NOVEL / GREEN ENERGY SOLUTIONS FOR TACTICAL SOLDIER APPLICATIONS

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ABSTRACT

Soldiers today are carrying more digital devices for communications and surveillance as well as many other operational missions on the battlefield, as such they are increasingly becoming prolific consumers of electrical energy. Though the Command, Control, Communications and Computers (C4) devices have become more efficient and lighter in recent years, soldiers are required to carry a great number and variety of devices for various missions. This places a heavy weight burden on our warfighters especially when is a need to carry extra batteries for different devices for sustained operations on the battlefield. Through this project, we will investigate more on the various novel and green energy solutions, by exploring multiple electrochemical systems and fuel cells to recommend an energy-dense and sustainable solution for tactical soldier applications.

INTRODUCTION

Technology has come a long way since lead acid batteries. A variety of new battery technologies are emerging and being researched today. From the commonly used Lithium-ion (Li-ion) batteries to new and promising alternatives such as solid-state batteries and hydrogen fuel cell, more research is being done on the materials that power our world. As soldiers increasingly utilize more electronic devices, it is imperative to manage the overall Size, Weight and Power (SWAP) requirements through the identification of novel and green energy solutions that offer higher energy density, safety, cost-effectiveness and sustainability.

AIM

To investigate energy-dense, lightweight, safe and sustainable emerging battery technologies for tactical soldier applications.

LITERATURE REVIEW

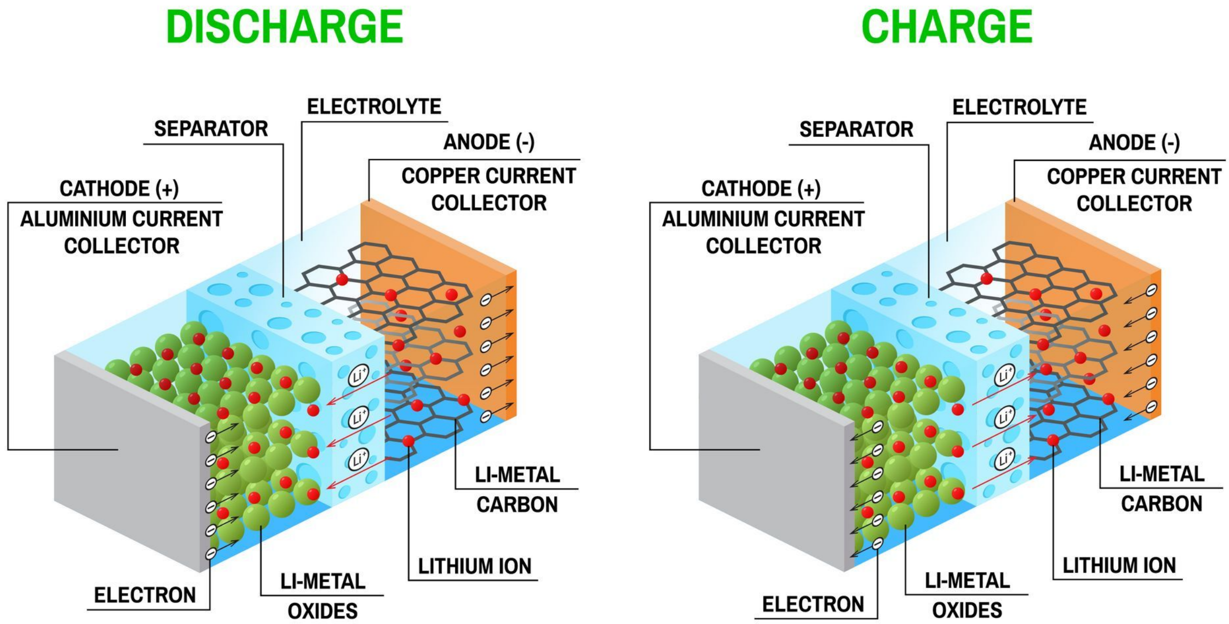
This report categorizes the energy technologies reviewed into 3 segments to facilitate the discussion and recommendations as follows: (1) Existing Technology (up to 2025), (2) Tech Ready (2025 to 2030) and (3) Tech Not Ready (2030 and beyond).

(1) Existing Technologies (Up 2025)

Li-ion Battery

Li-ion batteries are commercially available and widely used in rechargeable batteries. They utilise the reversible intercalation of Li+ ions into electronically conducting solids to store energy. The cathode is made of a composite material, an intercalated lithium compound while the anode is made out of porous lithiated graphite. The electrolyte can be liquid, polymer, or solid. The separator is porous to enable the transport of lithium ions and prevents the cell from short-circuiting and thermal runaway [1]. Refer to **Figure 1** for illustration of how a Li-ion battery works.

Figure 1: How a Li-Ion Battery Works [2]



Widely used commercially especially in Electric Vehicles (EVs) and Energy Storage System (ESS) due to its high energy density (200 to 300 Wh/kg) [3]. Li-ion batteries have higher voltages (nominal voltage of 3.6 to 3.7V [4]) than their counterparts and hence able to store more energy and discharge more power in heavy applications such as running an automobile at high speed.

Li-ion batteries however are still relatively expensive ($200 to $300 per kWh for an EV battery pack [5]). Li-ion batteries naturally degrade and will only be able to withstand 500 to 1,000 charge and discharge cycles before their capacity falls to 50%. If the battery's internal components become damaged due to extreme heat, overcharging (leading to dendrite formation), or physical stress, it can lead to a rapid increase in temperature and pressure within the battery cell i.e., thermal runaway and thus catch fire or explode. Additionally, destructive mining practices to extract lithium has led to pollution and other consequential implications [6].

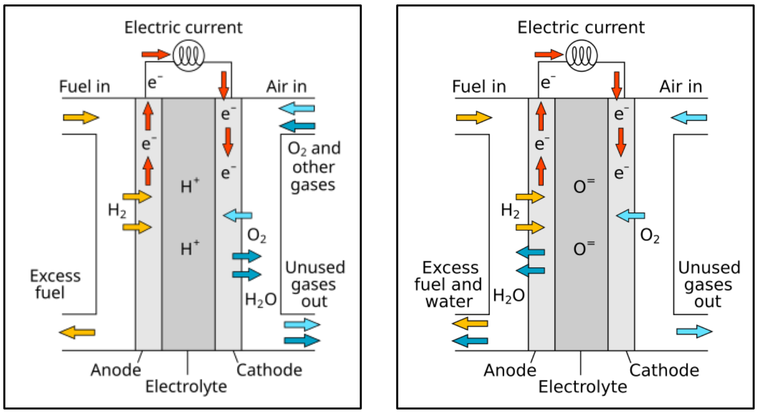
As the Army increasingly embraces technology to enhance warfighting capabilities, Li-ion batteries have become indispensable as they are used in a wide range of tactical C4 soldier equipment due to their high energy density and voltage. However, existing Li-ion batteries are extremely heat-sensitive and subject to explosion in certain combat circumstances. Soldiers will also be carrying heavy gear and conducting attack operations at night, thus reliant upon battery-powered weapons, sensors and computers. Hence, it is crucial to investigate further for a less flammable, more energy dense and sustainable alternative.

Hydrogen Fuel Cells

Hydrogen fuel cells convert energy stored in molecules into electricity through an electrochemical reaction [7]. It is composed of two electrodes separated by an electrolyte membrane. Hydrogen enters the fuel cell via the anode and generates electrical energy with oxygen. The hydrogen acts as an energy carrier and storage device, much like a battery [8].

One common type is a Polymer Electrolyte Membrane Fuel Cell (PEMFC), which uses a water-based polymer membrane as an electrolyte to convert hydrogen and oxygen into electricity and particularly suitable for use in vehicle applications as it is able to deliver high power density compared with other fuel cells. Another common type is a Solid Oxide Fuel Cell (SOFC), which has a solid oxide or ceramic electrolyte. At the anode, the fuel reacts with oxygen ions to produce water, carbon dioxide, and electrons. These electrons flow through an external circuit, generating electricity [9]. Refer to **Figure 2** for PEMFC and SOFC schematics.

<u>Figure 2: Different Types of Hydrogen Fuel Cell</u> [9][10]



PEMFC SOFC

Like all-electric vehicles, Fuel Cell Electric Vehicles (FCEVs) use electricity to power an electric motor. In contrast to other electric vehicles, FCEVs produce electricity using a fuel cell powered by hydrogen, rather than drawing electricity from only a battery [11]. Industry is driving FCEVs due to its high energy efficiency[1], energy density (450 to 650 km on a single tank of hydrogen [12]), fast refueling time (3 to 5 minutes [13]), minimal noise due to electric motors and are environmentally friendly as it only produces water as a waste product.

However, FCEVs require modern infrastructure such as hydrogen refueling stations, which are scarce worldwide, with most located in specific regions like California, Japan, South Korea, and parts of Europe. FCEVs are currently more expensive than conventional vehicles and hybrids, and transporting hydrogen is also energy-intensive and costly. In addition, storing/transporting hydrogen under high pressure is risky especially with the risk of collision.

The benefits have however driven Industry to push FCEV developments, which include:

a. <u>General Motors (GM) SURUS (Silent Utility Rover Universal Superstructure)</u>. A hydrogen-powered, autonomous platform designed for military and disaster relief operations. Provides silent operation, long range, and onboard power generation [14]. A modular platform was designed for heavy-duty trucks that will enable near-silent running, zero harmful emissions, and autonomous operation [15].

b. <u>US Army Hydrogen Vehicles</u>. The US Army is testing a new type of zero-emission hydrogen fuel cell vehicles in the form of a rescue truck with a massive 1,500-mile range between refueling, focusing on stealth and extended range [16]. Fuel cell vehicles typically have

[1] 50 to 60% compared to only 25 to 30% for gasoline internal combustion engines [17]

a larger range, are lighter, are still quiet, and can operate in areas away from an electrical grid, which can improve disaster response capabilities in emergency situations [18].

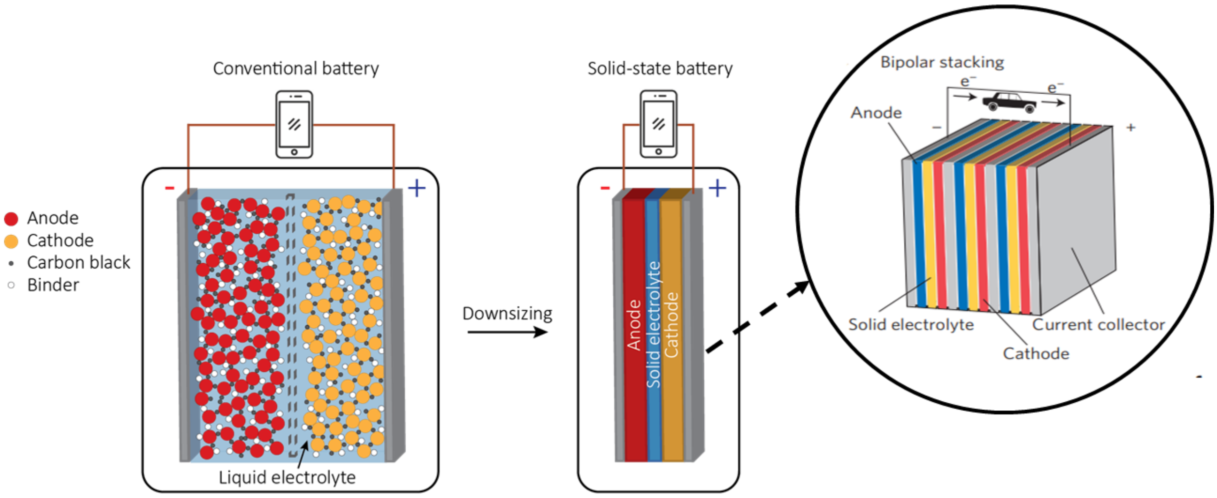
Whilst developments thus far have been largely focused on FCEVs, it is noteworthy that Industry is also developing a more man-portable version. **Honeywell won a contract in 2024 to develop a man-portable hydrogen fuel cell prototype for US Army soldiers** to power the myriad of electronic devices they carry. Development of the prototype will **take advantage of Honeywell's proven PEMFC technology** which is already in use in unmanned aerial systems for commercial and defence applications. The hydrogen fuel cell is intended to half the weight of currently carried batteries and provide power on the move [19].

(2) Tech Ready (2025 to 2030)

Solid State Batteries (SSB)

SSBs utilise solid electrolytes, instead of liquid or gel electrolytes which can be alternated and stacked with bipolar electrodes (cathode and anode material coated on opposite sides of the current collector) within a single package. Refer to **Figure 3** for illustrative explanation. This reduces the overall volume and weight of the application, increasing the energy density as compared with Li-ion batteries.

Figure 3: Conventional Battery Versus Solid State Battery Design [20]



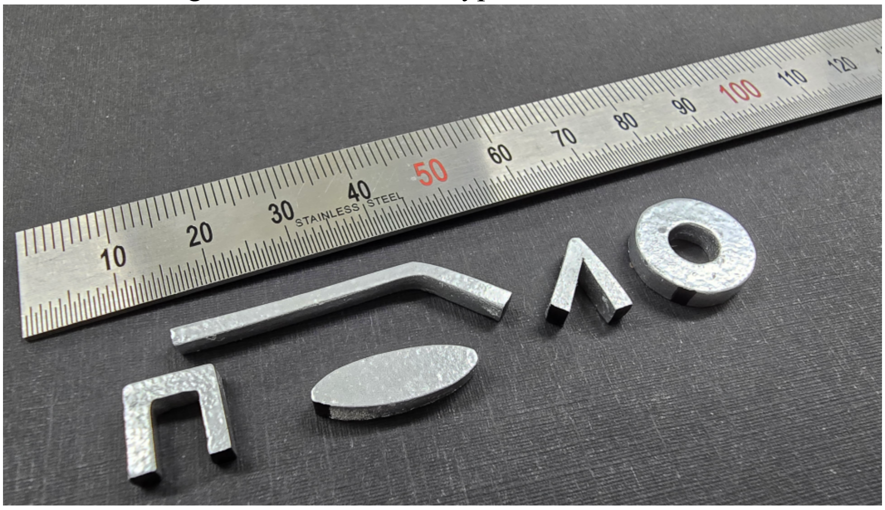
SSBs offer significant advantages [21] over conventional liquid electrolyte Li-ion batteries, due to their use of a metallic lithium anode and solid electrolytes made of oxides or sulfides. This results in higher energy density (*350 Wh/kg versus sub-300 Wh/kg for Li-ion*), higher specific capacity (*3860 mAh/g*) and are environmentally friendly as graphite and cobalt are no longer necessary. Additionally, the Solid-State Electrolytes (SSE)[2] within are non-volatile, non-combustible and thus inherently safer. SSEs address many of the challenges faced by liquid electrolyte batteries, such as flammability, limited voltage, and poor cycling performance [22]. SSE also suppresses growth of lithium dendrites [23], thereby providing a stable, uniform interface for Li-ion movement [24].

[2] Promising materials used for SSE include: (1) Lithium-stuffed garnet-type oxides e.g., $Li_7La_3Zr_2O_{12}$ (LLZO), due to their high ionic conductivity (above 10^{-4} S/cm at room temperature), excellent thermal stability, compatibility with lithium metal anodes [25] and (2) Chloride Solid Electrolytes for higher theoretical ionic conductivity, superior formability compared to conventional oxide-based SSE [26].

SSBs are however costly to manufacture/ acquire and projected to cost $800/kWh to $400/kWh by 2026. SSBs require high pressure and temperature to operate, and remains susceptible to lithium dendrite growth albeit a lower probability as compared to Li-ion batteries. However, if dendrites form, they do more damage to SSBs due to the inherently fixed SSE volume. SSBs are also susceptible to mechanical failure during discharging due to the rigid SSE which leads to stress at the interface [27].

Notably, **Samsung has unveiled SSB developments in 2024** which includes: (1) SSB for EVs (500 Wh/kg) which is capable of a 965 km charge in 9 minutes (20% to 80% capacity) with a 20-year lifespan [28] and (2) **Ultra-compact All-Solid-State Battery (ASSB) for wearable devices** [29]. It is an oxide-based small ASSB with **energy density of 200Wh/L, which is equivalent to Li-ion batteries but smaller in size**. Refer to **Figure 4** for size illustration. Product is currently under prototype evaluation.

Figure 4: Size of Prototype Small ASSB [29]



Lithium-Silicon Battery

Type of Li-ion battery that employs a silicon-based anode with Li-ions as the charge carriers. Lithium silicon batteries theoretically have a higher storage capacity[3] and low discharge potential. As silicon can absorb Li-ions, this leads to a significant increase in the energy density of a lithium-silicon battery, up to 400Wh/kg [30]. Silicon polymers, which have flexibility and elasticity can be used to enhance the mechanical stability of the silicon particles in the anode, reducing the likelihood of cracking during expansion and contraction.

However, it still expands and contracts a lot, leading to swelling [31]. In powder-based silicon anodes, the decrease in capacity during cycling results from the increasingly large volume changes in silicon as lithium insertion proceeds. Since silicon undergoes 400% volume expansion at maximum lithium insertion, it may not be possible to achieve a reversible volume change. Because of this expansion, stresses created in the anode may exceed the breaking stress of silicon, resulting in particle cracking and the unavailability of progressive amounts of silicon for further lithium insertion and extraction due to loss of inter-particle electronic contact [32].

[3] Up to 10 times more Li-ions than lithiated graphite anodes and much larger for various nitride and oxide materials [33].

For both silicon and graphite anodes, the Solid Electrolyte Interface (SEI) layer is the result of the reduction potential of the anode [34]. Silicon-based anodes have shown serious performance degradation under the conditions of study, which may be characterised as a result of anodic volume changes on cycling under constant pressure conditions. In such cases, anode expansion occurs on charge, and with the loss of interparticle electronic contact, anode capacity over time [34].

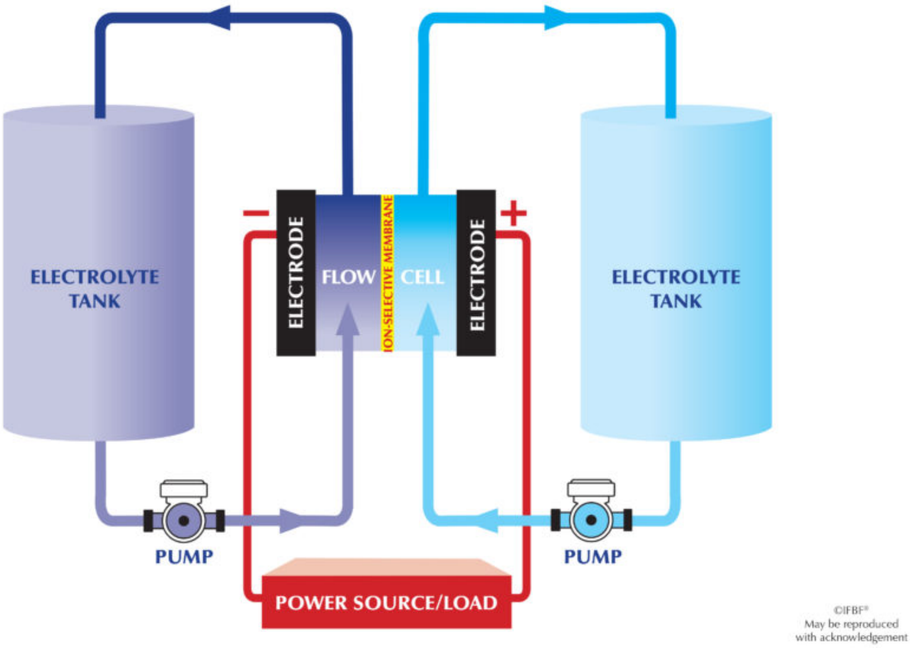
Sila Nanotechnologies was the first company to dramatically reduce swell and safely harness the powerful properties of silicon for commercial use in Li-ion batteries with their nano-composite silicon. The research was started due to its ability to store up to 10x more charge than widely used graphite. **Replacing graphite with silicon delivers a 20% energy density boost over the industry's best performing cells** and is **projected to achieve up to a 40% increase in the future releases.** These gains are attainable without sacrificing cycle life or safety, by containing swell to levels comparable to graphite [35].

(3) TECH NOT READY (BEYOND 2030)

Flow Battery

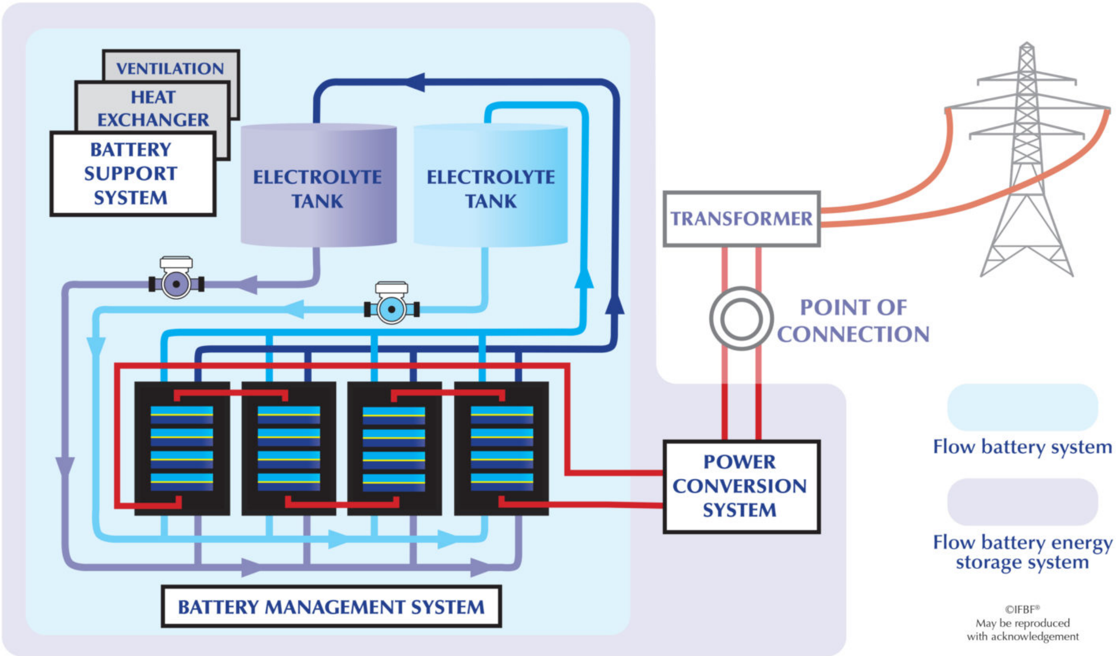
Rechargeable battery in which an electrolyte containing one or more dissolved electroactive elements flows through an electrochemical cell that reversibly converts chemical energy to electrical energy, and its fuel can be regenerated by recharging. Refer to **Figure 5** for schematic of a flow battery.

Figure 5: How a Flow Battery Works [36]



Individual fuel cells produce relatively small electrical potentials, about 0.7V, so cells are "stacked", or placed in series, to create sufficient voltage to meet an application's requirements. Refer to **Figure 6** for flow battery system design. With a simple flow battery, it is straightforward to increase the energy storage capacity by increasing the quantity of electrolyte stored in the tanks.[37]

Figure 6: Flow Battery System [36]



This decoupling of energy rating and power rating is an important feature of flow battery systems. The choice of redox pairs (electroactive materials / compounds that can reversibly undergo oxidation and reduction) is often used as a description of the type of flow battery. Some well-known redox pairs are: Vanadium / vanadium (which uses the four different valency states of vanadium), Iron / chromium and Zinc / bromine [36].

Flow batteries have almost an unlimited battery cycle life because of the absence of phase-to-phase chemical reactions and can be cycled every day for up to 30 years. Flow batteries use non-flammable electrolytes, such as vanadium solutions, which are less likely to catch fire and allows for the electrolyte tanks to be stored separately from the power stack, increasing their overall safety [38]. Flow batteries are made from low-cost materials, do not use limited resources such as cobalt and typically use vanadium as the electrolyte, which can be recovered from waste products and reused, reducing its environmental impact and cost of ownership [39].

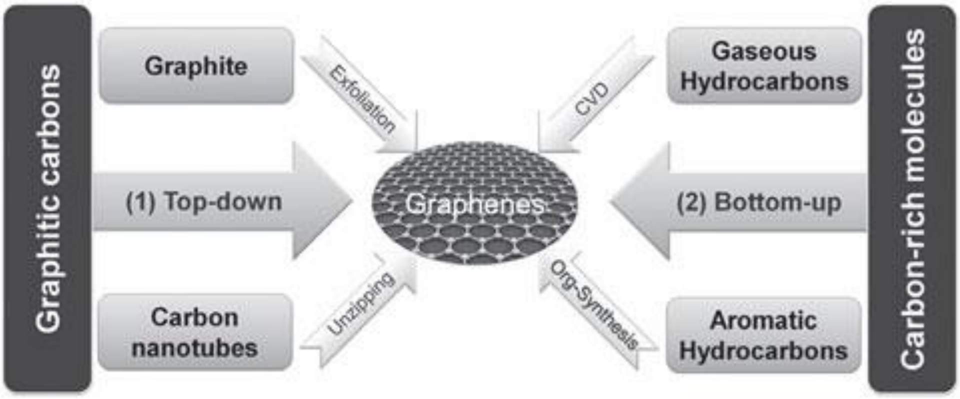
Flow batteries are however currently more expensive than Li-ion batteries. They have relatively low charge and discharge rates of up to 10 hours at a time, which requires a relatively large surface area to occur. This along with more pumps, plumbing, maintenance and the industry immaturity of flow batteries, makes it a more expensive option [40]. Conventional flow batteries pack very little energy into a given volume and mass, causing their energy density to be as little as 10 percent that of Li-ion batteries as it has to do with the amount of material an aqueous solution can hold. This causes flow batteries to be heavier than Li-ion batteries and takes up more space due to their considerably-sized bulky tanks [41].

Notably, Illinois Tech spinoff **Influit Energy** aims to commercialise [42] a prototype rechargeable electro-fuel, non-flammable, fast-refueling liquid flow battery that carries **23% more energy than lithium batteries**, making it more energy dense and hence more compact. Their **latest developments project an estimated 4 to 5 times higher energy density than Li-ion of about 550-750 Wh/kg, at a third the cost of Li-ion batteries** [43].

Graphene

A single layer of carbon atoms, arranged in a hexagonal lattice or honeycomb-like structure. Refer to **Figure 7**. The sheet of graphene is very thin and is often regarded as a two-dimensional structure [44]. This unique property lends itself well for battery production as it also has excellent electrical conductivity, low weight, and a strong physical structure [45].

Figure 7: What Makes Up Graphene [46]



By incorporating graphene into the electrodes of Li-ion batteries, it can improve performance [47] such as increasing battery conductivity (faster charge and discharge cycles), increasing energy density due to high surface area of graphene and increasing storage capacity by creating a myriad of pathways for Li-ions to intercalate [48]. The use of graphene also prevents oxygen release into the electrolytes by forming carbon-oxygen bonds and thus prevents battery fires from occurring. Additionally, graphene is of nanometer-scale thickness which adds virtually no extra weight to the battery [49].

Mass production of graphene is prohibitively expensive and extremely complex, putting it out of reach for the vast majority of applications. This is also due to the lack of mass-production techniques for manufacturing high-quality graphene batteries, resulting in high costs[4] of graphene batteries. Graphene has extremely high first cycle loss at 50%-60% and low cycling efficiencies at 95%-98% at current densities. With poor capacity retention, the battery's lifespan is reduced, leading to more frequent replacements, which can be costly and environmentally impactful. Lacks a bandgap, which implies that there is no place in the material where electrons do not exist and therefore cannot be switched off. Thus, an artificial bandgap must be engineered in graphene to overcome the challenge. However, introducing a bandgap often reduces graphene's conductivity, which could negatively impact charge/discharge rates and battery efficiency [50]. Lastly, the preparation of graphene-based nanomaterials with well-defined structures and the controllable fabrication of these materials into functional devices remains to be challenging [51].

In recent years, **BeDimensional teamed up with the Italian Institute of Technology and the largest battery manufacturer in Europe, VARTA Microinnovation, to develop graphene-enabled silicon-based lithium-ion batteries [52].** Lithium-silicon batteries expand and contract, which mechanically stresses and fractures the material, eventually causing the battery

[4] Current production cost of 1 kg of graphene ranges between tens and thousands of dollars, which is substantially higher compared to the production cost of activated carbon at $15 per kilogram.

to fail after just a few cycles of use. Researchers from these companies have envisioned a way to stabilise the batteries using a little graphene. These **newly developed graphene-enabled batteries can withstand over 300 cycles and have capacities that are 30% higher than any currently available alternative** [53]. Eliminating the main disadvantages of the lithium-silicon battery, their research allows for a compact and energy dense battery to be produced.

NanoGraf's Silicon Oxide-Graphene (SOG) battery uses a patent-pending graphene scaffolding system to contain and protect silicon nano-particles in the anode. It combines the power of a silicon oxide anode with their own proprietary graphene scaffolding, an atomically-thin material. These batteries are estimated to be **15% lighter than their competitors**, and also **last 15% longer** [54].

CONCLUSION

Though Li-ion batteries are widely used today for military equipment and devices, they add-on to the warfighter's weight burden alongside other drawbacks. Through this literature review, we have **identified promising developments in the near term** such as **(1) man-portable hydrogen fuel cells** which are more energy-dense and projected to reduce battery weight by half whilst being sustainable, **(2) ultra-compact ASSBs** for wearable devices which provide a safe, energy dense and extremely small power source suitable for tactical applications and **(3) lithium-silicon battery developments** which project to achieve 20% to 40% increase in energy density. In the **longer term**, **(4) development of an inherently safe flow battery** with 4 to 5 times higher energy density than Li-ion batteries and **(5) incorporation of graphene into Li-ion batteries** to reduce weight and increase capacity by 30%. Please refer to **Annex A** for a more detailed comparison.

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ANNEX A

COMPARISON BETWEEN DIFFERENT BATTERY TYPES

How Safety and Sustainability are evaluated below:

- Safety is evaluated by how susceptible the battery is to thermal runway, i.e., the chances of the battery igniting.
- Sustainability is evaluated by how easy the material is to obtain (whether it requires man labour and/or if destructive mining practices are involved) and how long-lasting the battery is, i.e., how long it can be used before it has to be disposed of.

		Factors for Comparison			
Timeline	**Energy Solutions**	**Energy Density (Wh/kg)**	**Safety (Y / N)**	**Sustainability (Y / N)**	**Cost (USD / kWh)**
Existing	**Li-ion**	250 - 270	Y	N	2021: 132 2022 & 2023: 200 - 300 2024: 89
	Hydrogen Fuel Cell	39000	Y	Y	0.10 - 0.15
Tech Ready (2025 - 2030)	**Solid State Batteries**	400	Y	Y	80 -90
	Lithium-Silicon	400	Y	N	2
Tech Not Ready (Beyond 2030)	**Flow Battery**	Different Redox Pairs Vanadium-cerium: 20 - 35 Zinc-bromide: 60 - 70	Y	Y	800
	Graphene	1000	Y	N	118