RECHARGEABLE BATTERY PACK TECHNOLOGIES FOR FUTURE MILITARY OPERATIONS

April 2026

EXECUTIVE SUMMARY

The electrification of the modern battlespace is accelerating, driven by rising energy demands from advanced sensors, computing, communications, robotics, and emerging high-energy systems. Lithium-ion batteries have become the dominant technology due to their high energy density, performance, and established supply chain, and they now power everything from soldier-borne equipment to unmanned aerial systems and hybrid and electric propulsion systems in vehicles. As defence platforms become more power-intensive and interconnected, the need for safer, higher-performing, and more sustainable energy storage technologies grows correspondingly.

Current market trends show a broad shift away from legacy chemistries toward modern lithium-ion systems, particularly NMC, LFP, and LTO variants, each offering different balances of energy density, power capability, cycle life, and safety. However, the diversity of military applications—ranging from micro-drones to megawatt-class directed energy weapons—means that no single battery cell solution can satisfy all operational requirements. Temperature-sensitive high-power systems demand active thermal management, while portable soldier systems require lightweight, passively cooled designs. This role-to-role variability complicates procurement, storage, maintenance, and lifecycle management, especially given the effects of calendar aging, high cycling rates, and long-term storage.

The variety of chemistries, formats, and performance characteristics demanded by different roles creates a growing risk of inefficiencies, cost escalation, and inconsistent readiness. Modular and interoperable battery system architectures—successfully applied in some sectors of electric mobility—offer potential solutions by enabling multi-sourcing, simplified charging infrastructure, scalable capacity, and easier maintenance. However, achieving higher levels of interoperability (especially for actively cooled systems) remains technically challenging, and complete standardisation across all platforms is unlikely.

Looking ahead, a hybrid approach that embraces modularity, scalable architecture, selective standardisation and sovereign control will be essential. Defence organisations must invest in next-generation chemistries, sovereign industrial capability, improved battery system management and cooling systems, and logistics processes that support rapid swapping, safe storage, and predictable replacement intervals. This strategy will enable the armed forces to meet future energy demands while ensuring safety, resilience, and operational superiority across diverse mission environments.

CURRENT BATTERY TECHNOLOGY LANDSCAPE

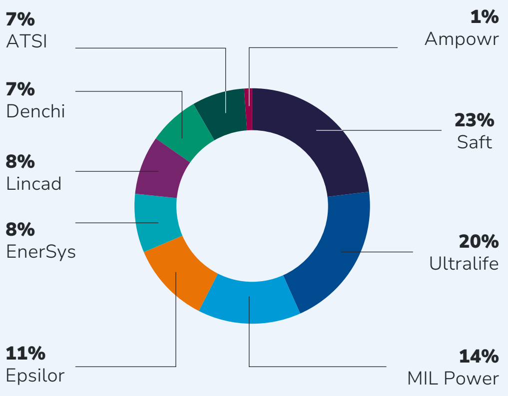
Batteries have been essential items across the armed forces for decades, from simple primary alkaline cells powering radios to secondary cell banks of lead-acid or nickel-metal-hydride batteries powering electrical systems in ships, aircraft, and land vehicles. With the advent of lithium-ion technology, secondary rechargeable battery cells have enabled more compact products with higher energy capacity and higher charge/discharge rates. Li-ion battery cells today power communications, surveillance, computing systems, robotics, unmanned platforms, and weapons in addition to electrical systems on board vehicles in land, air, and sea.

The battlefield is becoming more electrified to maintain superiority [1]. Advanced computational systems and connectivity requires more power and energy. Electrified robotics and autonomous systems provide superior surveillance, and reduced noise and thermal signatures. In all new applications the battery cell technology of choice is lithium ion. The technology is mature, with a robust supply-chain, and a roadmap to full sustainability on the back of legislation in the automotive industry on top of hazardous waste legislation. In the long term, doubling in energy capacity in battery cell technology is anticipated, through, for example solid-state batteries. This continuing trend in increasing battery energy density will facilitate electrification of increasingly larger platforms and more capable mission systems.

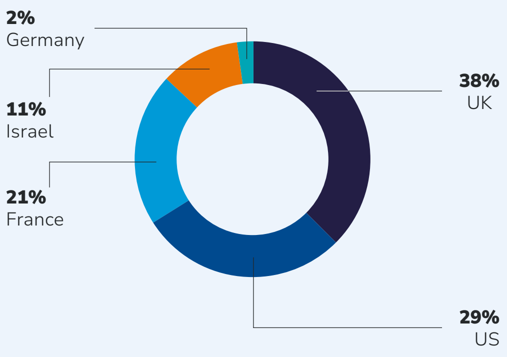
To prepare the armed forces for this transition, further R&D and investment will be required including replacement of old chemistries for Li-Ion [2], demonstration programmes of high energy systems and fully electric or hybrid vehicles, and larger deployment of BESS in operating bases.

Ricardo has conducted a survey of battery pack suppliers to the UK MoD. The share of products surveyed is shown below by company and country of manufacture.

Share of batteries per manufacturer

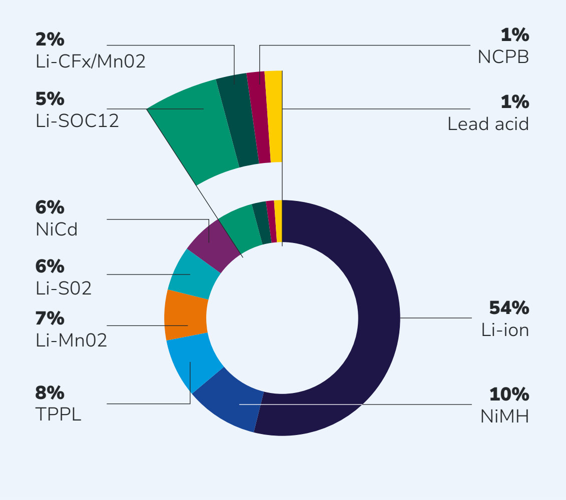


Share per country of manufacture

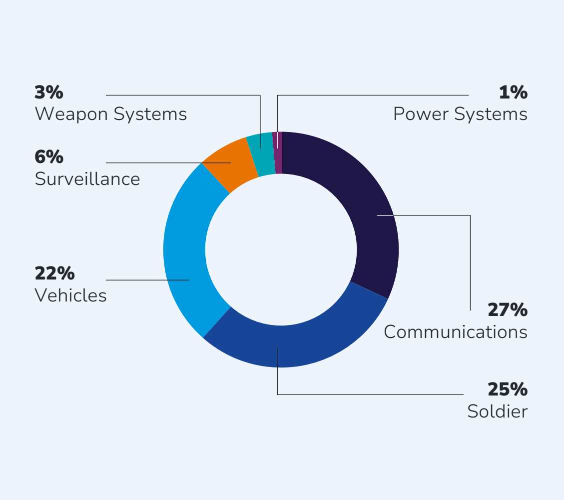


Today there is a clear trend to replace legacy chemistries with higher performing Li-Ion. Below illustrates the share of chemistries from the surveyed companies and products. Most rechargeable batteries are used in portable equipment as indicated by the application distribution shown in the chart.

Share of battery chemistry

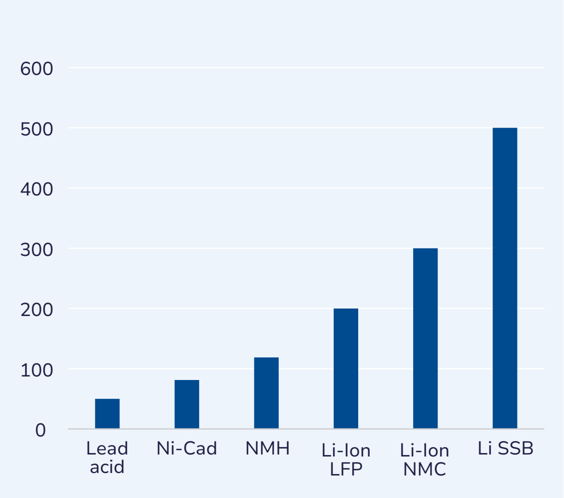


Battery split by application



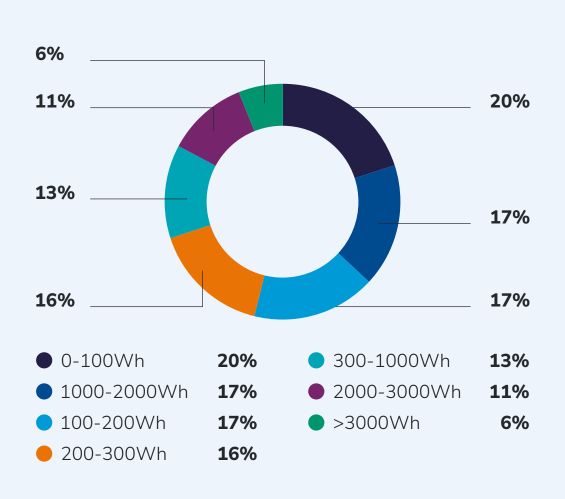
The primary reason is the higher specific energy density of more recent chemistries compared to old technology, as illustrated in the chart below, which also shows the potential for solid-state technology.

Energy Density (Wh/kg)



The largest share of rechargeable batteries are small capacity for solider-borne equipment and communications equipment.

Share of battery by capacity



There is a large share around the 2kWh capacity used for vehicles and for general purpose power systems. Most batteries in this capacity bracket align with standard MIL-PRF-32565C [3] for 24V nominal voltage and peak energy capacity of 1.3kWh or 2.1kWh. The standard defines physical form factor, electrical power interface characteristics, CAN bus communication format, and minimum performance requirements.

These batteries can be connected in series and parallel to achieve higher voltages, currents, and capacity. However, as the power terminals are exposed, additional mechanical packaging would be required to prevent hazardous conditions. Furthermore, these batteries are passively cooled and performance of larger arrays may be limited by temperature.

Image: *Example 6T MIL-PRF-32565C Battery*

Recent conflicts have demonstrated the use and effectiveness of battery-powered unmanned vehicles. Drones, in particular, have been shown to considerably increase surveillance and attacking capabilities, ranging from single use devices for precision strikes to large reusable units for reconnaissance, surveillance, and electronic warfare. Battery capacity requirements for these units therefore range from a few Watt-hours for micro-drones to hundreds of kilowatt-hours for large drones [4]. Power requirements equally range from hundreds of watts to several kilowatts. This wide range of battery system requirements increases the complexity of procurement and maintenance activities in the MoD when considering shelf life (e.g. 12 months) and cycle life (e.g. 1,000cycles / 5 years) compared to vehicle life (> 10 years).

Image: *Picture alliance / AA | Wojciech Grzedzinski ©*

ENERGY OR POWER BATTERIES

Batteries can be broadly classified as either energy or power depending on whether the load requires low or moderate power for long durations or high power for short durations. Yet some applications require a mix of reasonable energy capacity but capable of high peak power discharge. Recent advances in materials has enabled a new range of lithium-ion batteries with a good compromise between energy and power capabilities.

The choice of cell type depends on the load cases, platform type, and system complexity. Generally, and except for some cell chemistries, high power batteries will require advanced thermal management systems to extract the heat from the cells that is generated during high discharge rates. This prevents their use in systems with no access to active cooling such as soldier-borne equipment, small drones and robotic systems.

The chart below provides a high-level view of cell chemistry properties. For example, NCA cells offer high energy density but their cycle life, cost, and safety is not great. Similarly, LTO cells have excellent peak power discharge capability but their energy capacity and cost is not good. NMC cells are usually selected for applications requiring a good mix between high energy capacity and power capacity.

Graph: *Cell Chemistry Properties*

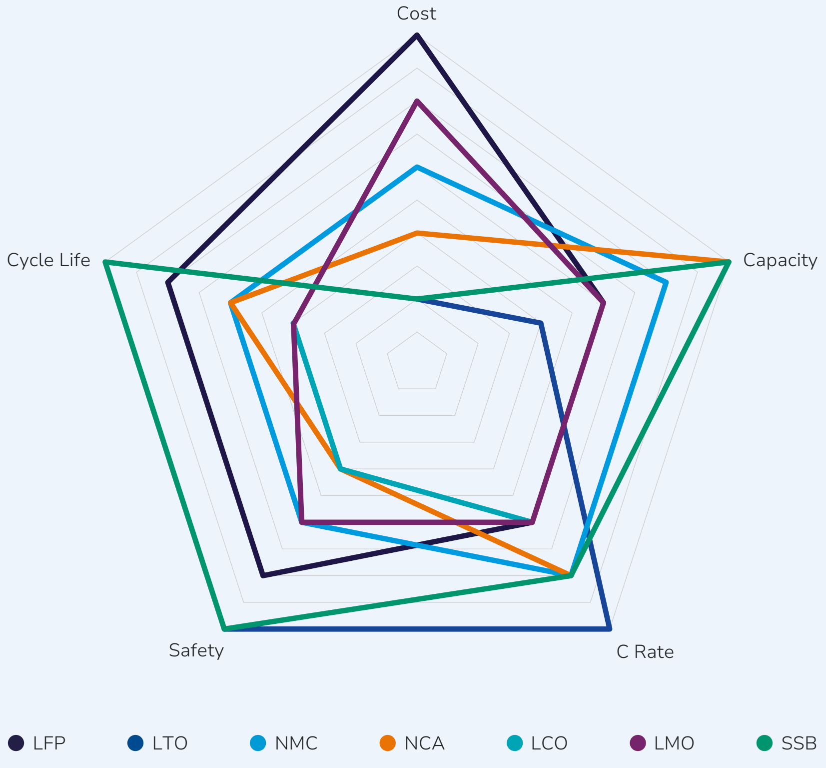


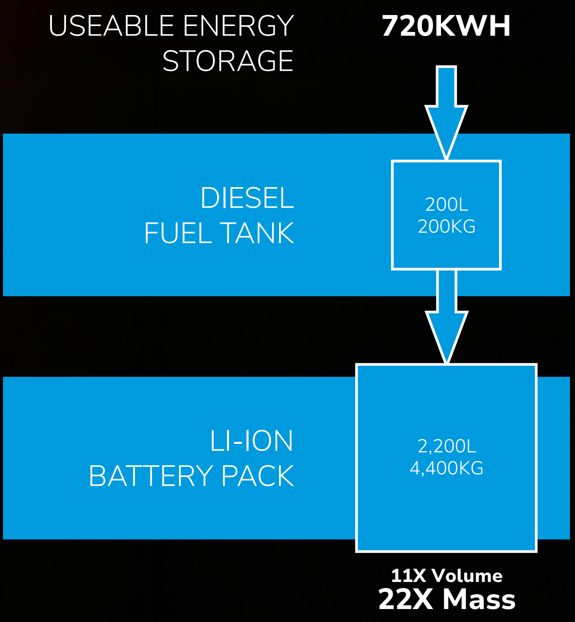
Image: *UK MoD DragonFire Test*

NEED FOR HIGHER POWER AND ENERGY

Beyond unmanned aerial vehicles, the armed forces will require high-power electrical sources to satisfy the goals of future battlespaces. Future weapon systems such as DragonFire high energy laser [5] and RapidDestroyer radio frequency systems [6] will require high-capacity Battery Energy Storage Systems (BESS) but must be sufficiently compact to be transported in land vehicles and aircraft. In addition, very high pulse power requirements are required to discharge energy in short bursts. Although actual power and discharge requirements are closely protected, it is expected that these systems will initially require hundreds of kilowatts increasing to megawatts as more capable weapons are developed with longer range and increased lethality. Conventional engine driven generators are incapable of delivering the pulse power required by these systems. Advances in lithium-ion power battery cells such as those found in motorsports like Formula 1, designed specifically with low internal resistance, are an ideal power source for these systems. Due to the very high power, active cooling of the battery cells is fundamental to prevent hazardous temperature rises that could lead to thermal runaway failures.

Despite incredible advances in energy density afforded by Li-Ion battery technology they cannot compare to the thermal energy stored in the molecular bonds of traditional liquid hydrocarbon fuels such as diesel and kerosine. The illustration below compares the motive energy storage capacity of a 200L fuel tank as found in a 10T armoured vehicle (assuming 35% thermal efficiency) with an equivalent Li-Ion battery pack (assuming 80% efficiency).

Image: *Vehicle Energy Storage Comparison*



As a result, it is accepted that liquid fuels, fossil derived or sustainable/synthetic, will be the primary energy vector to sustain the modern battlefield but utilising battery storage to increase the efficiency and ease of energy distribution. Consequently, heavy armoured vehicles are unlikely to be fully electrified due to their size and mission criticality while supply vehicles and personnel transports are good candidates for electrification. These platforms will use ruggedised technologies developed for the automotive industry. The larger land platforms are likely to be hybridised to take advantage of the electric power source to power high-energy systems but also to provide new mission capabilities such as:

- Reduced noise
- Reduced thermal signature
- Reduced idling and emissions
- Increased torque and acceleration
- Improved fuel efficiency
- Enable future electric armour and protection systems
- Enable electronic counter measures
- Enable advance computing and communication systems
- Enable high-energy/power systems

These improvements will not only increase the effectiveness and capability of the platform but also improve the efficiency of diesel fuel usage and therefore reduce the volume of fuel consumption and in turn the logistical burden of supplying the primary energy vector. It is estimated that every litre of fuel delivered to the front line requires 7 litres of fuel in transportation. It is therefore imperative that the fuel is used as efficiently as possible.

The battery cell technology found in fully electric vehicles differs from that of hybrid vehicles on the energy capacity and pulse power capability. While the former requires high energy capacity to achieve long range operations, the latter utilises fuel as its primary energy source and so requires a significantly smaller battery with high pulse power capability to act as an energy accumulator to harvest braking energy and recuperate it for traction, thus reducing fuel usage. Some platforms are likely to require a combination of both: moderate range under electric power and high pulse power capability. But it must always be considered that while clean and quiet, battery energy storage is a heavy means to carry energy compared to liquid fuel.

> Liquid fuels will remain the battlefield’s primary energy source.

With higher energy and power capacity in batteries comes higher risk of catastrophic damage in case of thermal failure events. Some battery chemistries and technologies are inherently safer against failures that result in a fast release of energy which in turn causes a catastrophic temperature rise and thermal runaway of the battery cell. If the single cell thermal failure is not contained, it can propagate to adjacent cells causing a complete battery pack failure and potential loss of platform. Chemistries such as LFP (lithium iron phosphate) and LTO (lithium titanate) are more stable (less reactive) than others like NMC (nickel manganese cobalt) and when failures occur from abuse or internal degradation, they will not fail in ways that causes a fast energy release. However, they may still undergo thermal runaway if their temperature is allowed to rise above safe levels through a combination of high charging, discharging, and ambient operating conditions. Therefore, regardless of battery cell chemistry, a Battery Management System that monitors cell temperatures and a cooling system that keeps the cells within an acceptable operating window are essential for meeting safety requirements.

PROCUREMENT, DEPLOYMENT, LIFETIME, AND MAINTENANCE

Battery packs used by the UK armed forces are mostly built within the UK, Europe, or the United States. The individual cells within those packs are manufactured in countries with high specialism in battery technology such as USA, South Korea, Japan, Taiwan, France, Germany, and China. With the exception of dedicated electric vehicle battery manufacture and assembly lines, there are no independent series production manufacturers of Li-Ion cells in the United Kingdom, which significantly limits the sovereign control of our electrification technologies in the defence industry.

The life of a battery depends on a number of factors such as chemistry, usage duty cycles, operating temperatures, and calendar life. Batteries can lose approximately 1% to 6% capacity per year when kept within rated temperatures and at State of Charge (SoC) between 20-80%, [7], [11]. NMC chemistry ages faster (up to 6%) compared to LFP and LTO (as low as 1%). This aging can be doubled in batteries that are kept at very low or very high SoC or at extreme temperatures. Calendar aging is important when considering that spare batteries will be kept in storage for several months if not years before they are fitted to their intended equipment or platform. A brand-new battery may only have 88% total capacity when installed after two years of storage. This may impact the ability to fulfil some missions if full capacity is required.

In addition to calendar aging, batteries also lose capacity after cycling, which again depends on chemistry, charge/discharge rates, operating temperature and depth of discharge. LTO chemistry offers the highest cycle life, in excess of 5,000 cycles, compared to NMC chemistry which is typically 1,000 cycles. This cycle life is based on a 20% capacity loss over the number of cycles at a low charge/discharge rate of typically 0.3C to 1C. Capacity loss increases dramatically at higher rates, e.g. 30% at 5C and 50% at 10C. In short, the life of a battery will heavily depend on its operating duty cycles. Equipment used frequently at high charge/discharge rates will require more frequent battery replacement, e.g. in less than 2 years. In contrast, batteries in assets that tend to be unused for long periods of time with some occasional use at low rates may last a long time, e.g. more than 10 years.

Consequently, the task of procuring, storing, replacing, and disposing of battery packs in future electrified platforms is a logistical challenge. Some batteries may need replacing in as little as 2 years, while some batteries in storage may last only 2 years without substantial loss of capacity. Compound this by the different chemistries and form factors across different platforms and we can quickly end up wasting considerable money to maintain platform capability. It would be a logical step to attempt a level of standardisation of large battery system akin to the MIL-PRF-32565C Type 6T battery, but is this a sensible approach?

CAN ONE-SIZE FIT ALL?

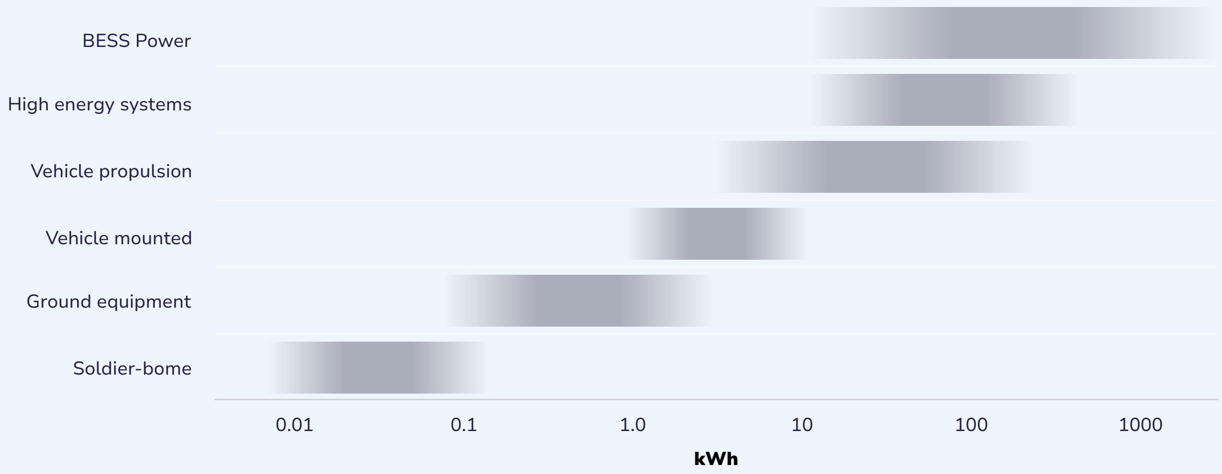
Evidently the range of applications is so vast that there is no single battery solution that fits all. Once we group applications by energy requirements, we can see that clusters start to form, for instance applications could be divided into three power levels with building blocks of 1kWh, 10kWh, and 100kWh. Modular systems can then be built from the basic building blocks. Yet, it is unlikely that all applications could be met with generic building blocks as each platform may have specific form factor, mass, and performance requirements.

From a performance point of view, batteries also vary widely in attributes:

- Cooling method: passive or active (air cooled, liquid cooled with water/glycol or dielectric fluid)
- Peak discharge: from 1C to 100C
- Cycle life: from 200 to 10,000 cycles
- Operating temperature range
- Cell venting behaviour

These considerations will further constrain the general application of a common battery module. However, are there any lessons that we can learn from the civilian mobility industry?

Image: *Energy Capacity Requirements*



MODULAR, INTEROPERABLE, SWAPPABLE BATTERIES

Modular, interoperable, and swappable batteries offer a wide range of benefits:

1. Multi-sourcing the supply: eliminates single purchasing option, reduces cost and risks with supplier resilience and reliability
2. Single charger type: simplifies asset management and deployment
3. Simpler logistics: procurement, storage, distribution, maintenance, replacement, and disposal
4. Established performance for well-define vehicle use-cases
5. Ability to scale system for higher capacity
6. Fast swapping for continued vehicle operation

Automotive, commercial vehicle and motorcycle OEMs have developed modular and swappable battery systems with mixed success. Generally, it is easier to support battery swapping on small light duty, domestic equipment but storage and handling issues become increasingly challenging with larger, heavier duty, industrial equipment.

To date, few interoperable batteries have been developed for mobility platforms despite some concentrated effort by a handful of companies [9]. Motorcycle OEMS and Battery Swapping Service providers in East Asia have been the most successful at implementing swappable batteries. Both private and commercial users like the capability as the vehicle is always ready to run, especially those with dual batteries. Swapping of a battery pack at a service station can take as little as 3 minutes. Swappable motorcycle battery packs range in capacity from 1kWh to 4Wh, with nominal voltage of typically 48V or 72V.

Image: *Ricardo's EV Motorcycle Swappable Battery Pack*

Image: *NIO Battery Swapping Station*

Commercialisation of swappable batteries in larger vehicles has been driven by Chinese EV and battery OEMS with some success, but adoption in Europe and USA remains weak, mostly due to the need for substantial infrastructure to deploy large battery swapping stations. The Chinese manufacturer NIO is expanding its network of swapping stations in Europe, currently totalling 61.

NIO uses a robotic system to get under the car to swap the battery. With the weight of the pack exceeding 300kg and the need to align coolant and electric connections, an automated system like this is required for fast swapping.

Italian-Chinese startup company XEV manufactures a small car, L7e category, featuring modular swappable batteries that can be replaced by hand. The vehicle system comprises three identical modules, each of 24V and 3.4kWh, that are connected in series inside the vehicle to provide a 72V bus to the electric powertrain. The battery is passively air cooled and can only charge and discharge at rates lower than 1C, [10].

Image: *XEV YOYO Swappable Battery System*

As with motorcycles, there are no standards enabling the interoperability of swappable batteries across different vehicles. However, as these batteries can still charge with standard charging station infrastructure, some commonality exists, and we are able to define interoperability levels as listed below.

Level 1 interoperability is the easiest to achieve and is common in the automotive EV sector. Level 2 would bring standardisation of the BMS physical communication and message interface to be able to operate the battery pack safely in a platform. Level 3 would offer ultimate interoperability, as has been achieved for Type 6T batteries.

An important factor to consider in swappable and interoperable battery packs is the cooling requirements. Batteries that are passively cooled are easier to integrate into platforms. In contrast, batteries requiring active cooling, water/glycol or dielectric fluid, put requirements on platform cooling systems to meet fluid type, pressure rates, flow rates, and fluid temperature. Interoperability of actively cooled battery packs is more difficult as the pack and platform need dry-break connectors, compatible coolant mix, and tightly controlled pressure drop and flow rate.

Level	**Standardisation**	**Description**
0	None	No interoperability possible.
1	Connectors and charging protocol	Possible to connect to a standard charger, negotiate a charging session, and complete charging process.
2	As L1 + BMS interface	Same as L1 plus ability to electrically connect the battery pack to different platforms to perform operations, monitoring, and diagnostics. Useful for deploying batteries in stationary applications or in load bays in vehicles.
3	As L2 + physical form factor	Same as L2 plus ability to fit to different platforms and maintain vehicle integrity.

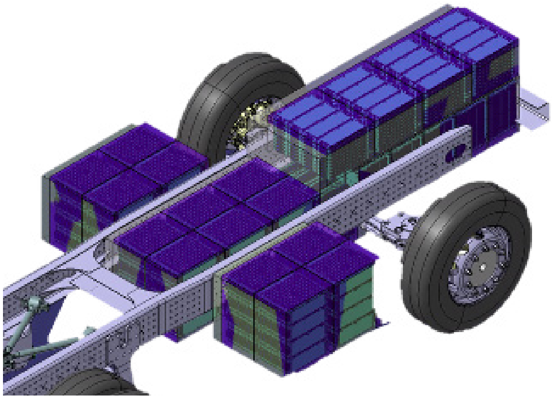
Image: *Ricardo's 10MWh Battery Energy Storage System for Ship Propulsion*

SCALABLE BATTERY SYSTEMS

Platforms with very high power and energy demand are designed with modularity due to system complexity, platform layout, and safety. For example, heavy-duty road electric commercial vehicles may contain two to six 100kWh battery packs. Even larger systems can be found in fully electric mining vehicles, some with up to ten 200kWh battery packs. High modularity systems allow faults to be contained, isolated, and repaired at a module or pack level while allowing the system to continue operation.

Modular packs can be connected in series and/or parallel, although paralleling is most common. Failures in one pack can be isolated while the system continues to operate with the remaining packs. This modularity enables systems to grow to any size up to several MWh like those used in grid energy storage and ship battery systems.

Image: *Ricardo's Modular Battery Pack Layout in Heavy-Duty Vehicle*



> A common core module enables scalable battery systems across fleets, delivering flexibility in capacity while maintaining consistent safety and design principles.

> Where space and weight are critical, cell-to-pack architectures replace modular systems to maximise energy density.

Although modular systems bring flexibility, the extra enclosures, connections, and electrical components have a detrimental effect on energy density. In land and air vehicle applications where space and weight are at a premium, modular systems are not the best choice. Instead, the preference is for a cell-to-pack or cell-to-chassis architecture that maximises energy density at the expense of interoperability and modularity.

In a module-to-pack approach modules can be assembled independently before combining into a complete pack. Safety is addressed at the module level, for example thermal management, failure management, and venting. In a cell-to-pack approach all these aspects are handled at the pack level.

While cell-to-chassis approaches would offer even higher energy density than cell-to-pack, the complexity of removing packs for maintenance or in swap systems is greatly increased as the internals of the assembly would be exposed during the operation.

A modular system also offers scalability with minimum incremental cost. Battery packs of different capacity can be designed using the core module while applying the same safety principles to pack design. This can be beneficial when a diverse fleet of vehicles are electrified: same core module, scalable pack capacities.

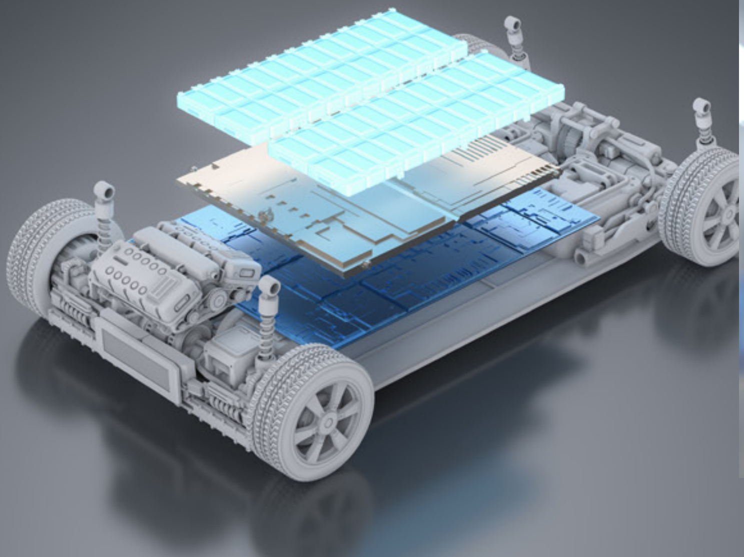
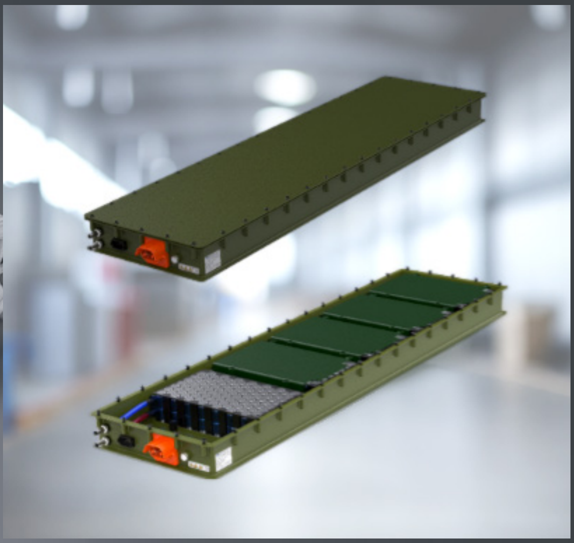


Image: *Ricardo's Module-to-Pack Battery Pack*



CONCLUSIONS

As the battlespace becomes increasingly electrified, the importance of advanced, reliable, and adaptable battery technologies will only continue to grow. Lithium-ion systems already underpin most modern military platforms—from soldier-borne electronics to unmanned systems and emerging high-energy weapons—and future operational effectiveness will depend on further improvements in energy density, power capability, safety, and sustainability. While next-generation chemistries such as solid-state, LFP, and LTO offer promising benefits, no single solution can meet the wide spectrum of military power requirements. Instead, a strategic combination of modularity, interoperability, and scalable design will be essential.

The diversity of mission profiles, environmental conditions, and platform architectures means that defence organisations must adopt a holistic approach that spans R&D, procurement, logistics, safety, and lifecycle management. Standardisation efforts—such as leveraging common building blocks or adopting shared interfaces—can simplify supply chains and reduce costs, but they must be applied thoughtfully to account for technical constraints like cooling, thermal runaway behaviour, and platform integration.

To maintain capability over the next decade and beyond, the UK armed forces will need to invest in sovereign solutions and a robust support infrastructure. By embracing emerging technologies, improving energy management, and preparing for the high-power demands of future weapons and autonomous systems, our armed forces can ensure that electrification becomes a strategic advantage rather than a logistical burden. The transition is already underway, and those who adapt early will shape the next generation of military operations.

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