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Multifunctional Power Systems for Improved Size, Weight, and Power (SWaP) in Portable Electronic Systems

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Abstract

Multifunctional energy systems use a single material system to perform multiple functions in a larger system. For example, structural components can be made out of materials that not only provide mechanical strength but also store energy, or protective components can be made out of materials that not only provide protection, but also harvest energy. By satisfying multiple requirements with a single material system, multifunctional energy systems can eliminate some components of the system and improve overall system size, weight and power. This report examines several multifunctional energy systems and quantifies the potential impact of these systems.

Executive Summary

Traditional material systems are designed and built for a single purpose. A composite wing is built to provide lift for an aerial vehicle, a window is designed to allow visible light into a building, and a road is designed to allow for the safe passage of ground vehicles. The multifunctional systems examined in this report add electrical power and energy capabilities to traditional material systems. These Multifunctional Energy Systems (MFES) are a novel approach to system optimization and can significantly improve their Size, Weight, and Power as well as Cost (SWaP-C).

MFES encompass a wide variety of materials including textiles, building materials, vehicle structural materials, and protective materials. They can be used to store various forms of energy (electrical, thermal, kinetic, potential, chemical, etc.) or to harvest various forms of power (solar, kinetic, thermal, etc.). MFES generally involve some performance compromises, since a single material system must perform multiple functions. In a number of applications, these performance compromises can be more than offset by improved system performance.

A review of literature shows that many MFES are impractical due to fundamental physical limitations, materials requirements, and costs. This literature review also highlighted several MFES with the potential to provide significant system benefits.

Structural electrical energy storage, where a single material provides both structural strength and electrical energy storage, is a promising MFES. Batteries and supercapacitors are commonly used for electrical energy storage and can consume significant weight and volume in high performance applications. With the proper materials choices, these batteries and supercapacitors can also provide structural support. Calculations of the performance of multifunctional supercapacitor/body armor show that such a system could store between 100 Wh and 750 Wh of energy and significantly reduce the number of batteries carried by a dismounted warfighter. Calculations of small UAV performance show that UAV flight time could increase by up to 200% and 46% through the use of structural batteries and supercapacitors, respectively, as UAV wings. Autophagous systems that use fuel for structural support may also have applications on aircraft. These systems may be able to achieve specific energies up to 319 $Wh \cdot kg^{-1}$ but need improved specific power to be feasible.

Transparent photovoltaics could be used to both transmit visible light and harvesting non-visible light. These MFES could replace simple windows with ones that generate power. Experimental results have demonstrated up to 6.4% efficiency with 43% visible spectrum transmission [1]. Theoretical calculations suggest this efficiency could be increased to 10.8% [2] and result in a south facing window that could generate up to 380 $Wh \cdot m^{-2} Day^{-1}$.

Photovoltaics and electrical energy storage can also be integrated into textiles. Since textiles are light and have relatively small volumes in most systems of interest, electrical energy storage in textiles is not particularly promising. With current technology, a shirt with an 0.5 lbs integrated battery can only hold only 6.5 mWh of energy. Integration of photovoltaics with textiles is more promising since textiles have a large surface-to-weight ratio. A multifunctional textile shirt with 5% integrated photovoltaic threads could collect 26 $Wh \cdot Day^{-1}$ in full sun using current technology. Theoretical estimates project this could be increased up to 170 $Wh \cdot Day^{-1}$ in the future.

Structural electrical energy storage appears to be the most promising multifunctional energy system of those examined in this work. These MFES could dramatically improve SWaP-C in systems like unmanned aerial vehicles, dismounted warfighters, and small sensor systems.

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1 Introduction

Traditional material systems are designed and built for a single purpose. A composite wing is built to provide lift for an aerial vehicle, a window is designed to allow visible light into a building, and a road is designed to allow for the safe passage of ground vehicles. The multifunctional systems examined in this report add electrical power and energy capabilities to traditional material systems. For example: the composite wing of an aircraft could serve not only as a flight surface but also as electrical energy storage, the window acts not only to transmit visible light but also to convert solar energy into electrical energy, and the road not only supports ground vehicles but also converts temperature differences into electrical power. All of these devices are essential to their systems, but by incorporating additional capabilities significant advantages can be realized with thoughtful system-level design of multifunctional energy systems (MFES).

Some of the primary concerns of the Department of Defense (DoD), the Intelligence Community (IC), and other government organizations are size, weight, power, and cost (SWaP-C). Multifunctional devices represent a significant step toward improving these characteristics by approaching the challenge from a system optimization viewpoint as opposed to an individual component standpoint. For example, a dismounted warfighter carries both body armor to provide ballistic protection and batteries to power electronic equipment. Both of the components are individually optimized, but the overall warfighter system that combines these components is not optimized. If the dismounted warfighter's body armor could be redesigned to also serve as energy storage, the batteries that the warfighter carries could be minimized or eliminated, allowing the size and weight of the load that the warfighter carries to be significantly reduced. This type of system level optimization using multifunctional energy systems represents a novel method to improve many systems for government and commercial applications.

There are three main types of multifunctional energy and power devices which can be used to improve the SWaP-C considerations: energy storage, power conversion, and power harvesting. When these energy and power devices are combined in a single material system with existing system components such as structural components, armor and protection materials, and even decorative components, significant SWaP-C improvements can be achieved.

The goal of this study and subsequent analysis is two-fold. First: identify existing multifunctional energy and power systems. Then evaluate them for their maturity and potential ability to impact SWaP-C considerations. Second: quantify the current and potential future impacts of the most promising devices and applications on SWaP-C.

2 Potential MFES

A very broad range of devices and applications were included in the initial survey. These devices came from a search of prior art as well as brainstorming for innovative ideas. In this section, they will all be discussed briefly in terms of their scope, feasibility, and possible impact.

2.1 Textiles

Many researchers are developing energy systems incorporated into textiles. These devices can be applied to the dismounted warfighter and other platforms in the form of clothing, backpacks, tarps, tents, and more. For example, Lee *et al.* [4] developed a textile-incorporated battery which was then formed into a shirt and a wrist watch band. This is only one example, but in general the community is still in the proof-of-concept phase. The potential impact of having portions of heavy fabrics such as backpacks store electrical energy makes this technology worth further investigation. Researchers have also been working on textile-incorporated supercapacitors as demonstrated by the work of Bao and Li [5]. The electrodes were manufactured using a simple process, making textile-incorporated supercapacitors an attractive technology due to their potential low manufacturing cost. A third promising application of textile-incorporated systems is the creation of solar cells consisting of a single braided section of wire. Chen *et al.* [6] demonstrated a system using titanium (Ti) wire and carbon nano-tube (CNT) fibers. Their system achieved photovoltaic power conversion efficiencies (PCE) on the order of 3-5%, but the potential mass savings compared to carrying more efficient independent solar harvesting systems is significant due to the large amount of fabric carried by soldiers.

Thermal energy is another possible application area for textiles. A couple of research groups developed pyroelectric textile devices which convert changes in temperature into electrical energy [7], [8]. Although there is a significant amount of available thermal energy in the environment and on many systems, it is typically at very low rates of change and low overall temperatures. The devices demonstrated generate nW for large, 30-40 °C, temperature swings at high rates. Therefore the power gains are not projected to have an appreciable impact on system performance for the majority of applications. Another related area of research is thermal energy storage textiles. These textiles maintain a more constant temperature during large shifts in environmental temperature by incorporating a material which goes through a phase change in the target temperature range. An advantage would be improved body temperature regulation in extreme climates with large temperature swings, such as the desert. Aside from the material energy storage performance, a current challenge is the flammability of the most common phase change materials, a fundamental sticking point of incorporating this technology in the future.

2.2 Building materials

Other platforms for energy harvesting and storage are building materials such as concrete, steel, and sheetrock (drywall). Thermal energy storage in concrete and other building materials has been used for centuries, and more recent work has explored increasing the performance using phase change materials [9]. Significant cost and manufacturing challenges need to be overcome before phase change materials become viable for this application.

Thermal energy harvesting in concrete, specifically for roads and runways, was investigated because of the large temperature gradient between the solar-heated surface and the ground-cooled bottom. However, the possible electrical power output using current methods makes the technology impractical. Using results from Wen and Chung [10], it was estimated that if all of the Denver Airport runways were converted to thermoelectric concrete, approximately 168,000 m^2, it would produce less than 40 mW even with a 50 °C temperature gradient. While other methods of thermal power harvesting roads are under development, such as using embedded liquid heat exchangers [11], it is not expected to produce the orders of magnitude improvement necessary for practical, widespread application.

Two other multifunctional devices that harvest solar energy were explored: building-integrated photovoltaic thermal harvesters and transparent photovoltaics. A common example of a building-integrated photovoltaic (BIPV) was unintentional: the creation of a solar concentrating skyscraper façade in Eastcheap, London. Hotspots of over 90 °C where detected, showing the potential for building-integrated mirrors to act as solar concentrators at certain times of the day. However, the cost of developing systems which are beneficial during larger stretches of time is likely problematic. Building-integrated photovoltaic thermal (BIPVT) harvesters combine flat plate photovoltaics and heat exchangers into a single device which replaces a section of the roof in a building or structure. Combining the photovoltaic cell efficiency and the heat absorption of the heat exchanger, Ibrahim *et al.* [12] were able to obtain a 59% average conversion efficiency. A caveat is the specific application to a structure which would need/benefit from the low-grade heat produced by the heat exchangers. Also, the primary multifunctional aspect is the exterior solar panel operating as a section of roofing, which does not have the potential paradigm shifting impact of some of the other multifunctional energy devices also considered in this study.

Transparent and semi-transparent solar cells possess significant promise. Solar energy harvesting windows and architectural features are a good example of potential applications. Current research has gone into optimizing these systems in terms of high power conversion efficiencies (PCE) and visible spectrum transparency [1], [13]. Also, Lunt [2] published a study which examines the theoretical ceilings for the PCEs of transparent and semi-transparent single-junction and multi-junction solar cells. These works can be used to predict the potential impact of transparent solar cells when integrated into different systems.

Another multifunctional energy system explored as part of this project is the use of potential energy storage with buildings and other systems serving as the proof mass. The general premise is to take a large-mass structure such as a building, and use an active foundation to raise it during times of cheap grid electricity or available off-the-grid energy, and lower it to reclaim the energy during times of high prices or need. A large variety of designs have been investigated for making structures earthquake resistant [14]. A small number of which would be amenable to the integration of potential energy storage, such as active shock absorbers and air cushions [15]. As cost is typically listed as a consideration for why such technologies have not seen wide-spread integration even in earthquake-prone locations and lower-cost passive options exist for basic structures, the future impact and applicability of building potential energy storage is likely limited.

2.3 Vehicle structural materials

A very novel idea which takes a conventional energy source, hydrocarbon fuel, and utilizes it in a multifunctional structure is an autophagous fuel storage system. Researchers at the U.S. NRL published multiple studies exploring the use of pressurized hydrocarbon fuel to provide stiffness to the lightweight and flexible tank, which could then serve as a structural element [16], [17]. The research aims to take advantage of the orders-of-magnitude higher gravimetric energy density of common hydrocarbon fuels such as butane and propane (12.9 and 12.7 $kWh \cdot kg^{-1}$) as compared to modern lithium battery systems (~200 $Wh \cdot kg^{-1}$). The technology has the potential to allow for the use of hydrocarbon fuels on smaller-scale, weight-restricted systems such as unmanned aerial vehicles (UAV) by reducing the amount of weight required for a baseline system. At the same time, the higher gravimetric energy content of the fuels could drastically increase the capabilities of the systems.

Two companies have reported prototype fiber composite systems which also have the ability to store electrical energy in the same manner as a battery or supercapacitor, potentially saving on system weight and cost by reducing the standard battery and energy storage system requirements. BAE Systems partnered with Lola to integrate composite structural batteries into the Lola-Drayson B12/69EV Le Mans Prototype electric race car [18]. Volvo integrated composite structural supercapacitors into the S80 in the form of a trunk lid and a plenum cover [19]. A significant amount of research has also occurred simultaneously in academic institutions, such as the 'Lightweight structural energy storage materials' project centered at Swerea SICOMP in Sweden [20]. Extending beyond automotive applications, composite materials are heavily used in many other fields where the size and weight of structural components are critical. These systems could take advantage of significant increases in capability and/or significant decreases in mass with structural composite energy storage technology, and are explored in detail in this report.

Jankowski and McCluskey [21] conducted a review of thermal energy storage in automotive applications such as cabin environmental controls, cold start emissions and efficiency improvement, vehicle battery thermal buffering, and more. The initial results show potential for high-impact technologies, such as tests with a 50% reduction in cabin cooling load in desert environments. However issues with cost, manufacture, and material flammability represent significant challenges which need to be overcome for wide-spread adoption.

2.4 Protective materials

Some of the heaviest components carried by a dismounted warfighter or used on military vehicles is the armor. Since 2001 the weight of the vehicles fielded by the U.S. military has increased by 75% [22]. A significant portion of this weight increase is additional armor that has been added to the vehicles. Similarly the body armor for U.S. soldiers weighs between 33 lbs [23] and 51 lbs [24] and makes up over 35% of the typical Soldier load. While no work has been published in this area, a system similar to the fiber composite systems under investigation for vehicle structural materials could be used in armor systems. Supercapacitors and batteries formed out of armor materials such as Kevlar and boron carbide (B_4C) could act not only as protective systems but also as energy storage systems and reduce overall size and weight.

3 Promising MFES and their Potential Impact

In this section, the most promising MFES are analyzed further. The technologies and ideas researched in Section 2 are evaluated based on their applicability to the goals of the project and their potential impact on the SWaP-C considerations of MITRE's sponsors. These technologies are: multifunctional structural composite batteries and supercapacitors, autophagous hydrocarbon fuel systems, transparent building-integrated photovoltaics, and textile-incorporated power and energy devices.

3.1 Multifunctional Structural Composites

Structural composite energy storage technologies have been applied primarily to automotive applications thus far, but hold promise in many different applications. When size, weight, and cost are important design criteria, structural composite energy storage technologies can take the space and mass of necessary structural elements and use it for electrical energy storage, reducing the necessary traditional energy storage mass or enhancing system capabilities. This section will explore current structural composite supercapacitor and battery technologies, and their application to automotive, personal protection, and aerospace systems. For the analysis herein, the density and stiffness of carbon fiber is 1600 $kg \cdot m^{-3}$ and 70 GPa (ACP Composites, Accessed 2014). The density and stiffness of Kevlar is 1400 $kg \cdot m^{-3}$ and 82 GPa (DuPont's Kevlar 29, Accessed 2014).

3.1.1 Structural Composite Supercapacitors

Supercapacitors are relatively simple structures, requiring two (sometimes identical) electrodes, an ionically-conductive electrolyte, and an electrically insulating separator. Traditional supercapacitors typically use a salt-based liquid electrolyte for high dielectric performance. However, structural composite applications require mechanical load to be efficiently transferred between the two electrodes. Subsequently, researchers are exploring solid-polymer electrolytes to achieve good mechanical performance as well as good electrical performance.

Shirshova *et al.* [3] report the results of both electrical and mechanical tests on structural composite supercapacitors composed of carbon fiber electrodes, a glass fiber separator, and solid-polymer electrolyte. The active surface area of the carbon fiber electrode was increased using a potassium hydroxide (KOH) solution to create activated carbon fiber (ACF). The solid-polymer electrolyte used was a crosslinked polymer matrix of multifunctional resin (Poly(ethylene glycol) diglycidylether, or PEGDGE) and lithium salt (bis(trifluoromethane)sulfonamide, or LiTFSI), with or without ionic liquid (IL). Table 3-1 lists the electrical and mechanical properties of the tested specimens. It is important to note that the values for the compressive strength were obtained based on delamination, as opposed to complete material failure.

Table 3-1 Experimental properties of composite supercapacitor devices from Shirshova *et al.* (2013). The electrical properties were calculated using an assumption of an externally applied 2.0 V.

Property	ACF/PEGDGE/LiTFSI	ACF/PEGDGE/LiTFSI/IL
Spec. P ($W \cdot kg^{-1}$)	0.05	2.68
Spec. E ($mWh \cdot kg^{-1}$)	3.2×10^{-3}	1.43
Spec. C ($mF \cdot g^{-1}$)	1.4	52.2
Fill Factor, v_f (%)	45.6 ± 1.74	38.6 ± 1.4
Comp. Modulus, E_C (GPa)	32.03 ± 2.8	18.04 ± 1.4
Comp. Strength, χ_C (MPa)	29.35 ± 3.05	7.52 ± 0.51

Table 3-2 Composite mechanical properties from Shirshova *et al.* [3]

Property	ACF/PEGDGE/LiTFSI	*/IL	CF/MVR 444	ACF/MVR 444
Fill Factor, v_f (%)	45.6 ± 1.74	38.6 ± 1.4	51.6 ± 1.33	43.3 ± 0.88
Comp. Modulus, E_C (GPa)	32.03 ± 2.8	18.04 ± 1.4	31.01 ± 0.79	40.23 ± 2.29
Comp. Strength, χ_C (MPa)	29.35 ± 3.05	7.52 ± 0.51	36.21 ± 3.03	49.84 ± 5.63

Table 3-2 compares the mechanical properties of the experimental specimens with baselines created by the researchers. The two baselines were regular carbon fiber and activated carbon fiber composites cured with the standard aerospace epoxy-based resin MVR 444.

3.1.2 Structural Composite Batteries

The research on structural composite batteries is not as far along as that for supercapacitors, likely due to their more complex nature. Most researchers are focusing on improving the performance of the individual components or interfaces [20], [25]. However Ekstedt, Wysocki, and Asp [26] produced initial specimens based on lithium iron phosphate ($LiFePO_4$): a carbon fiber weave anode with a copper current collector, a glass fiber weave separator, a $LiFePO_4$ cathode coated onto aluminum fiber weave, and a PVDF-based solid polymer electrolyte.

The authors used theoretical modeling to provide estimates for the electrical and mechanical performance of the device. These results can be used to project device capabilities for initial system feasibility analyses. Using electrochemistry theory and a measured 2.3 V nominal potential, it was estimated that the devices had theoretical specific charge and energy values of 116.6 $Ah \cdot kg^{-1}$ and 268.2 $Wh \cdot kg^{-1}$. The micromechanics rule-of-mixtures, Halpin Tsai, and laminate theories were applied to predict a 53% decrease in stiffness from a standard carbon/epoxy composite at 75 GPa, or 35.25 GPa.

3.1.3 Automotive Applications

As mentioned in Section 2, there are two examples of industry development of multifunctional structural composite energy systems for automotive applications. The Lola/Drayson B12/69EV electric-powered Le Mans Prototype utilizes structural batteries as the moveable rear aero wings [18]. Also, Volvo fabricated structural composite supercapacitors to replace the conventional trunk lid and the plenum cover in a Volvo S80 experimental model [19]. The new trunk lid is 50% lighter than the traditional piece due to the switch to composite materials. The plenum could replace the traditional front-stabilizing rally bar and the start-stop battery.

To judge the potential future impact of structural composite energy systems for automotive applications, it is important to understand the relationship between performance and overall mass. An Idaho National Laboratory study examined just that for multiple vehicles [27]. The current results indicate that the overall mass of a Nissan Leaf electric vehicle does not have a significant effect on the energy efficiency for highway driving: 0.03 ratio of percent decrease in energy consumption over percent reduction in vehicle mass. The results for a Fusion Hybrid are similar with a ratio of 0.08. Although more significant gains can be realized during more aggressive or city driving (up to a ratio of 0.38) and for highway driving with conventional internal combustion vehicles, the potential impact of structural composite energy storage systems is greater for aerospace and dismounted warfighter applications.

3.1.4 Body Armor

The body armor that a warfighter carries makes up a significant portion of the overall weight burden and contributes to reduced maneuverability, reduced endurance, and increased musculoskeletal injury. By using the weight of this body armor as an energy storage medium, the weight of dedicated batteries the warfighter must carry could be dramatically reduced.

An excellent candidate for energy storage/body armor integration is a boron carbide (B_4C) supercapacitor. B_4C is a lightweight refractory material and the third hardest material known to man. It has a high melting point, a high resistance to chemical attacks, high thermal stability and a large neutron absorption cross-section. These properties make B_4C an excellent candidate for use in body armor, and it is currently being used by the military in their advanced body armor. B_4C in bulk form, however, is a brittle material. To further improve performance, composites using B_4C nanowires are being studied which have shown improved mechanical properties. Researchers in the US, China, and Switzerland have demonstrated a B_4C nanocomposite made from cotton tee shirts [28] that may be an excellent candidate for body armor applications.

Supercapacitors are energy storage devices with very high power capabilities, but lower energy density than most batteries. The best commercial supercapacitors are made with nanoporous carbon electrodes and have specific energies up to 30 Wh/kg, whereas commercial lithium-ion batteries have energy densities up to ~200 Wh/kg. Theoretical work [29] suggests that replacing the nanoporous electrode with a nanowire or nanosphere could result in significantly improved specific energy. Some experimental work supports this idea, and carbon nanotube supercapacitors have demonstrated specific energies reaching up to 35 Wh/kg [30].

Another approach to increasing the specific energy of a supercapacitor is to change the electrode material. Researchers have performed quantum mechanical calculations of the capacitance of various atoms and molecules [31]. This work shows that while carbon molecules have very high capacitance, boron molecules have even higher specific capacitance. So, a change from a carbon electrode to a boron electrode will result in an increase in the specific energy of the supercapacitor.

The combination of these effects in the form of boron-based nanowire electrodes could produce supercapacitors with dramatically improved specific energy. These supercapacitors could be improved further through the use of an ionic liquid electrolyte to increase the voltage of the supercapacitor. Figure 3-1 shows the calculated specific energy for carbon nanotube supercapacitors as well as B_4C nanowires with ionic liquid electrolytes. The results suggest that a B_4C nanowire and ionic liquid electrolyte supercapacitor could outperform lithium-ion batteries in terms of specific energy.

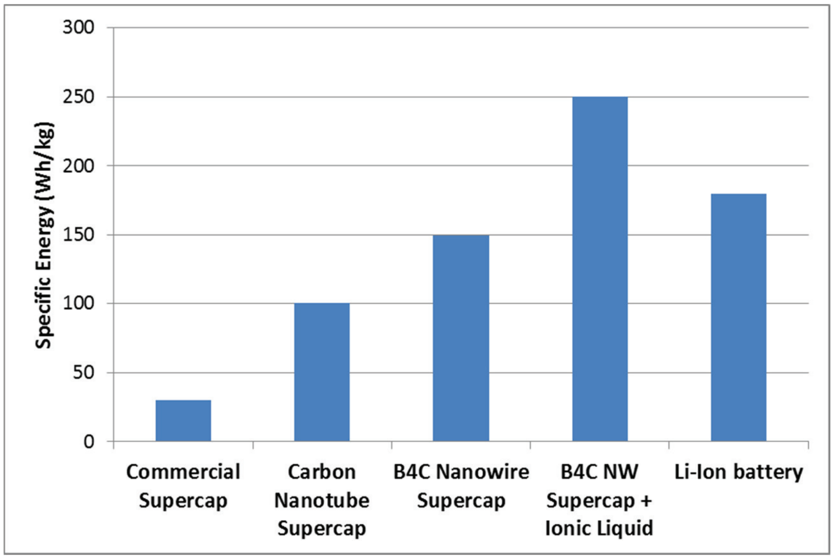

Figure 3-1 Projected improvement in the specific energy of supercapacitors from the use of nanowires, boron carbide (B_4C), and ionic liquids. For reference the specific energy of a commercial supercapacitor and a commercial lithium-ion battery are also shown.

If the specific energy of B_4C supercapacitors approaches that of batteries, supercapacitors would offer many advantages over batteries. Supercapacitors have high power capability which means they can be used in a hybrid system with batteries to improve the battery lifetime under pulsed load conditions. The high power capability of supercapacitors also means that they can be recharged in minutes instead of hours. Supercapacitors also have much greater cycle life than batteries. They can survive thousands of cycles while batteries typically fail after a few hundred cycles. As a result, supercapacitors do not have the capacity fade seen in batteries nor do they need to be replaced as frequently. This is a key feature for multifunctional systems where replacement may be expensive and difficult.

While a stand-alone B_4C supercapacitor may provide operational performance advantages over a battery, an integrated B_4C supercapacitor is even more compelling. When the B_4C in body armor is also used as a supercapacitor electrode, substantial weight savings can be realized. Typically, body armor consists of layers of high strength material separated by a softer film. This same structure is used for a supercapacitor. B_4C nanowires could serve as both the supercapacitor electrode and the high strength material layer in the body armor. The supercapacitor electrolyte/separator would serve as the separator layer in the body armor. The integration of a supercapacitor with body armor would allow added energy storage without additional weight. For a body armor vest weighing about 7.5 kg, half of the weight may be from the B_4C. This 3.8 kg of B_4C could store over 100 Wh of energy if it has the energy density of current supercapacitors and up to 750 Wh if the improved performance from B_4C, nanowires and ionic liquids could be realized. This means that the soldier could carry the capacity of one to four additional BA-5590 batteries with no additional weight.

An added benefit of this body armor/supercapacitor integration is that it may provide added protection to the soldier. Electromagnetic reactive armor uses high pulses of electromagnetic power to vaporize projectiles. The integrated supercapacitor is ideal for this response. When a metallic projectile impinges on the body armor and penetrates multiple layers of the supercapacitor, it will short out the supercapacitor. Since the supercapacitor has very high power density, a large impulse of current will flow through the projectile and could significantly change its mechanical properties. This added protection comes at no additional cost in weight since the structure needed for the electromagnetic reactive armor is already included in the integrated body armor/supercapacitor.

3.1.5 Airplane Endurance Analysis

Mass is a significant constraint in the aerospace industry. For example, rotorcraft are typically designed with a 2-to-1 lift to weight ratio. For every additional pound of cargo or fuselage mass the drivetrain needs to be capable of producing an additional 2 lbf of lift. It is in this domain where the impact of structural composite energy devices is expected to be significant.

To evaluate the potential impact of a structural composite battery or supercapacitor, it is necessary to have a system-level model which can capture the relationship between the stored energy, the system mass, and a performance metric. Thomas *et al.* [16] derived an expression, equation (1), for the flight endurance (t_E) of a UAV system with energy harvesting capabilities (P_{Harv}) that also depends on the battery system energy (E_B) and the system mass (W_T).

$$t_E = \frac{E_B \eta_B}{\left(W_T^{3/2} - P_{Harv}\left[\frac{\rho S C_L^3}{2C_D^2}\right]^{1/2} \eta_{M-P}\right)} \left[\frac{\rho S C_L^3}{2C_D^2}\right]^{1/2} \eta_{M-P} \tag{1}$$

Equation (1) can be simplified to a more applicable form for analyzing the effects of structural composite energy storage devices. The first assumption is that there is no energy harvesting present on the examined systems. After setting P_{Harv} to zero, the expression for the difference in flight endurance between the original system, 1, and the new system with structural composite energy storage, 2, is significantly cleaner as seen in equation (2). Some other assumptions were made as well: the battery energy extraction efficiency (η_B), air density (ρ), wing surface area (S), coefficient of lift (C_L), coefficient of drag (C_D), and the motor-to-propeller efficiency ($\eta_{M\text{-}P}$) all remain constant from system 1 to system 2.

$$\Delta t_E = \left(\frac{E_{B1}}{W_{T1}^{3/2}} - \frac{E_{B2}}{W_{T2}^{3/2}}\right) \eta_B \left[\frac{\rho S C_L^3}{2C_D^2}\right]^{1/2} \eta_{M-P} \tag{2}$$

Equation (2) can be generalized with respect to all of the aerodynamic constants and the two efficiencies by calculating the percent change in the endurance. The result, equation (3), more clearly shows the relationship between the flight endurance, the carried battery energy, and the system mass. This relationship will be used in later, platform-specific analyses.

$$\%\Delta t_E = 1 - \frac{E_{B2} W_{T1}^{3/2}}{E_{B1} W_{T2}^{3/2}} \tag{3}$$

For now, equation (3) will be further generalized to show the potential improvements for a large application space. First, the amount of energy carried will be set constant, or $E_{B2} = E_{B1}$, such that the immediate analysis will look at the effect of the system mass savings (m_{B1} vs. m_{B2}) as a result of the use of structural composite energy storage, equation (4). Next, two new variables will be defined: K, the scaling factor between the gravimetric specific energy of the standard system batteries ($\bar{E}_B$) and the structural composite batteries ($\bar{E}_{MF}$); and P, the portion of the overall system mass ($m_{B1} + m_{Rest}$) replaced by multifunctional composite energy storage materials (m_{MF}). This analysis assumes that the structural performance of the composite energy storage matches the original structural composite.

$$\%\Delta t_E = 1 - \left[\frac{m_{B1} + m_{Rest}}{m_{B2} + m_{Rest}}\right]^{3/2} \quad (4)$$

$$K\bar{E}_B = \bar{E}_{MF} \rightarrow \; m_{B1} = m_{B2} + Km_{MF} \quad (5)$$

$$\%\Delta t_E = 1 - \left[\frac{m_{B1} + m_{Rest}}{m_{B1} - Km_{MF} + m_{Rest}}\right]^{3/2} \quad (6)$$

$$(m_{B1} + m_{Rest})P = m_{MF} \quad (7)$$

$$\%\Delta t_E = 1 - (1 - KP)^{-3/2} \quad (8)$$

Equation (8) shows the resulting relationship between the specific energy scaling factor K, the multifunctional mass proportion, P, and the percent change in flight endurance. By reducing the relationship to just two independent variables, it is possible to examine the application space and its potential impact on the system flight endurance. Figure 3-2 shows the percent increase in system flight endurance as a function of the percent decrease in the structural composite energy storage specific energy compared to that of the standard batteries. The different series account for the different values of the variable P, or the percent of the original overall system mass replaced with multifunctional structural composite materials.

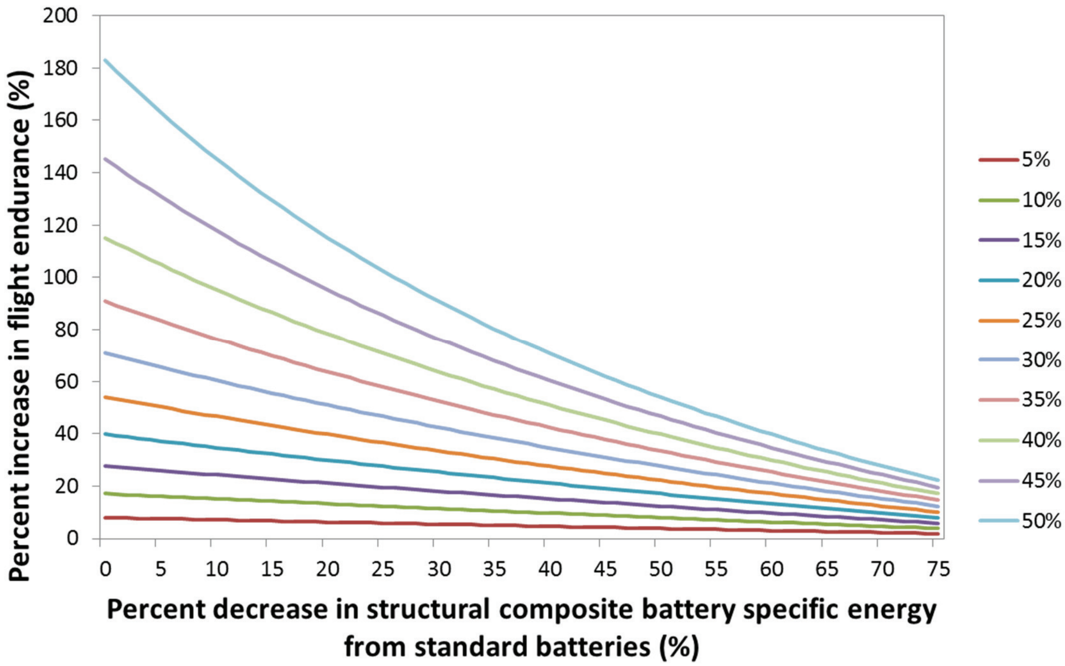

Figure 3-2 Flight endurance as a function of the structural composite energy storage gravimetric specific energy performance and the multifunctional mass as a percent of the overall system mass.

The generalized analysis illustrates the immense potential of multifunctional structural energy storage systems, showing flight endurance increases close to 200%. Also, specific system applications should have a large percentage of the overall system mass dedicated to energy storage and components which can be converted to multifunctional composite energy storage. Otherwise, the gains are minimal.

3.1.5.1 UAVs

This section applies equation (3) specifically to a small-scale UAV system, the AeroVironment Raven. The wing will serve as the component replaced by multifunctional structural composite material. Maintaining the stiffness at the base of the wing, *EI*, will be the focus of this analysis. This assumes a significant factor of safety for the failure of the wings and instead considers performance. Here *M* is the bending moment on a beam, *E* is Young's Modulus, and *I* is the area moment of inertia.

$$M = EI\frac{d^2w}{dx^2} \tag{9}$$

The Raven's wingspan is listed at 4.5 ft (1.37 m) and the cord at the base of the wing is 8 in (0.203 m). The entire wing weighs 10.8 oz (0.306 kg), and consists of 0.012 in (0.3 mm) thick painted Kevlar with a foam core. It is assumed to have approximately an ag26 Bubble Dancer airfoil profile. As noted in sections 3.1.1 and 3.1.2, the compressive modulus of the multifunctional composite materials differs from standard composite systems. It will be assumed in this analysis that the compressive modulus is equal to the bending modulus. To allow for quick calculations, the ag26 profile will be simplified to a rectangular tube with the same chord and a height determined such that the profile cross-sectional area remains the same, or 0.34 in (8.63 mm). Therefore, equation (10) can be used to govern the wing area moment of inertia and compensate for a reduction in the modulus. Here b is the outside width, d is the outside height, and t is the wall thickness of the simplified wing cross-section.

$$I = \frac{bd^3 - (b - 2t)(d - 2t)^3}{12} \tag{10}$$

Ekstedt *et al.* [26] presented both the theoretical modulus and the electrical performance of their structural composite battery system, 35.25 GPa and 268.2 Wh·kg^{-1}. The 57% decrease in the modulus from Kevlar results in a 150% increase in wing mass to 0.768 kg. This extends to a 24% increase in the overall system mass. Equation (11) shows the calculation of the percent change in the flight endurance. The result is a ~200% increase in the flight endurance. The 63 Wh base energy storage comes from the known capacity of the Raven's BA-5557 battery.

$$\%\Delta t_E = 1 - \frac{E_{B2} W_{T1}^{3/2}}{E_{B1} W_{T2}^{3/2}} = 1 - \frac{(63 + 206\ \text{Wh})(1.9\ \text{kg})^{3/2}}{63\ \text{Wh}\ (0.768 - 0.306 + 1.9\ \text{kg})^{3/2}} = -2.08 \tag{11}$$

Table 3-3 compiles the results of these calculations for both battery and supercapacitor multifunctional structural composite systems. It lists the example calculation using the properties from Ekstedt *et al.* [26] as the current potential for the structural composite batteries. An upper limit is also calculated assuming that future technological advancements eliminate the 57% decrease in the modulus for the multifunctional composite. The potential results for the structural composite supercapacitor use the experimental stiffness from Shirshova *et al.* [3] along with the electrical properties of large-scale graphene supercapacitors reported by Kannappan *et al.* [32]. The lowest mass limit for structural composite supercapacitors is obtained using the stiffness of standard carbon fiber composites with the same electrical properties. The density of the material for all four calculations is assumed to be the same as standard carbon fiber. Also, the mass of the interior foam was assumed to be approximately 49 gm, the value which caused the calculations using the simplified wing cross-section to match measured properties.

Table 3-3 Structural composite AeroVironment Raven wing performance

Structural Composite Wing Type	Increase in Flight Endurance (%)	Increase in System Mass (%)
Battery: Current Potential[1]	200	24
Battery: Lowest Mass Limit[2]	140	2
S.C.: Current Potential[3]	46	29
S.C.: Lowest Mass Limit[4]	42	2

The results shown in Table 3-3 for the AeroVironment Raven illustrate the significant potential of multifunctional composite energy storage materials for small-scale UAV applications. This is expected because the traditional energy storage mass for systems on this scale typically ranges from 20-35% of the overall system mass, which satisfies the criteria mentioned during the generalized analysis.

3.1.5.2 Commercial Planes

Due to the large quantity of fuel regularly consumed, increasing the fuel efficiency or range of commercial airplanes would have a substantial impact on the cost of air travel and shipping. However commercial airplanes present a different mass distribution compared to small-scale UAV systems.

The Boeing/NASA N+3 Subsonic Ultra Green Aircraft Research Volt, an all-electric concept airliner, is used for an analysis into performance potential [33]. It has a 154,9000 lbs maximum takeoff weight and is predicted to require 20,900 lbs of 750 $Wh \cdot kg^{-1}$ batteries to achieve a 900 nautical mile flight. Note that the 750 $Wh \cdot kg^{-1}$ batteries are a projection of where the authors of [33] believe the technology will advance to.

The aerodynamic surfaces of the wings weigh 4,925 lbs and will serve as an initial target because it would be analogous to replacing the fiber composite of the Raven wing. Using equation (6) results in a 5% increase in flight endurance when $K = 1$, or the gravimetric specific energy of the structural composite energy storage is equal to the 750 $Wh \cdot kg^{-1}$ projected battery systems. As K decreases, the flight endurance improvement decreases linearly to approximately 1% at $K = 0.25$. The result is expected as the aerodynamic surfaces of the wings only represent 3% of the overall system mass. Also, the batteries only represent 13.5% of the system mass themselves. While the overall mass of the components replaced with structural composite energy storage can be increased, it will not have the same level of impact as it did for the Raven, where the current battery system is 26% of the overall mass.

Lastly, the time and cost to integration would likely be significantly longer and higher than for small-scale UAV systems due to safety regulations associated with commercial airliners or cargo

[1] Using theo. properties from [26]
[2] Using theo. electrical properties from [26] and plain carbon fiber stiffness
[3] Using exp. electrical properties from [32] and exp. stiffness from [3]
[4] Using exp. electrical properties from [32] and plain carbon fiber stiffness

jets. Taking this into consideration as well leads to small-scale UAVs possessing the best combination of potential impact, cost, and time to prototype and deployment.

3.2 Autophagous Hydrocarbon Fuel Systems

Autophagous systems for aerial vehicles were proposed by researchers at the Naval Research Laboratory [17]. The general premise is to store liquid hydrocarbon fuel in a flexible tank whose stiffness is derived from pressurization. As the liquid fuel is burned off, the byproduct gasses left in the tank maintain its stiffness until no fuel is left. This allows for the fuel tank to replace necessary structural components, such as wing spars. The heat from burning the fuel was converted to electricity using a thermoelectric generator (TEG). The goal of the researchers was to use these mass savings and the high gravimetric specific energy of hydrocarbon fuels to increase the flight endurance of small-scale UAVs.

To allow for the comparison of the autophagous hydrocarbon fuel systems with electrochemical battery systems, the authors used the specific energy of the overall energy system in equation (12). Here $\bar{E}$ is the gravimetric specific energy for the autophagous or battery system, h_c is the fuel heat of combustion, $\eta_c$is the combustion efficiency, η_h is the thermal efficiency for conducting the heat of combustion to the TEG, η_T is the efficiency of the TEG, η_e is the power conditioning efficiency, and η_m is the mass efficiency, or the percent fuel mass of the autophagous system mass.

$$\bar{E} = \frac{usable\ energy}{energy\ system\ mass} = h_c \eta_c \eta_h \eta_T \eta_e \eta_m \tag{12}$$

Baucom *et al.* [17] make a couple of assumptions in their calculations. The thermoelectric efficiency is estimated to be around 5% and the electrical power conditioning efficiency is estimated to be around 90%. These values are appropriate based on modern thermoelectric materials and synchronized switching DC-DC power converters. However, depending on the current and voltage levels produced by the TEG, the DC-DC power converter efficiency could be as low as 50%. Based on the characteristics of the experimental system developed by the authors, the mass efficiency was 15.5%.

One caveat for this comparison is that the gravimetric specific energy for the battery system, 200 Wh·kg^{-1}, does not include the characteristics of the electric motor which provides the thrust. This would involve both the efficiency of converting electric power to propeller thrust and mass. Also, another note is that the calculations are based on a full fuel load. As hydrocarbon fuel is consumed the mass of the system decreases, which does not occur with battery systems.

3.2.1 Rotary Internal Combustion Engines

Internal combustion engines (ICEs) are a traditional method for converting hydrocarbon fuels and are used for automobiles, large-scale UAVs, and many more applications. This analysis will focus on the potential impact of autophagous rotary ICEs on UAV systems. This is primarily motivated by the significant impact of mass savings on airborne systems, as shown in section 3.1.5.

Eardly and Katz [34] estimated that the fuel-to-shaft efficiency of a UAV carrying a Cox TD 010 Model 130 engine is approximately 2.6%. The authors also cited another report which estimated an efficiency of 5.5% using slightly different components. By altering equation (12) to use the 5.5% fuel-to-shaft efficiency in place of the TEG-related efficiencies, it is estimated that the autophagous system would require a mass efficiency around 30%.

Compared to the 15.5% mass efficiency of the autophagous system developed by Baucom *et al.* [17] and taking into account the different natures of the gravimetric specific energy calculations for the two systems, autophagous systems for small-scale UAV applications using rotary ICEs show the potential to have longer endurance capabilities than traditional battery-powered systems.

A major challenge with the integration of autophagous ICEs for small-scale UAV systems is not the performance, but the noise levels generated. All electric propulsion is desirable for systems which require a measure of stealth or wish to reduce overall noise pollution levels. ICEs are notoriously loud, and mufflers would reduce the 5.5% efficiency value.

3.2.2 Hydrocarbon Turbines

Gas powered small-scale turbines are commonly used for large-scale remote-controlled airplanes as they are extremely fast and highly capable. However, their fuel-to-thrust efficiency is directly related to the system airspeed as shown in equation (13). Here sfc is the specific fuel consumption in units of kilograms fuel per Newton thrust per second, $\dot{m}_f$ is the fuel mass flow rate, LCV is the lower calorific value of the fuel, and v is the system speed.

$$\eta_O = \frac{\text{Thrust} \times \text{speed}}{\dot{m}_f LCV} = \frac{1}{sfc}\frac{v}{LCV} \tag{13}$$

Using the operational specifications for a modern, small-scale turbine engine and assuming a 15.5% autophagous system mass efficiency, the necessary UAV air speed for competitive conversion efficiencies can be determined. The P20-SX, Kerosene or Jet-A1 fueled, engine can be used as a benchmark. It has a maximum thrust of 5.5 lbs, weighs 0.8 lbs, has a 2.34 in. diameter, is 7 in. long, and at full power draws 3 fl. oz. of fuel per minute. Kerosene's lower calorific limit is 43.1 $MJ \cdot kg^{-1}$ and it has a density of 0.78 $g \cdot cm^{-3}$. Based on the 15.5% autophagous mass efficiency and a battery system gravimetric specific energy of 200 $Wh \cdot kg^{-1}$, the UAV would need to be traveling at least 196 $m \cdot s^{-1}$ for its efficiency to be high enough to be competitive with a battery powered system.

Again the caveat must be mentioned that the 200 $Wh \cdot kg^{-1}$ battery system performance does not include the motor and propeller characteristics. However, by comparing the 196 $m \cdot s^{-1}$ result with the maximum speed of existing UAV systems (Predator: 61.7 $m \cdot s^{-1}$; Raven: 22.6 $m \cdot s^{-1}$) the result is an order of magnitude away from being practical for small-scale UAV systems. If the system were to operate at the Predator speeds, it would require a mass efficiency around 50% for the autophagous small-scale turbine system to be competitive with battery-based propulsion systems. Compared to the achieved 15.5%, this would present a significant challenge.

3.2.3 Thermoelectrics

Baucom *et al.* [17] did their initial analysis targeting a TEG system based around a combustion chamber for the hydrocarbon fuel. Thermoelectrics possess many advantages, however low efficiency levels are typically a stumbling block for the use of the technology. Yoshida *et al.* [35]

published the performance of a hydrogen-powered miniature TEG system, 14 x 10 x 8 mm overall, and the results can be used to calculate a more exact measurement of the potential of thermoelectric-based autophagous devices for small-scale UAV applications.

The authors achieved a fuel-to-electricity efficiency of 2.8% using hydrogen fuel. They also used butane fuel for their experiments, but the TEG was unable to sustain combustion under load. Assuming that the system can be developed to sustain combustion with butane fuel, and again using a 200 $Wh \cdot kg^{-1}$ baseline for the battery, autophagous thermoelectric devices would require a mass efficiency greater than 56% to be competitive.

One of the advantages of TEG systems is their small size. As a result, a 56% mass efficiency is an achievable goal. The mass of a single TEG system can be estimated using the overall volume of the system (14 x 10 x 8 mm), and the density of silicon (2.3290 $g \cdot cm^{-3}$), resulting in 2.61 grams. The specifications of the GasSpar II prototype developed by Baucom *et al.* [17] can be assumed for the autophagous fuel tank: 46 gm spar mass with the ability to hold 69 gm of liquid-butane fuel. As a result, a maximum of 3 TEGs can be used concurrently without going below the 56% mass efficiency mark.

Based on the reported 184 mW output of each of the TEGs, the system with 3 TEGs and 69 gm of liquid butane can provide 0.552 W of electrical power and 24.5 Wh of electrical energy. Overall this gives the autophagous thermoelectric system a gravimetric specific energy of 319 $Wh \cdot kg^{-1}$ and a gravimetric specific power of 7.19 $W \cdot kg^{-1}$. While the specific energy is higher than for currently available packaged lithium-polymer batteries, the specific power is 3 orders of magnitude lower (> 1 $kW \cdot kg^{-1}$). Although the specific power consumption of existing small-scale UAV systems is not readily available, the average power requirement for the Raven is in the neighborhood of 50 W. While promising from an energy storage standpoint, the power performance is a significant roadblock to the integration of this technology in small-scale UAV applications.

3.2.4 Thermophotovoltaics

Thermophotovoltaics are a relatively new technology, where an intermediate material absorbs heat and emits radiation to an accompanying photovoltaic. The heat energy can come from a variety of sources, such as solar radiation or combustion. Due to the ability of an intermediate absorber to emit radiation at a specified wavelength tuned specifically to the photovoltaic, the process has a theoretical maximum conversion efficiency of 85% [36]. This value assumes black-body radiation absorption and ideal photovoltaic conversion.

Lee and Kwon [37] present a design and analysis of a microemitter (70 mm long x 8 mm dia.) for a micro thermophotovoltaic system. The authors predict a 4.8 W power output and a 4.3% overall efficiency for the device by assuming a 0.9 microemitter wall emissivity and a 10% PCE for the photovoltaic. Again using the analysis from Baucom *et al.* [17], an autophagous thermophotovoltaic system using the above device would require a mass efficiency greater than 36.5% to be competitive with a 200 $Wh \cdot kg^{-1}$ battery system. Due to the small size of these devices this target is achievable.

The mass of the combustion chamber is assumed by calculating the overall volume and assuming a 50% fill factor. Using the density of silicon carbide (SiC; 3.21 $g \cdot cm^{-3}$), the target material for the microemitter, its mass can be estimated as 5.6 gm. Assuming the mass of the photovoltaic and any associated hardware is negligible, 13 thermophotovoltaic devices can be used concurrently while still achieving an autophagous mass efficiency greater than 36.5%. As the thermophotovoltaic systems predicted by Lee and Kwon [37] produced 4.8 W, the overall autophagous system using 13 devices can potentially produce 62.4 W and provide 37.7 Wh of energy if used in conjunction with the GasSpar II produced by Baucom *et al.* [17]. The gravimetric specific power and energy of the proposed system are 440 $W \cdot kg^{-1}$ and 265 $Wh \cdot kg^{-1}$.

As with the thermoelectric system proposed in section 3.2.3, the specific energy performance is better than that provided by modern battery systems. However, although higher than thermoelectric systems, the specific power is still an order-of-magnitude lower than the performance capabilities of modern commercial battery systems. As a result, autophagous thermophotovoltaic have the potential to displace batteries as the power source for small-scale UAV systems in the future, but significant progress needs to be made in the specific power performance of the systems.

3.3 Transparent Photovoltaics

Traditionally, integrating photovoltaic systems into buildings, automobiles, or airplanes involves bulky mounted arrays on rooftops or flexible thin-film devices adhered to available surfaces. Transparent photovoltaics present the promise of a different paradigm by allowing for solar power harvesting from windows and transparent architectural features. To give an idea as to what levels of visible spectrum transmissibility are acceptable or already in use, automotive glass is typically 55-90% transparent and architectural glass is typically 70-80% [38].

A significant bulk of research is being performed on these systems currently. Chen *et al.* [1] reported polymer semi-transparent solar cells in tandem structures. Lin *et al.* [13] produced organic planar mixed hetero-junction devices. Also, Lunt [2] calculated the theoretical maximum PCE values for practical single- and multi-junction devices based on the available energy in the solar spectrum at each frequency. Table 3-4 displays the reported experimental and theoretical performance of the devices.

Table 3-4 The reported performance of published transparent and semi-transparent photovoltaics

Author	Device	PCE (%)	Visible Spectrum Transmission (%)
Chen *et al.* [1]	Tandem Polymer (a)	7.3	30
	Tandem Polymer (b)	6.4	43
Lin *et al.* [13]	Hetero. JCT. Org. (a)	3.24	40
	Hetero. JCT. Org. (b)	2.11	50
Lunt [2]	Theo. 1-JCT	10.8	100
	Theo. 16-JCT	20.3	100

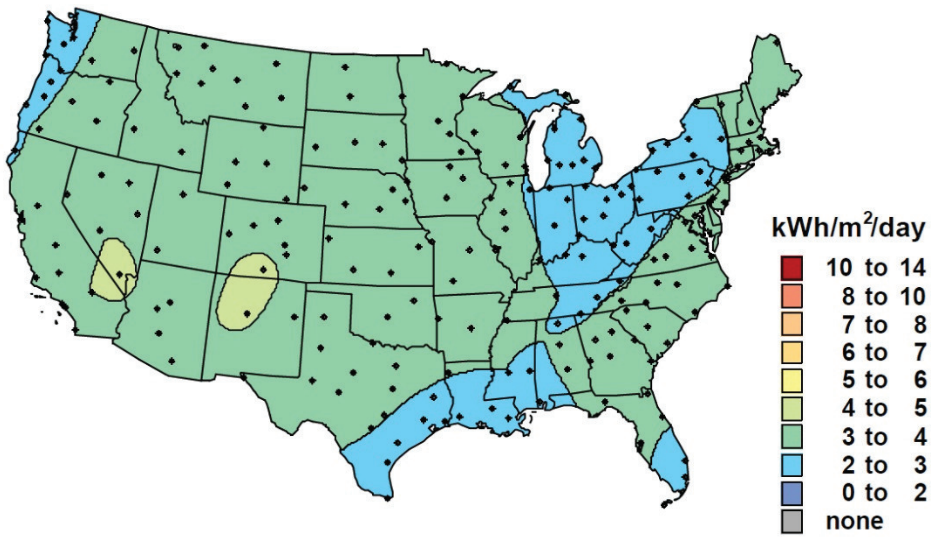

Figure 3-3 NREL annual average daily solar radiation for a south-facing vertical flat plate [39].

The National Renewable Energy Laboratory (NREL) publishes solar resource maps for the U.S. that provide the average amount of solar energy available over the course of the year [39]. Figure 3-3 shows the annual average daily solar radiation for a south-facing vertical flat plate, which would best approximate a south-facing window or architectural feature on a building. Also, the World Energy Council's report on solar resources lists an annual average irradiance of 185 $W \cdot m^{-2}$ for the U.S. [40]. Combining this information, the average daily energy and the average power output of a proposed system can be predicted. Table 3-5 shows the predicted annual average performance of the devices in Washington, D.C.

Table 3-5 The predicted performance of vertical, south-facing transparent solar cells in Washington, D.C.

Author	Device	Annual Avg. Daily Solar Radiation ($Wh \cdot m^{-2} Day^{-1}$)	Annual Avg. Irradiance ($W \cdot m^{-2}$)
Chen *et al.* [1]	Tandem Polymer (a)	256	13.5
	Tandem Polymer (b)	224	11.8
Lin *et al.* [13]	Hetero. JCT. Org. (a)	113	5.99
	Hetero. JCT. Org. (b)	73.9	3.90
Lunt [2]	Theo. 1-JCT	380	20.0
	Theo. 16-JCT	713	37.6

Based on the predicted performance of a vertical, south-facing transparent panel, these applications show significant promise. However, it is difficult to fully gauge their feasibility based on their potential power and energy performance alone. Buildings and structures, a target application for this technology, are built to stand for decades. Depending on the manufacturing cost coupled with the expected lifetime of the transparent photovoltaics, it might be economically prohibitive. Particularly as the operational lifetime of modern organic solar cells is an issue. Therefore significant strides need to be made in their long-term performance, lifetime, and manufacturing cost to integrate them into most long-term applications.

3.4 Textile-Incorporated Systems

Researching “smart” or multi-purpose fabrics has received a significant amount of attention. Given the ubiquity of textiles in everyday life, seemingly countless applications exist for clothes, packs, bags, cases, and more. Related to power and energy technologies, textile-incorporated batteries, supercapacitors, and solar cells are of interest and hold significant promise.

Multiple researchers constructed energy storage textiles by layering traditional textile materials loaded with active electric materials. Lee *et al.* [4] produced a prototype textile battery system using multiple layers of fabric as the different battery components. The devices had an approximate specific energy of 36 $mWh \cdot kg^{-1}$ at a density of 8720 $g \cdot m^{-2}$. Bao and Li [5] developed textile supercapacitors constructed from cotton t-shirt material serving as the base for each of the electrodes. The result is a 66.7 $Wh \cdot kg^{-1}$, 2 V supercapacitor which experienced a 2.5% loss in capacitance after 1,000 cycles. Although Bao and Li did not report any mass information for their specimens, Jost *et al.* [41] did for carbon-loaded cotton textiles. They achieved a 17.6% mass loading of carbon on the cotton fabric; this value will be used along with the electrical performance reported by Bao and Li [5] for subsequent analyses.

Another approach, which showed promise for photovoltaics, was the intertwining of different types of individual wires and fibers. Chen *et al.* [6] wrapped carbon nanotube (CNT) fibers around coated titanium (Ti) wire populated with titania nanotubes to serve as the two electrodes. The active material coating the Ti wire is a combination of a dye and a lithium iodine solution. The devices achieved a maximum PCE of 4.6% and can be estimated to weigh approximately 461 $g \cdot m^{-2}$.

3.4.1 Army Combat Shirt Application

An Army Combat Shirt is an example of a piece of clothing that a soldier will likely never be without and even typically carry a spare. The surface area of the fabric can be approximated as 3200 in^2 (2 m^2) of material based on the standard t-shirt requiring approximately 2 yards of 45 in fabric to make. The Army Combat Shirt weighs about 1.02 lbs (0.463 kg), resulting in an areal density of roughly 222 $g \cdot m^{-2}$.

Table 3-6 The potential and predicted upper limit performances of textile-incorporated energy systems

	Battery	Supercapacitor	Photovoltaics
Covered Surface Area (%)	1	100	5
Added Mass (lbs)	0.5	0.2	0.06
Potential Added Energy (Wh)	6.5×10^{-3} [5]	6.4 [6]	26 / 24 Hr [7]
Potential Battery Mass Savings (lbs)	7×10^{-8} [5,8]	0.06 [6,8]	0.3 / 24 Hr [7,8]
Upper Limit Added Energy (Wh)	36 [8]	8 [9]	170 / 24 Hr [10]
Upper Limit Battery Mass Savings (lbs)	0.4 [8]	0.08 [8,9]	1.9 / 24 Hr [8,10]

Table 3-6 shows possible performance values for the textile energetic materials if they were to be incorporated into the Army Combat Shirt. As the areal densities of the battery and photovoltaic active materials are significantly greater than the base shirt material, only small amounts were incorporated to limit the added mass. The battery added 0.5 lbs to the weight of the shirt, approximately a 50% increase in mass. Using the properties reported by Lee *et al.* [4] this would result in a 6.5 mWh battery. If the soldier was carrying traditional 200 $Wh \cdot kg^{-1}$ batteries and a multifunctional battery shirt, they could leave behind a negligible weight in batteries compared to only having traditional batteries. If it were assumed that the textile batteries reached 200 $Wh \cdot kg^{-1}$ themselves, then the shirt would contain a 36 Wh battery. This would result in a mass savings of 0.4 lbs compared to a traditional battery with a net increase of 0.1 lbs overall. The results for the textile supercapacitors are similar, although the current prototype electrical performance is closer to that of the larger-scale systems.

Photovoltaic wires incorporated into textiles show significantly more promise. It was assumed the spare shirt would be placed flat on the ground. This would be best approximated by a horizontal flat plate harvester (Figure 3-4). If only one half of the shirt is populated with photovoltaic threads at a surface concentration of 10%, then the shirt would have a 5% overall surface area coverage. This results in a 0.06 lbs increase in mass, or 6%. Using the performance reported by Chen *et al.* [6] this would replace 0.3 lbs of 200 $Wh \cdot kg^{-1}$ conventional battery mass over the course of a day, resulting in a 0.24 lbs net loss in mass. To determine the possible upper limit for this kind of technology, it is assumed that the photovoltaics are able to achieve a 30% PCE, close to the current maximums seen by commercial products. In this case, there would be a net mass savings of 1.84 lbs for a 24 hour period.

[5] Based on [4]
[6] Based on [5]
[7] Based on [6] using flat horizontal shirt arrangement in San Diego, CA
[8] Using 200 Wh/kg battery system
[9] Based on [32]
[10] Using 30% PCE

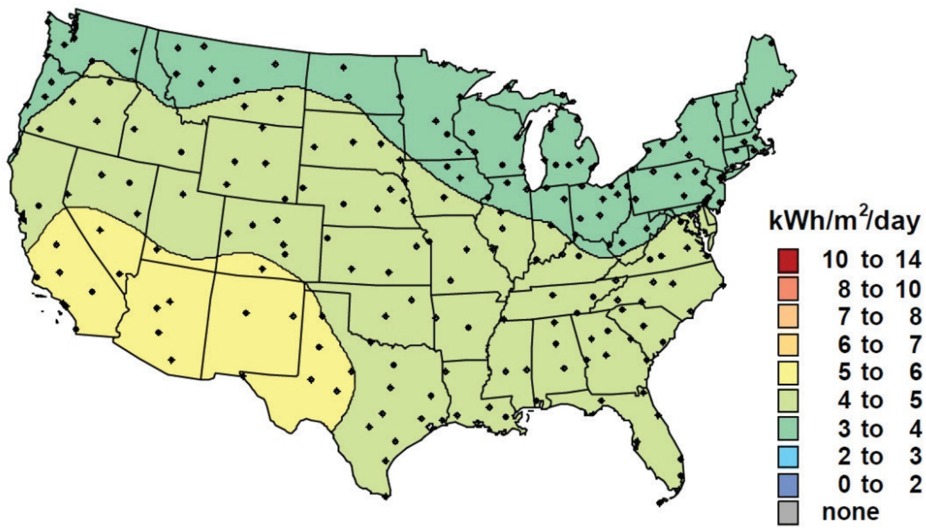

Figure 3-4 NREL annual average daily solar radiation for a horizontal flat plate [39].

It is necessary to determine if there are potential benefits from textile-incorporated photovoltaics as compared to stand-alone devices. Global Solar markets a line specifically for rugged military applications. The P3-62 and P3-124 devices provide maximums of 42.7 $W \cdot kg^{-1}$ and 61 $W \cdot m^{-2}$ at an average 11.8% PCE. In San Diego, a horizontal configuration would produce an average of 693 $Wh \cdot m^{-2} Day^{-1}$ and 454 $Wh \cdot kg^{-1} Day^{-1}$. The potential Army Combat Shirt photovoltaic system, using the performance reported by Chen *et al.* [6], provides 25 $Wh \cdot m^{-2} Day^{-1}$ and 929 $Wh \cdot kg^{-1} Day^{-1}$ based on the 1600 in^2 surface area for half the shirt and 0.06 lbs increase in mass. Even though the areal performance and the PCE are significantly worse than the commercial systems, by weight the multifunctional system outperforms the commercial systems by more than 100%.

4 Conclusions

Multifunctional energy systems (MFES) are a novel approach to system optimization and can significantly improve SWaP-C. MFES can be made from a wide variety of materials, including textiles, building materials, vehicle structural materials, and protective materials. They can be used to store various forms of energy (electrical, thermal, kinetic, potential, chemical, etc.) or to harvest various forms of power (solar, kinetic, thermal, etc.). MFES generally involve some performance compromises, since a single material system must perform multiple functions. These performance compromises can be more than offset in a number of applications. In general, large mass and volume components are good candidates for energy storage multifunctional systems and large area components are good candidates for power harvesting applications. Systems where weight or size is critical stand to benefit the most from MFES, such as sensors, aircraft, and dismounted warfighters. MFES can also provide significant cost benefits in systems where they lead to substantial material reuse or elimination of expensive components.

A review of literature shows that many MFES are impractical due to fundamental physical limitations, materials requirements, and costs. This literature review also highlighted several MFES with the potential to provide significant system benefits.

Structural electrical energy storage is a promising system. Batteries and supercapacitors are commonly used for electrical energy storage and can consume significant weight and volume in high performance applications. Both batteries and supercapacitors are good choices for use in structural electrical energy storage systems. Supercapacitors have higher power density and longer cycle life, but lower energy density than batteries. Since all three of these parameters are important for structural energy storage, both supercapacitors and batteries should be considered for future systems. Calculations of the performance of multifunctional supercapacitor/body armor show that such a system could store between 100 Wh and 750 Wh of energy and significantly reduce the number of batteries carried by a dismounted warfighter. Calculations of small UAV performance show that UAV flight time could be increased by up to 200% through the use of structural batteries as UAV wings and up to 46% through the use of structural supercapacitors as UAV wings.

Autophagous systems that use fuel for structural support may also have applications on aircraft. These systems may be able to achieve specific energies up to 319 $Wh \cdot kg^{-1}$ but need improved specific power to be feasible.

Transparent photovoltaics are currently a very active area of research. These multifunctional systems could be used to transmit visible light while harvesting light from the rest of the solar spectrum, replacing simple windows with windows that generate power. Experimental results have demonstrated up to 6.4% efficiency with 43% visible spectrum transmission [1]. Theoretical calculations suggest this efficiency could be increased to 10.8% [2] and result in a south facing window that could generate up to 380 $Wh \cdot m^{-2} Day^{-1}$.

Photovoltaics and electrical energy storage can also be integrated into textiles. Since textiles are light and have relatively small volumes in most systems of interest, electrical energy storage in textiles is not particularly promising. With current technology a shirt with an integrated battery can only hold 6.5 mWh of energy. If the specific energy of these integrated batteries could be improved to match the current state-of-the-art, the shirt could store 36 Wh of energy, but would offer very little weight savings since the textile battery materials weight more than typical textile materials. Integration of photovoltaics with textiles is more promising since textiles have a large surface-to-weight ratio. A multifunctional textile shirt with 5% integrated photovoltaic threads could collect 26 $Wh \cdot Day^{-1}$ in full sun using current technology. Theoretical estimates project this could be increased up to 170 $Wh \cdot Day^{-1}$ in the future.

4.1 Way Ahead

Structural electrical energy storage is a very promising multifunctional energy system that could dramatically impact the performance of systems such as unmanned aerial vehicles, dismounted warfighters, and small sensor systems. The significant reduction in size and weight coupled with an increase in energy capacity that is possible with structural energy storage could bring transformative capabilities to Department of Defense, Intelligence Community, and Department of Homelland Security systems. Based on this assessment, we recommend further research into structural energy storage systems.

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