-based robots to autonomously navigate and deliver supplies.

Impact on battlefield power demands

The mission scope of a robotic platform is largely dependent on the electrical power available to it. The platform is inherently reliant on data from the external environment, so as mission complexity increases, so does the number of input sources required for effective operation, creating high energy demand.

This demand may be serviced by auxiliary power units or batteries, which increase overall platform weight and reduce agility.

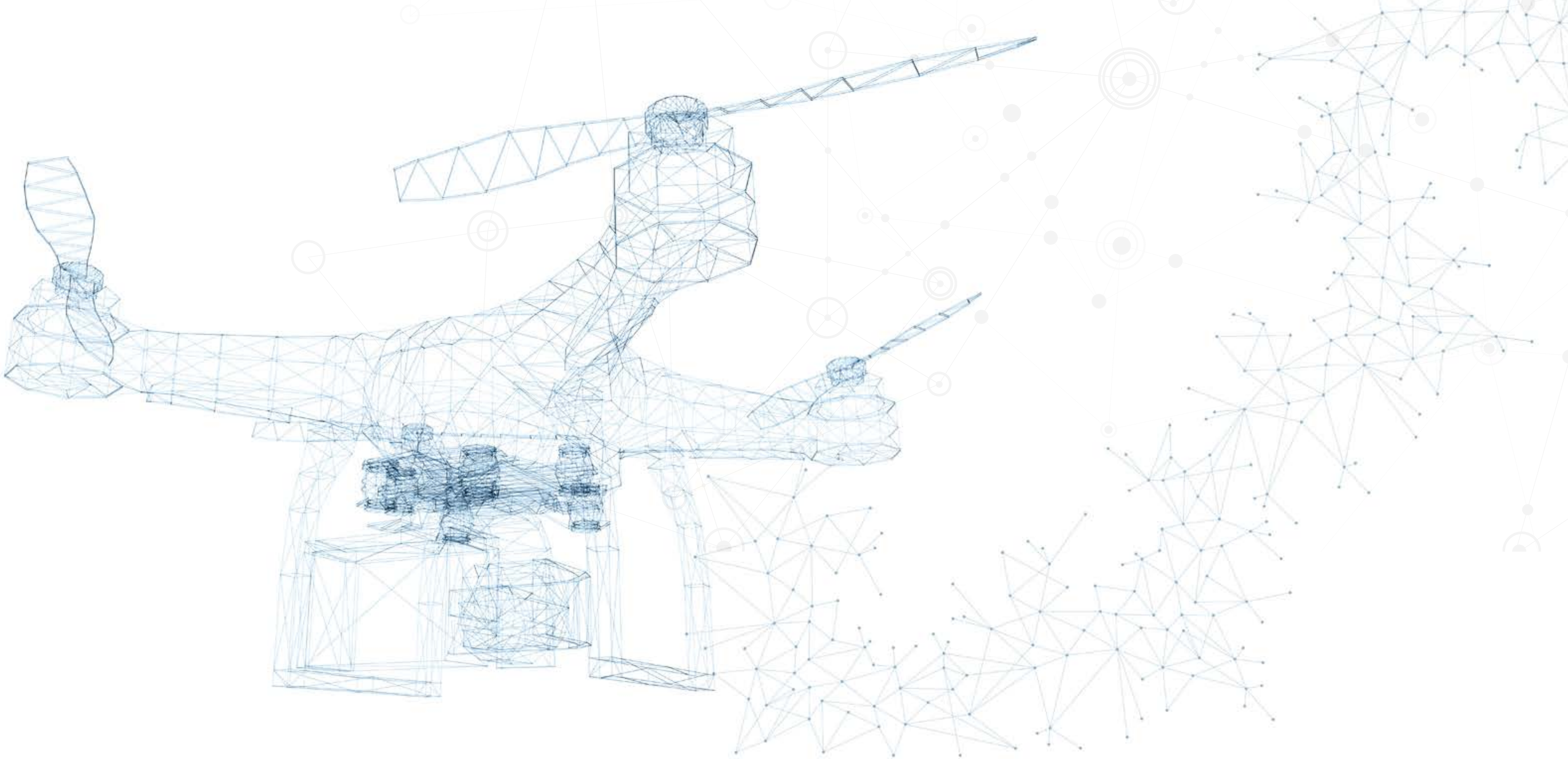
Where appropriate, a hybrid electric drive system can fulfil the requirement, giving the platform the ability to generate and store its own power that can be applied to propulsion, silent watch operations, or activation of payloads such as sensors, high-performance computing or directed energy systems. Future power solutions will enable the vehicle to store more of the energy generated by the hybrid system, increasing endurance, utility and mission scope.

On a fully electric platform, power limitations may necessitate a trade-off between its sensing and processing ability and its operational range. A proportion of investment in autonomous systems must be dedicated to improving the power to weight ratio of batteries and other energy sources, or power shortfalls will begin to constrain the advantages otherwise offered by the technology.

Where on-board power generation is not available, electric robotic and autonomous platforms must have the means to recharge from external power sources. At present, this is most likely to take place at a main or forward operating base over the course of several hours.

The area that a platform can cover before having to return to base is then restricted by the longevity of the battery, while the prolonged charging period limits the frequency with which the platform can be deployed.

A modernised infrastructure is needed in which platforms can draw power quickly from multiple sources, such remote charging stations deployed at strategic locations in the field, or even by sharing energy with other electrical systems. Reducing charging times will rely on advanced power cells that can recharge quickly, much like the 'fast charge' batteries in modern mobile phones and other consumer electronic devices. Where possible, renewable energy sources will replenish energy stores or even power whole platforms in real time.



Awareness of the available power is vital in deploying robotic and autonomous platforms. If a platform exhausts its power supply, it must either be retrieved, putting personnel in danger, or abandoned, which is uneconomical and presents the risk of it falling into enemy hands. Reviewing battery levels prior to deployment must be part of the operator's routine drill, like checking ammunition or rations.

During operations, power data from all active platforms will be available to a single overseeing operator, aiding decisions about which of the fleet to task and which to withdraw based on available power, location and range. To further ease the cognitive burden, some or all of these decisions may be automated. For instance, the platform will maintain awareness of its power level and its proximity to charging stations, and autonomously navigate to the most accessible charge point when necessary.

On the battlefield, proximity is not the only factor in deciding which charging station to navigate to, as enemy threats may prevent access to the shortest route. The platform must therefore be informed by the total situational awareness picture, including enemy locations and topographical data.

The collection, processing and transmission of data required to conduct such operations requires a vast amount of computing power and data bandwidth. Provision of these always-on communications consumes a great deal of electricity, which must be factored into the overall energy requirement picture.

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Technology focus: smart sensors

Sensors appear everywhere from operating bases to vehicle systems, whether for navigation, threat identification, target acquisition, surveillance or reconnaissance. Together they provide situational awareness, which is integral to modern-day access denial strategy. Many of the access denial tactics of the past, such as anti-personnel mines, have rightly been outlawed due to their indiscriminate nature and the continued danger they pose to civilians after conflict has ended. Today's tactics must be more discriminating, targeting only those who pose a genuine threat – but in the congested, contested environments typical in modern warfare, singling out the enemy is more challenging than ever. This means the importance of information has never been greater.

The electrification of warfighting technology eases the introduction of sensors and their supporting systems by removing clunky interfaces between electrical inputs and mechanical outputs, meaning virtually every platform or asset can be turned into a source of battlefield intelligence. However, every sensor consumes power. This requirement may be minimal when simply gathering and storing data in situ, but increases dramatically when that data is transmitted wirelessly. Multiple sensors operating simultaneously will create significant additional power and bandwidth demands that risk exceeding availability. One answer is to reduce the volume of data that is transmitted and distribute the processing burden, using intelligent sensors that interpret their own collected data at the edge, and make low-level decisions autonomously.

Advantages of smart sensors

Taking closed-circuit television (CCTV) as an example of a simple non-smart sensor, the camera continually relays unedited video directly to the operator in real time. The feed from that single camera can exhaust the attention span of the operator in 20 minutes, or significantly less under stress. If that operator is required to monitor multiple screens showing multiple live feeds simultaneously, the cognitive burden can quickly become unmanageable. Connectivity may also be very limited in the battlespace, severely restricting the bandwidth available for transferring the high volumes of data produced by large networks of cameras and other sensors.

The introduction of a smart element in this scenario may be as simple as equipping each camera with a movement sensor, so that it begins capturing footage only when activity is detected. It may then be tasked with showing the operator instances of movement as they are detected, or, if conducting longer-term reconnaissance, saving a series of time-stamped clips for later retrieval. Prioritising data and transmitting it selectively can significantly reduce power and bandwidth demands, as well as easing the cognitive burden on the operator by providing actionable information instead of raw data that must be manually interpreted. The intelligent sensor system may even make decisions on fulfilling higher-level objectives. For instance, a ground-based sensor may detect activity, then autonomously transmit the coordinates to an unmanned aerial vehicle and task it with conducting airborne surveillance.

All of this will depend on sensors' ability to communicate with each other. This will be facilitated by a central 'fusion engine' – a decision-making module that consolidates data from all available sources, such as radar, lidar, optical, acoustic and seismic, and uses it to control the whole system of systems. The fused data can then be prioritised, certain tasks initiated automatically, and the most critical information delivered to the operator on a single integrated display, preventing cognitive overload. This fusion engine must be built on open architecture, ensuring it is capable of receiving and processing data from sensors of all modes, produced by any manufacturer.

Impact on battlefield power demands

Smart sensors reduce the demand on any central computer by decentralising the processing requirement and distributing it across multiple locations. Each sensor creates its own small power requirement, which may be fulfilled using a main supply or a dedicated source.

As well as being highly reliable and long-lasting, these dedicated power sources must be hard for enemy sensors to detect. While smart sensors may slightly increase localised power requirements, the net power requirement for the whole system is greatly reduced as a result of minimising the transmission of unnecessary data.

A smart sensor network has secondary power saving benefits beyond the situational awareness system itself. The introduction of higher-powered computing systems has driven an increase in the requirement to control the temperature of facilities that house the equipment – whether air conditioning for an individual server rack, a container-based system, or a shelter. Air conditioning already generates a huge power demand for deployed elements in hot regions. Delegating processing duties out to the network of sensors reduces the temperature control requirement for the central computers and servers.

SECTION THREE:

Deploying electric technology in battle

In the mechanised battlespace that has been the norm for the last century, the introduction of a brand new piece of mechanical equipment has always been supported by well-established procedures and infrastructure. Supply chains have evolved in tandem with the development of equipment to cater for the delivery of fuel and ammunition, and manufacturers have consequently kept designing products that can slot right into this existing framework.

The challenge in deploying electrified technologies in battle is that a comparable infrastructure does not yet exist. A new piece of electrical equipment, such as a directed energy system or electrically-driven autonomous platform, may not be able to simply plug into an existing grid. Man-portable systems, such as computers, radios, sensors and life support, are designed and supplied with their own individual power sources. The outcome of this is a rampant multiplication of batteries and generators, each devoted to powering a single piece of equipment. Such unconstrained proliferation of diverse and often incompatible power sources is costly and creates significant logistical challenges for those on the front line.

The following sections examine the challenges of energy provision and their impact on platforms, dismounted soldiers and operating bases.

Platforms: Land, Maritime and Air

From the smallest drone to the largest aircraft carrier, the space available for power sources on board platforms is generally very limited. Introducing more batteries or generators to a platform adds weight, reducing mobility and range.

The challenge in all cases is to increase energy provision while maintaining or reducing the volume and mass of the power sources.

Land

The myriad electrified technologies available to land platforms create a power requirement that far exceeds that which can currently be resourced. Platform operators face a choice: continue to use existing power sources and employ new technologies selectively; or change the power source to lay a foundation for the introduction of multiple electrical systems.

A hybrid electric powertrain on a heavy armoured vehicle could make the difference between tens of kilowatts of available power and up to a megawatt. This will be the key to accommodating a wide range of capability-enhancing but power-hungry systems, such as active protection, directed energy weapons, cooling systems and more capable sensor suites.

Government departments and platform integrators are considering the introduction of hybrid electric propulsion for future fighting vehicles at a time when the civil market is investing billions in the development of parallel technologies for electric and autonomous vehicles. To facilitate the introduction of these capabilities, defence departments and original equipment manufacturers (OEMs) should be drawing on civil investment and looking to militarise it, rather than developing it in isolation.

Maritime

Using electric drive systems in ships offers the same design flexibility that it does in land vehicles and can also make the ship far more manoeuvrable. Electric propulsion is fast becoming a common feature of modern naval vessels, adopted by the US Navy for its Zumwalt-class destroyers and the Royal Navy for its Queen Elizabeth-class aircraft carrier and Type 45 frigate.

The performance of a large naval platform is less affected by small weight increases than an aircraft or armoured land vehicle, meaning energy provision for additional sensing and computing power is unlikely to have a significant impact.

However, space is limited and the types of equipment a large ship may be required to support, such as a directed energy weapon or electromagnetic aircraft launch system, have the highest power demand and fastest delivery requirements of any current or future platform-mounted capability.

The US Navy's Gerald R Ford-class aircraft carrier has produced huge leaps forward in power provision for large ships. Its reactors generate 25% more power than those on the Nimitz-class carrier, while reliance on steam and associated infrastructure is significantly reduced to save space and weight. Its electromagnetic aircraft launch system (EMALS) is claimed to save 30% of the interior hull volume, while its power storage and delivery system is capable of supporting directed energy weapons and even electromagnetic rail guns. Overall power availability on the carrier is twice that which is required by existing systems, leaving plenty of headroom for the introduction of future technologies.

On a frigate or similar sized warship, power availability is more limited, so the energy devoted to something like pointing, firing and cooling a directed energy system must not take power away from other vital systems.

Multi-stage systems comprising combinations of generators, ultra high-power batteries, supercapacitors and flywheels may be required to service competing storage and delivery requirements. Distributing energy from these multiple sources will require a precise understanding of ship-wide power usage and the states of the various sources, achieved by monitoring demand and availability across the whole system of systems.

Smaller vessels face comparable challenges to land vehicles, having to tread a fine line between power provision and mobility. Higher power density batteries, smart sensors and renewable energy will play a big part in meeting future power requirements.

Manufacturers of unmanned maritime systems are leading the way in the use of solar power and other renewable energies, like the AutoNaut surface vehicle, propelled entirely by the motion of the waves. Such innovations from the commercial sector are likely cross over into defence.

Air

The electrical energy requirement on manned aircraft is steadily growing with the addition of advanced situational awareness technologies, flight control systems and the necessary increase in computing power. The addition or redistribution of weight on board a fighter aircraft can have a significant effect on handing and performance, so opportunities to introduce extra power sources are limited.

The gyroscopic forces produced by flywheel systems make them impractical for aviation. Non-mechanical systems such as supercapacitors are air-transportable and exhibit higher power density than batteries and may be valuable for short bursts of power, but do not contain nearly as much energy. To increase the energy available to aerial platforms, specialised solutions may be required, such as load-bearing or flexible batteries that form part of the structure of the aircraft.

It is not yet clear whether electric propulsion could provide significant benefits for manned military aircraft. Hypothetical advantages are lower-emissions and reduced heat and acoustic signatures. Civil aerospace is starting to explore the concept, mainly in relation to single-occupancy 'air taxis', but it is unlikely that performance could match that of current combustion systems in a defence context.

Electric propulsion comes into its own with unmanned aircraft. For example, high-altitude pseudo satellites, like the QinetiQ-designed Airbus Zephyr, can already conduct continual aerial operations for weeks at a time, powered only by the sun.

Smaller, lighter batteries with higher energy density will be vital in increasing flight times and supporting additional sensing capability, as will deployable remote charging points away from operating bases that will allow unmanned air systems (UAS) to 'leapfrog' between them and travel over greater distances. A drone can land on the stations and charge on contact using wireless power transfer and fast-charging technology similar to that found in modern consumer smart phones.

As wireless power transfer technology improves, it will be possible to beam power from a directed energy system on the ground or water, enabling UAS to be charged in the air and avoiding the risks and disruption to operations caused by landing.

Enabling technologies and innovations for platforms

- Smaller, lighter, higher energy density batteries, to enable longer operation times and support more power-consuming equipment without reducing platform mobility
- Remote charging stations deployed in the field, which electrical platforms can 'leapfrog' between to expand their range
- Renewable energy sources to service low-level power requirements, such as wave-powered propulsion for maritime vehicles and solar cells to power self-sufficient smart sensors
- Wireless power transfer, either on contact or beamed from a directed energy system, to enable recharging with minimal disruption to operations
- Ultra high-power batteries and flywheels that can deliver huge bursts of energy in a very short space of time before returning to their full storage capacity within a matter of minutes – essential for technologies such as directed energy systems and EMALS
- Hybrid electric drive systems for land platforms, which create new design options that improve mobility, survivability and lethality
- Structural and conformable batteries, solid electrolyte batteries and load-bearing supercapacitors that form part of the hull, wing, fuselage or chassis of a platform, saving internal space and allowing for alternative weight distribution

The dismounted soldier

Militaries worldwide recognise the need for infantry soldiers to 'fight light' if they are to maintain peak physical and mental performance and avoid injury. Project Hercules – a series of studies conducted by the UK's Defence Science Technology Laboratory into the effect of load carriage on agility, lethality, survivability and cognitive ability – determined that equipment should not exceed 45% of bodyweight in marching order and 30% in combat. In Afghanistan, it was not uncommon for a British soldier to carry equipment totalling 58kg, which is closer to 70% of typical bodyweight.

This recognition of the urgent need to reduce the physical burden comes at a time of unprecedented innovation, when there are more tools available to the soldier than ever before – many electrically powered. Enthusiasm for adopting these emerging technologies, however advantageous each one may be in isolation, must be tempered with pragmatism about what the soldier can reasonably be expected to carry. This will come from taking a 'whole-system' view of equipment, taking into account the tactical advantage conferred by each technology, but balancing that against the tactical disadvantage created by the additional power requirement and the weight of the batteries needed to service it.

Power-consuming technologies

Technologies that contribute to the soldier's situational awareness will be among the most vital. As discussed in the opening chapters of this report, the dispersal of enemy targets across congested urban environments calls for real-time provision of high-fidelity data to enable fighters to confidently distinguish between insurgents and civilians.

This data will be drawn from myriad sources, including robotic and autonomous systems fitted with advanced sensors and communications equipment. The collected data will be prioritised, integrated and presented as live mission intelligence on head-up displays in visors or goggles, enabling fighters to react instantly to changing circumstances while avoiding cognitive overload. To achieve this, sensors, transmitters and receivers must be wirelessly networked to support co-ordinated engagements across disparate locations.

Soldiers must be able to retain situational awareness when satellite data is unavailable, either due to a denial attack or when operating underground or in buildings. In 2016, a UK partnership comprising Dstl, Roke, QinetiQ, and Systems Engineering and Assessment demonstrated a system of body-worn inertial and visual navigation sensors that can track personnel in environments where GPS is unavailable, improving navigation, detecting threats, and sharing information with other soldiers and commanders.

Body-worn or weapon-mounted gunshot localisation systems enable combatants to protect themselves from snipers and other gunfire threats by arming them with the situational awareness needed to pinpoint the source of gunfire and react immediately by taking cover or launching a counterattack.

All of these are crucial, lifesaving technologies – but they also come with their own power requirements, which, alongside those of other vital equipment like radios, tactical hearing protection, data terminals and night vision goggles, can quickly add up. If infantry soldiers are to reap the benefits of all these technologies at once, their power demands must be met in a smarter way.

Solution one: distributed body-worn power

Much of the added burden is due to each piece of kit having its own dedicated power source. This is compounded by the fact that not all are interchangeable, requiring infantry to carry spares of several different types of battery. It may not be practical to consolidate these batteries into a single centralised power source, as damage to the central source could cause all electrified equipment carried by the soldier to fail. It would also require helmet and weapon-mounted systems to be tethered to the body, restricting movement and making broken kit harder to discard quickly. The solution lies in multiple, mutually compatible batteries and fuel cells, integrated into clothing and distributed across the body. In the event of a power source failure, the affected equipment can be connected to a different body-worn source via breakaway connectors that allow damaged equipment to be dumped in an emergency.

Solution two: power scavenging

Further to introducing a common power source for each soldier, all power sources should also be made compatible with one another. Fully open architecture would enable individuals to 'donate' power to each other in the field, and recharge by plugging universal cables into power banks on platforms, equipment and in operating bases. Combined with a means of monitoring the power usage of the whole unit as a system, energy can be redirected to where it

is needed, reducing wastage and removing the physical burden of excess spares.

The barrier to success

Governments are beginning to acknowledge the importance of open architecture in dismounted soldier systems. The Australian Department of Defence, through its Diggerworks initiative, and the UK Ministry of Defence, via its Morpheus programme, have both made strides toward what they term 'generic soldier architecture' – the latter having introduced a formal defence standard (DEF STAN 23-012) to this effect.

OEMs too are starting to think about how to tackle these problems. BAE Systems' Broadsword Spine wearable technology uses conductive fabrics instead of wires and cables to move power and data around the body. Electronic devices can be plugged into the body-worn power source, resulting in a 40% weight saving. However, for this type of technology to become accepted requires competing OEMs to play ball. Currently, defence contracting tends to be geared toward through-life supply. A prime may be awarded a 20-year contract to provide a piece of equipment and the battery to power it. This suppresses innovation, as once the prime is under contract it has little incentive to upgrade the power supply, and the buyer is not permitted to procure newer, better solutions from other manufacturers. For example, QinetiQ has produced a battery that is lighter and longer lasting than those used in existing communication systems – but, under current contracts, use of such third-party batteries would void the manufacturer's warranty. Open architecture can only be fully exploited if it is supported by open, competitive procurement frameworks that prioritise operational performance over long-term supply.

Enabling technologies and innovations for the dismounted soldier

- Advanced situational awareness tools, such as head-up displays, gunshot localisation, and navigation that works in GPS-denied environments
- Batteries or fuel cells with greater power density, to provide more power without increasing the physical burden on the individual
- Easily portable power systems to fuel equipment and recharge on-person power in remote locations
- Integrated and ergonomic body-worn power systems that can draw power from multiple sources and supply it to any piece of equipment necessary, based on modular architecture so kit can be removed at pace in an emergency
- Situational awareness provided by remote smart sensors, such as those mounted on unmanned platforms, which process data at the delivery end to reduce the computing power needed at the receiving end
- Where practical, resupply using unmanned or autonomous systems to further reduce the burden on the soldier

Operating bases

Forward operating bases (FOB) consume enormous amounts of electricity, with one US Navy source estimating demand at 1000 kWh a day for a company-sized base. This demand is currently met almost entirely by generators fuelled with diesel, which is delivered via an expensive, inefficient and dangerous supply chain that puts convoys in the enemy line of fire.

The inefficiencies continue after the fuel has been delivered. Of each gallon burned by a generator, only 30% is converted into electricity that is actually used by the base, with the other 70% simply going to waste. This is the consequence of having to run generators continually to ensure there is always enough energy available to service a hypothetical peak in demand – even if that peak is never actually reached.

All of this contributes to vastly inflated expenditure, significant damage to the environment, and loss of human life. It is clear that urgent action must be taken to reduce dependency on, and wastage of, fossil fuels. Several governments have acknowledged the issue and launched initiatives to address it, such as the US Department of Defense's Green Warrior Implementation Strategy and the UK Ministry of Defence's Capability Vision of a Self-Sustaining Forward Operating Base. If they are to make a significant impact, they must achieve three objectives:

1 Reduce total power consumption

Reducing the amount of power consumed by an operating base is the simplest way to lower the financial, environmental and human cost of its reliance on diesel. Heating, ventilation and air conditioning account for 75% of FOB energy demand, with up to half lost due to inefficient structures. Building these structures using thermally insulating materials minimises the loss of hot or cold air, reducing the energy consumed by heating or air conditioning units and the fuel burned to generate it. It has the added advantage of lowering the structure's thermal signature, making it harder to detect and strike.

The fastest gains can be made by making relatively small changes, such as adjusting the set point on air conditioning thermostats and replacing fluorescent lighting with LEDs, which may save up to 10% and 3% of energy use respectively.

Recovery of certain waste products may also help to reduce the overall electrical load, such as using heat from generators to heat water. Water produced as a by-product of air conditioning units can also be recovered and used. The demand for water and the logistic burden involved in supplying it to a forward operating base is similar to that of fuel, so recycling it reduces both cost and risk.

2 Make power generation more efficient

It clearly is not possible to reduce power consumption to zero, so we must ensure that the remainder of the requirement is met as efficiently as possible.

Renewable sources, such as large deployed solar panels, or turbines driven by wind or water, will certainly play a part in bringing down the amount of diesel burned in generators in rear elements. However, they may not always be practical for forward tactical elements that are highly mobile, operate under camouflage nets, and need to minimise their visual signature. Renewable energy sources can also be intermittent and unpredictable, take time to deploy, and are not yet sufficiently advanced to provide enough power for a whole base. This creates a new challenge for power storage and distribution: to exploit intermittently available power for varying power demands will require an interim mixed system with renewable and diesel generators operating in tandem.

While diesel generators will remain a feature of the forward operating base for now, in future they will be lighter and more compact, reducing the logistic burden associated with their transportation and deployment. They will form part of a multi-stage system, or hybrid field power unit – a small lightweight diesel generator combined with a battery and inverter system, which could reduce diesel consumption for small command posts by up to 80%.

Crucially, these generators will not all run continually to provide power in real time, but create energy which is then stored in batteries for round-the-clock provision at lower levels, and combined with ultra-high power batteries, flywheels or supercapacitors for the bursts required to operate directed energy weapons and other power-hungry systems.

All generators can be switched on in times of peak demand, or switched off completely, with the base falling back on its stored energy if there is a need to maintain low acoustic and thermal signatures. Use of generators can be wound back in favour of longer-term sustainable sources, like fuel cells, as the camp becomes more established.

3 Monitor power demand and usage

Generating less power may feel risky, as it is critical that demand is not permitted to exceed supply. This makes the third and final objective the most important of all. To achieve optimum efficiency, a base's power generation must be matched to its load requirements – but this is only possible with the means to measure usage and forecast demand.

An energy informed operations microgrid is a self-contained deployed power infrastructure in which power input, output and storage is monitored. Voltage and current on each circuit can be viewed wirelessly on a user interface, and circuits can in turn be connected or disconnected remotely as needed. The system gives the user a digital map of power consumption for the whole base, informing decisions on the generation, storage and conservation of energy.

The next step is the full integration of the microgrid with all equipment that may be expected to draw power from it. By understanding the power availability and demand both inside and outside the base, the user can manage not just present, but future power requirements. Take this hypothetical scenario for example:

> A squad is expected to return to base in an hour's time following an operation and will need to recharge their body-worn power packs and several robotic systems. Before the soldiers arrive, their power packs and robotic systems wirelessly communicate their remaining battery levels to the microgrid, which then calculates the additional energy that will be required to recharge them. This calculation is then supplied via an interface to an operator at the base, who can switch on additional generators, switch off other power-consuming assets, or redirect power from alternative sources to guarantee sufficient provision.

With the addition of artificial intelligence (AI) to the central power management system, this entire process could even be automated.

Enabling technologies and innovations for operating bases

- Advanced materials that improve the thermal performance of structures, minimising the loss of hot or cold air and reducing the power generation requirement through decreased wastage
- Sustainable power sources, such as large rapidly deployable solar panels, or turbines driven by wind or water, to supplement diesel generated power
- Hybrid field power units – small, lightweight diesel generators combined with fuel cells, batteries and inverter systems to reduce diesel consumption for small command posts by up to 80%
- Energy informed operations microgrids, in which power input, output and storage are monitored, informing decisions on energy generation, storage and conservation
- Integration of microgrids with external power consumers and providers to offer a system-of-systems view of total power availability and demand
- AI-enabled power management system, which integrates power data from all sources and takes automated steps to increase generation, reduce consumption, or redirect energy from other sources

SECTION FOUR:

Recommendations

We conclude this report with six recommendations to help government defence departments and industry instil the system-of-systems mindset and build the supporting infrastructure critical to enabling new electrical technologies to live up to their promise.

1 Match power generation to demand

The defence sector has an unfortunate tendency to operate in silos. Power provision for a forward operating base is conceived independently of that for a platform, which is in turn conceived separately from that of an infantry unit. To exacerbate the issue, each piece of equipment is often supplied with its own dedicated battery or generator, significantly adding to the physical and logistical burden. All of this creates a huge power surplus – yet one which cannot be exploited, meaning it simply goes to waste. To achieve true power efficiency, it must be possible to match power generation as closely as possible to actual demand – not just within each forward operating base, or on board each platform, or for each soldier, but across the whole system of systems.

We urge the implementation of energy informed operations – the practice of monitoring and forecasting the total energy requirement to support decision making on the consumption, generation and allocation of power. It is enabled by individual pieces of equipment communicating their power status to a central computer, which prioritises the data and presents the operator with recommendations, such as turning off inactive assets or switching on additional generators, via a user interface. The case for energy informed operations is strong, but to implement it will require significant shifts in mindsets within government and industry. This begins with the political will to solve the problems outlined in this report, and readiness among defence suppliers to step out of their silos and collaborate in pursuit of the greater good.

2 Become smarter at generating and transferring power

Energy informed operations provides an understanding of battlefield power demands, but to capitalise on that understanding relies on the ability to generate, store and transfer power to where it is needed. Generators are often required to run continuously at full capacity, even during periods of low usage, to ensure power is available in the event of a sudden spike or sustained increase in demand. To achieve true efficiency, the same levels of power must be available during peak periods, but without generating excess in between.

The solution lies in multi-stage power systems, in which generators or fuel cells supply power in real time, but can also place the excess into storage. This storage may take the form of a battery that provides sustained and silent low-level power; and an ultra-high power battery, flywheel or supercapacitor that can discharge its energy in intense bursts. Hybrid electric drive systems for land platforms work on a similar principle, while offering additional design freedom and performance benefits. For energy informed operations to work at a system-of-systems level, all systems must be interoperable and power must be transferrable between them. These concepts are critical to the success of emerging electrical technologies, and the first nations to turn them into reality will seize the strategic upper hand. We have the ability to do it, but there is currently an imbalance in research and funding between technological showpieces, like robots and laser weapons, and power sources on which they depend.

Governments and industry must commit sufficient resources to the development of power sources, or their militaries will be unable to exercise the technological advantage promised by their flagship capabilities.

3 Open up system architectures

Imagine that you are working in an office and need to charge your phone. All of your colleagues have different chargers, but not one of them is compatible with your specific model. Unable to borrow a charger, your battery dies. Now imagine that instead of your phone, the item you need to charge is a piece of battlefield equipment on which your life depends. You are carrying multiple batteries, but each one is purpose-built for a specific bit of kit. You are accompanied by an unmanned ground vehicle with a generator on board, but are unable to draw power from it because there is no common cable.

This highlights the absolute necessity for open architectures and standards in managing the system of systems power requirement. A battlespace in which all power sources are mutually compatible will conserve energy, increase its availability, and reduce the weight that soldiers and platforms carry, improving their mobility, survivability and lethality. We suggest looking to the mobile phone industry to understand how organisations can work together to agree and implement standardised protocols.

In 1998, competing telecommunications companies recognised the need for a common technical standard for accessing information over wireless networks if their products were to realise their potential. They formed a working group that led to the introduction of the Wireless Application Protocol (WAP), enabling mobile devices to support web browsing. We recommend the formation of a similar working group in defence, dedicated to the creation of standard protocols for battlefield power provision.

4 Adopt a more flexible approach to procurement

It is not uncommon for an original equipment manufacturer to be contracted to provide a piece of equipment throughout its service life – and with it, the battery needed to power it. This may tie the buyer to a specific battery for decades. During this period, other manufacturers may produce lighter, more durable, longer-lasting batteries compatible with that piece of equipment, but to adopt them would void its warranty, so the user sticks with the inferior product. The system stifles competition and offers no incentive for the incumbent to innovate and improve. Equipment must be procured via open, competitive frameworks that prioritise operational performance over long-term supply. If a prime is awarded a supply contract, it should be incentivised to optimise the power source and integrate it with other systems for the full life of that contract.

5 Implement an energy conservation culture

The most urgent objective for any fighting force should be to minimise its power needs. Lowering the power demand gives militaries more freedom to operate by allowing greater flexibility, easing the burden on local populations, reducing signatures, and shortening logistical supply chains.

Technologies such as thermally efficient construction materials for forward operating bases offer valuable quick wins in the drive for greater energy efficiency, but the key to achieving longer-term success is implementing a culture in which conservation runs throughout everything. Simple actions like adjusting thermostats and recovering waste products can make a significant difference when practiced at scale.

Our recommendation is to appoint an 'energy czar' responsible for understanding total battlefield power requirements and usage, identifying opportunities for efficiencies, producing guidelines and training personnel. A wider cultural shift towards energy conservation will also stimulate further innovation. This will produce technological solutions that employ big data, artificial intelligence and systems automation to improve the effectiveness of energy management and reduce the need for human intervention.

6 Continually scan the horizon and keep innovating

The technologies and solutions outlined in this report will be game-changing in terms of the operational and environmental benefits. These are the best available solutions to the problems immediately in front of us – but in the longer term even they may not be sustainable. Materials used in modern batteries, such as lithium and cobalt, are finite resources, and mined in some of the world's most politically unstable countries.

Hybrid systems still burn diesel and so are likely to be phased out in favour of fully electric systems as fossil fuels become scarcer and the need to reduce harmful emissions becomes even more urgent. It is therefore imperative that we continue to think two steps ahead and invest now to develop the technologies that, once sufficiently advanced, will eventually supersede those of tomorrow.

Putting these technologies to the test in live collaborative exercises will be essential. There must be a willingness to try new technologies and experiment with them to understand their potential, their weaknesses, and how they might be used in theatre. This must be coupled with an acceptance that some technologies may not live up to expectations, in the knowledge that experimentation offers a mechanism by which to rule out suboptimal capabilities quickly, before excessive time and money have been invested in them.

The final word

The success or failure of electrical technologies in defence will depend on the quality of the infrastructure behind them. While power provision may not grab headlines like laser weapons or robotic systems, governments and industry must commit adequate money, time and resources to research and development projects that support the creation of that infrastructure. If they do not, the battle-winning potential of their headline-grabbing technologies will never be fully realised.


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EXECUTE P-003 DATA IN PROGRESS : 88.76 COMPLETED
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