POWER AND ENERGY ARCHITECTURE FOR ARMY ADVANCED ENERGY INITIATIVE

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ABSTRACT

The Army Research, Development, and Engineering Command's (RDECOM) Power & Energy Integrated Product Team (P&E IPT) has initiated the Army Advanced Energy Initiative (AAEI) concept. Although there are multiple reasons driving the need for this program, foremost is an urgent requirement to address the need for better integration among programs developing advanced power and energy technologies for the Army. The current P&E architecture is an amalgam of independent programs, which traditionally have been developed in stovepipe organizations, and often as an afterthought to the development of other advanced technologies. The requirement for power and energy in a rapidly modernized, highly digital, and network-centric Army is growing exponentially. Simultaneously the ability to provide these growing demands imposes significant logistic penalties -- fuel consumption, size and weight, reliability, and environmental issues.

1. INTRODUCTION

This paper describes the Power & Energy IPT's Army Advanced Energy Initiative (AAEI). The AAEI has been an evolving concept, arising from issues identified as part of the IPT's technical analysis and roadmapping of key power and energy technologies. In the end, though, the foremost reason for the AAEI is as a tool to address the perceived lack of integration in the Army's Power and Energy (P&E) programs. There have been many proactive and innovative P&E programs aimed at solving the Army's critical energy needs, yet traditionally have been no overarching means to bring them together, to ensure that they were complementary vice duplicative. Too often power and energy are often an afterthought in the development cycle for a technology, even though advanced technologies continue to require more power at ever growing rates. Moreover, power and energy enabled capabilities are not free, as they incur penalties in fuel consumption, size and weight, and environmental issues. A concept paper currently under development codifies significant P&E issues facing the Army today, and is intended to stimulate thought and discussion, and to ultimately provide the foundation for AAEI..

The AAEI concept will not only outline an architecture to better allow "plug and play" among power and energy technologies "*Foxhole to Base Station*," but also will help identify and validate technologies that will enhance current and future force operations. The concept will provide synergy to requirements, platforms, network architectures and technologies based upon visibility, direction and standardization driven by the P&E IPT and key Army agencies.

Usually energy sources, whether a battery or a generator, have been treated as individual components of a specific system, instead of as generic, shareable resources. Each system has an associated individual battery, engine or generator to make it work. There is often little or no redundancy built into this traditional system if the primary energy source is lost. Because the modern Army relies more on electrical energy today than any time in its history, the loss of battlefield energy imposes a significant loss in capability and operational performance. The ability to cross-level power and energy supplies between operational systems is paramount. The loss of an energy source at one system no longer needs to degrade its performance – IF the excess power from other adjacent systems can be effectively and efficiently shared. In short, we must move from a "stranded" energy architecture to a "networked or grid" architecture.

The Army needs to view battlefield energy holistically – from a system of systems perspective, based on the concept of energy sharing. Systems must be able to share energy with other systems - obtain it from those that have excess and move it to those that need it. The Army needs to build an energy sharing infrastructure – effectively creating redundant sources of energy supply. If the Army can implement this concept, it will have more effective and efficient combat power - meaning it can fight longer and significantly reduce the logistical burdens associated with providing power.

Figure 1 provides a notional concept for electrical power distribution. The control and network architecture is not only at the heart of a power network, but functions as the brain as well. A well designed and integrated architecture has enormous potential to reduce power and energy requirements in accordance with Power Management principles. Because the architecture is key to the AAEI concept, outlining such an architecture is a prime focus of this report. With today's advances in digital control, integrated power management software promises high payoff in terms of cost and performance for future systems. In addition to the technical architecture, the AAEI concept describes a building block approach using self-contained power modules and subsystems, scalable from the individual Soldier to the installation level. Defining such a framework will help to facilitate the integration of systems as well as contribute to reliability. In order to realize this concept, good systems engineering must be performed up front. Codes, standards and interfaces need to be addressed by the materiel developers, with an emphasis on using commercial codes and standards when possible.

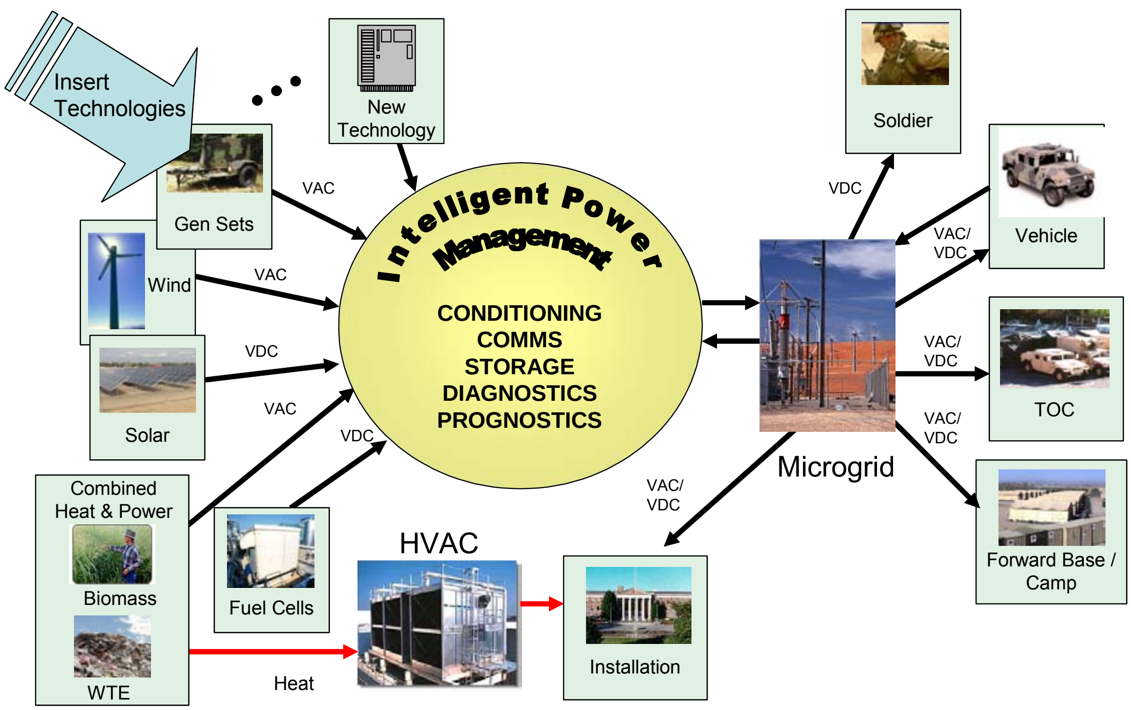

Figure 1. Army Advanced Energy Initiative

systems and managing power distribution across the force. TEP and energy sources are encompassed in all systems, e.g., weapons platforms (onboard and exportable power), tactical vehicles (air & ground), Soldier systems and all electrical/electronic systems. Reducing the power needs of supported systems greatly impacts the sustainment support system by producing many operationally significant benefits."

The AAEI concept paper provides a first draft of the Army's energy architecture to support these capabilities. There are many technical, operational and logistical challenges associated with delivering power to the field. If it were possible to safely "beam" power to soldiers and deployed battlefield systems, then power and energy logistical issues would be relatively small. Unfortunately there are presently no feasible solutions to do this, so we must determine how best to project forward energy with minimal logistical burden and cost. The problem of projecting power and energy is further compounded by a diverse number of platforms that need to be integrated while operating over an even greater range of missions with diverse energy requirements.

3. POLICY AND ISSUES

AR 11-27, Army Energy Program (AEP) provides guidance for Army energy objectives and policy. The AEP objectives are:

a. Ensure the availability and supply of energy to the Army in accordance with mission, readiness, and "quality of life" priorities.

b. Participate in the national effort to conserve energy and water resources without degrading readiness, the environment, or quality of life.

c. Attain established energy and water conservation goals.

d. Participate in research and development (R&D) efforts regarding new and improved energy.

AR 11-27[2] clearly states that energy and water efficiency and availability will be a factor in the decision process and will be stressed in the design, development, procurement, production, and operation of equipment, weapon systems, and facilities. AR 11-27 also states that it will not be cited as authority to place additional burden on weapon system program managers.

Other policies, directives, Executive Orders, energy coordinating regulations and programs are in place to control the increased demand for energy and to minimize cost. There is not, however, a document to coordinate the use of energy at the tactical level other than AR 70-1[3], which addresses the acquisition and fielding of batteries. If adopted the AAEI will provide the first integrated "Systems of Systems" approach to power, energy, and power management – and as it evolves, is expected to become integral to the development of future systems.

4. PLATFORMS

The AAEI classifies power and energy platforms into three main categories: 1) Soldier Power, 2) Mobile/Field power, 3) Stationary/ Installation power.

Soldier Power: Soldier power constitutes lightweight energy sources that are either carried by the Soldier or are highly portable – and include such items as batteries, battery chargers, man-portable fuel cells and photovoltaic arrays, or hand/leg crank generators.

Soldier power systems pose significant challenges. Current soldier power sources based on the use of non-rechargeable batteries present less then optimum performance for meeting mission requirements, are a significant drain on operation and support costs during peacetime, and a significant logistics challenge during a deployment.

Soldier power requirements range from 4 W continuous today to approximately 200 W continuous for future systems. Today, Soldiers rely on stand alone batteries as their principal energy sources. However, batteries, by themselves, lack sufficient energy density to meet demand profiles over required mission duration. While primary "one time use" batteries are prohibitively expensive, comparable rechargeable battery counterparts represent a viable alternative for many applications.. Even though batteries lack required energy density for extended missions, they remain the only near term affordable solution for the dismounted Soldier Yet the insatiable demand for Soldier power calls for improved sources, devices that provide both power and energy density to match the future mission requirements and duration. Although development of such hybrid solutions will increase source capacity, an even greater need to reduce growing load demands will drive developing intelligent power control and management systems.

Mobile/Field Power: Mobile/Field Power encompasses a broad range of systems and applications. These include small man-portable battery chargers, small portable power sources (<3 kW), 5-60 kW medium power sources (skid and trailer mounted), large (100-200 kW) mobile generators, and large ~1MW prime power transportable systems. It also includes platform based auxiliary power units (APUs) to provide power to on-platform systems or as exportable convenience power.

Mobile electric power applications are extremely important because they provide electricity to vehicles, command and control systems, base camps, and for Army logistics systems. The wide variety of demand profiles compounds system design, yet simultaneously requires a set of standard power systems to ensure logistics supportability. Distributed mobile electric power must also be quickly and easily reconfigured.

Current mobile electric power systems would benefit from being lighter, smaller, more fuel efficient and quieter, to include silent watch capability. Design of power systems for Army's new Tactical Operations Center's (TOC's) is challenging because of the diverse demand profiles required to support varied unit missions. Diesel power systems are unlikely to be replaced anytime soon because of their versatility and the high power density that is provided by the mature, yet still improving, diesel engine technology. TOCs and vehicles need to have increased capability for importing and exporting power to other platforms and weapon systems.

A key feature for all future mobile/field platforms is the inclusion of exportable power. This power would normally be AC, have common distribution voltages derived from a higher voltage AC source on a vehicle and convertible in both voltage and frequency by an AC/AC converter with no magnetic components. To accomplish this, hardware will have to be modified so that exportable power can be provided with minimal weight and size increases over today's standard engines.

Stationary/Installation Power: Stationary and installation power differs dramatically from the other categories above, in that it is typically fixed installation power. Typically installed in more benign environments it is far more tailorable to the specific energy and environmental environment, and is not generally constrained by the strict size/weight limitations of deployable systems. Moreover, more fuel choices are available for these systems.

Yet Stationary/Installation power is unique in that it requires interfaces with existing grid power systems in addition to soldier and mobile power systems. Stationary systems must be capable of interfacing with both AC and DC distributed power generation technologies at any location in the world. Stationary power systems must be capable of a wide range of input energy sources (both AC and DC) such as: synchronous and induction powered generator sets at 50 and 60 Hz, from 120 VAC single-phase to 480 VAC three-phase, as well as other high voltage voltages associated with the commercial power grid.

Stationary systems must be capable of safely operating in grid connect and grid isolation configurations, meet National Electric Code (NEC) requirements and adhere to IEEE interconnection standard 1547. Communication protocols must be capable of interfacing with grid protocols in addition to protocols established by the military. Stationary systems must be capable of manual and automated grid disconnections and adhere to Prime Power safety procedures.

The AAEI concept would initially network existing distributed generation (DG) capability at the installation, typically building-dedicated back-up diesel generators, so they would be capable of running in parallel with the local grid or, in the event of a power outage, be able to isolate from the grid and continue to supply power to mission critical facilities. An advantage here is that current back-up generators are generally oversized to accommodate the maximum facility load, which is rarely experienced and is typically twice the normal operating load. The networked generators could be brought online incrementally to meet whatever the mission critical load is at the time, which would likely mean only about half of the installation generators. This obviously increases overall system reliability and therefore enhances energy security, which is one of the Army's energy goals.

These first networked systems might also include a few non-conventional distributed generation technologies like solar, wind, geothermal, biomass, fuel cells, microturbines, etc., at installations where these technologies are already being used. Once the network is established, it facilitates future implementation of these renewable and advanced energy technologies and optimizes the power they provide to the installation, again increasing energy security. Greater use of renewable energy resources and decreased dependence on imported energy is also one of Army's energy goals.[1,2]

Control architecture for an installation power distribution network would be designed to optimize the power delivered to the loads, which includes storing energy for use later. Under normal operating conditions, decision criteria would mostly be based on economics, delivering in real time whichever is the least expensive power commodity. In this mode, the distributed generation assets would be used for peak shaving and/or load sharing, whenever that action helps reduce the installation's utility costs. But in emergency situations, when the grid goes down through natural disaster or terrorist attack, the installation power network becomes a strategic resource for the installation commander to use as necessary for continuation of mission.

5. POWER DISTRIBUTION AND CONTROL ARCHITECTURE

5.1 Overview

Power distribution, control and network technologies are at the heart of the AAEI. A well designed and integrated architecture integrating these technologies has enormous potential to reduce power and energy requirements – as well as reducing the logistics burden associated with them. Because the power distribution and energy sharing are key aspects to the AAEI concept, outlining an enabling architecture is a prime focus of the effort. With today's advances in digital control, integrated power management software promises high payoff in terms of cost and performance for future systems. In addition to the technical architecture, the AAEI concept describes a building block approach using self-contained power systems, scalable from the individual Soldier to the installation level. Energy management software will be central to energy reductions and power quality. To achieve this, energy control systems must have an embedded high level architecture with "plug and play" capabilities in addition to the ability of integrating legacy systems that do not have embedded intelligence. As system configurations are changed, the power management must be capable of recognizing those changes. Systems must be lightweight, have an open architecture, have embedded prognostics, diagnostics, self-healing capabilities and be capable of selective load shedding. Codes, standards and interfaces need to be addressed, with an emphasis on using commercial codes and standards when possible.

With today's advances in digital control systems, integrated software power management will most likely provide the best payback in terms of cost and performance in future systems. It is envisioned that advanced sensor technologies will be incorporated into all platforms. Power management must be as robust and versatile as the equipment it is used with and the missions to which it is applied. It needs to be capable of managing not only single energy devices, but must also be designed from the systems perspective.

As system configurations are changed, the power management must be capable of recognizing those changes. Ideally, all devices connected to the system would have multiple power states (e.g., off, standby, ready, max) and would provide the system with profiles describing the services they provide and how they operate. Systems must be lightweight, have an open architecture, have embedded diagnostics, self-healing capabilities and be capable of selective load shedding. Industry standards should be used where possible.

5.2 Information and Intelligence

Energy network architecture would allow for the use of intelligent techniques for shaping and managing demand when requests for services (location, targeting, mobility) are made. Ultimately, such decisions would be made across an entire unit, resulting in power efficiency for an entire team. This architecture would also allow for tracking energy, as a resource, at all levels of leadership and provide logisticians with better information for re-supplying the force. During Operation Iraqi Freedom, the Army tracked what was demanded, not what is actually consumed (i.e. how many batteries a soldier wants versus what they actually used), but lacked detailed information required to develop better systems. Additionally, if designed into future systems, energy could be better transferred between fixed assets, mobile power, vehicles and soldier systems.

Future energy systems will need to have the ability to turn loads on or off depending on the situation. For example, today's military installations use a dual classification system for loads; critical and non-critical. Critical loads are equipped with highly oversized backup generation and non-critical loads have no backup capability. An intelligent architecture would know how to handle different states of loads and be able to turn on essential, semi-essential or non-essential loads under variable conditions. Multi-intelligent loads, which have peer-to-peer command and information sharing, would have self-healing capabilities under variable conditions such as "normal" conditions or a state of duress when a portion of the grid has been damaged.

5.3 Demand Management

A networked energy approach provides the potential to aggregate loads or to efficiently manage assets, even if distributed. Using traditional power management thought processes, demand is of utmost importance and must be serviced by available energy sources. In future energy systems, demand must be managed just as any other limited resource. This implies the intelligent cycling of devices where devices are only powered when needed. This could be as simple as shutting off devices when not needed. This paradigm shift in architecture may mean short (although acceptable) delays in asset availability. This concept is not new to military systems. For example, if tactical radar systems were continuously operated, their signature would disclose their location. For security reasons they are cycled on and off intelligently, providing a balance between collected information and signature. Similarly, radio silence is not a new concept either. It is envisioned that many more if not all devices could be cycled in this manner to balance source and demand and reduce overall energy consumption. This will require socialization of the concept. If a modular building block approach was used as described below, then a similar architecture could be used from soldiers to installations.

Rapid advances in microelectronics, computing and communication technologies has disrupted the established technology of centralized switches and copper pipes in other industries (such as cell phones and wireless data communications), and a similar paradigm is envisioned for an overall energy distribution system. However, energy distribution systems must also be able to be fail-safe even when communications systems fail. Fail-safe means that a failure does not entail entire system failure. When there are sub-system failures, the overall system would need to determine what could be done and then take the best available course of action. This implies the need to locate intelligence at or near the point of demand. Communication between devices should also be embedded in the electrical wires so that separate communications signals would not be needed.

Lowering the energy demand that systems use is key in the strategy for reducing energy requirements. One way to achieve this is by developing devices that have been designed and built for increased efficiency. New methods to achieve this must be investigated across the full range of energy consuming devices, which will result in substantial demand reduction as a whole. The benefits of demand management are detailed by Nygren et. al.[4]

5.4 Modularity

Modularity refers to the use of common mass-produced building blocks networked together to realize higher performance at lower cost. Building blocks would be self-contained power systems that could be scaled from soldier to installation level. They would have points of common coupling to allow for power distribution if required. Points of common coupling would have voltage conversion equipment to support the transfer of energy between systems of different voltages.

The Army would benefit from methods to network power. Electrical utility companies have learned that networked power grids provide for much more efficient power generation and load balancing, which reduces energy requirements considerably. Networked power could provide redundancy that would increase reliability. Massive redundancy, coupled with self-organizing and self-healing properties, help realize high system reliability and availability. Systems would be implemented incrementally with full backward compatibility and could be upgraded as technology or customer needs change.

Unlike fixed installation power grids, the Army's mobile, networked power grids provide many challenges, although technically feasible, with today's technology. Interface standards and improved energy management schemes will be required.

5.3 Control Software

Energy systems would need to be scalable across all platforms. To do this, they would need to have embedded control software that has embedded ability to register, monitor and control all system devices. In addition to managing demand and source energy, control software would need to integrate mission needs. This implies the need for a supervisory controller that maintains a system model and contains an embedded energy management function and an associated communication manager to track communications.

Diagnostics/Prognostics: Diagnostics/ Prognostics must be considered and implemented during the initial design of the system architecture – not as a retrofit. In addition to detecting system failures and enabling graceful degradation, diagnostics can also provide real-time logistics information and tracking that will allow logisticians to better manage supply needs and assist research agencies and project managers better develop next generation equipment. Appropriate sensors and networking will be needed to support integrated diagnostics/prognostics and energy control.

Duty cycles: The intelligent design of an energy architecture starts with the understanding of duty cycles, which drives the requirements and design of energy source technologies. In military applications, duty cycles can vary considerably, making the design of energy sources difficult.

The variability of duty cycle combined with the vast array of potential demand and energy source devices will dictate the need for intelligent power management as described earlier. The architecture will be required to accommodate Soldier duty cycles, which have yet to be fully developed and mobility/field power duty cycles that change considerably with mission.

System modeling: All energy-related devices must be designed to account for the total cost of energy in force and equipment design decisions in terms of the soldiers, equipment and training necessary to distribute the fuel at all levels in the supply chain. The savings are larger than a cursory review might indicate and can result in a distinctly more effective expeditionary and campaign capable military force. Decision makers at the highest levels must be made aware of the design tradeoffs involving energy in the acquisition of military systems and that investment decisions be based on the true cost of delivered fuel and on warfighting and environmental benefits. Simulation models are an implied requirement to support the decision making process. . For many systems, especially those that require primary batteries, the cost of the batteries can far outstrip the cost of the system over the system's life.

Codes and Standards: Codes and standards will be critical for an overarching power and energy structure. Liquid fuels are relatively easy to transfer between applications because they operate on a common fuel. However, electricity is not as readily scalable since voltages are different. Additionally, as energy sources become smaller, they tend to move away from the use of diesel fuel or JP-8.

Security: Integrated energy systems with embedded communication between devices will inherently raise security issues. The requirement for secure communications itself will increase energy requirements, which will be most important for low energy systems where energy is limited (such as Soldier Systems).

6. Technologies

Renewables: The AAEI must accommodate today's as well as future power technologies. Renewable sources have historically not been used by the Army, but they could be well suited for small-scale applications where conventional power sources of less than 2 kW remain a challenge for the Army. Renewable technologies can significantly reduce the logistical burden for small-scale power systems, especially by reducing need to refuel/change energy sources. Due to their intermittent availability, some renewable technologies will require energy storage, which implies increased system complexity. Renewable technologies and energy storage should be co-developed as an optimized sub-system. Primary renewable technologies include photovoltaic, wind, biomass and hybrids (renewable/energy storage).

Batteries: Today's energy storage is primarily accomplished with batteries. Primary battery chemistries currently have up to three times the energy density of rechargeable cells. However, this increased energy density comes at significantly increased cost in addition to the requirement to transport and distribute the batteries. Advanced energy systems need to be able to incorporate rechargeable batteries that may have lower energy densities and require time to be recharged to their original state. The AAEI also needs to consider other energy storage devices such as ultracapacitors, flywheels, hydraulic boost, hydrogen, superconducting magnetic energy storage (SMES), and charging devices required exchange energy with other sources.

Power Architecture and Interface Technologies: There is a need for a detailed power architecture study, with appropriate recommendations for standards on interface technologies. Interface technologies would have to be developed for multi-intelligent loads, which have peer-to-peer command and information sharing, self-healing capabilities under variable conditions such as "normal" conditions" or a state of duress when a portion of the grid has been damaged.

Electric Drives: Optimizing the motor on the basis of overall hybrid system design can reduce the size of the control electronics and battery requirements, but there is no one single "best" motor or generator design. As an example, Commercial Off-the-Shelf (COTS) industrial designs are unsuitable for hybrid electric vehicles (HEV) applications without extensive redesign and real-world, verifiable mission profile testing. Every electric machine design has tradeoffs. High temperature operation for example is a limiting factor for permanent magnet motors and generators, as is the failure mode of the power electronics controlling them in field-weakened regimes. In-hub motors are as mature as any other from a performance standpoint and are an enabler for new wheeled vehicle architectures and capabilities. In-hub challenges include resistance to extreme shock and vibration, plus the need to transfer power and coolant to the wheel. New magnetic and conductive materials, new architectures and technologies need to be vetted against production capabilities and failure modes. Performance density should be measured with a common metric. The electric machine area has potential to leverage and benefit from commercially developed systems; however, care will have to be taken to insure that commercial components can be modified for military applications.

Thermal Management: As power and energy requirements increase, so does the need for thermal management. Thermal management devices are generally heavy and because they come from technically mature fields that are limited by laws of nature, significant advances in thermal management devices are unlikely. Thermal management could be reduced if device operating temperatures could be increased. This could reduce the need for mechanical cooling or completely eliminate it with natural cooling.

Energy Harvesting: An effective method for reducing demand is to re-use energy in applications where possible. In many cases, the effective utilization of waste heat from heat engines is a viable solution. Energy harvesting could come in the form of energy scavengers that consolidate small amounts of unused energy sources to make a single useable energy source. An example of this is a device that scavenges energy from primary batteries to charge a rechargeable energy source. Energy harvesting has an additional benefit of reduced thermal signature for most applications. A variety of new micro and nano structured materials and components offer potential for significant recovery of losses across a variety of scaled regimes (devices, components, subsystems, systems).

The potential for energy harvesting is relatively unknown due to lack of data collection. For example, much is made about regenerative braking. The amount of regenerative braking energy that can be recovered depends on the driving cycle, the size of the energy storage device and the rate that the device can safely absorb and discharge energy (system impedance, charge rate acceptance and rider comfort). However, vehicle duty cycles have not been quantified and the true potential is unknown.

7. Summary

This paper, in outlining the evolving RDECOM P&E IPT concept for the Army Advanced Energy Initiative, barely begins the process of defining and articulating the challenges, technologies, and benefits that an AAEI approach offers the Army. When distilled to the lowest common denominator, AAEI offers a method for developing the control architecture that will enable the Army – for the first time – to have a comprehensive "smart power grid" for integrating dispersed energy resources. It offers the potential for improved power management, reduction in and balancing of power demands, improvements in reliability, and a reduction in the logistics burden. More important still, it offers the ability for commanders and logisticians to have the first "real-time" picture of power use and management on the battlefield – so they can make better operational and logistics decisions, such as aggregating available energy at key times and places to enable superior capabilities.

The AAEI will integrate additional technology development that leverages ongoing and planned R&D in the immediate future. It will provide the interface standards, protocols, architecture, and hardware for merging the current disparate array of power sources that have been developed by parochial, stovepipe organizations into a monolithic power support system. Moreover, it provides the underlying structure that will enable newly developed technologies – even those that are but a dream today – to be rapidly and seamlessly integrated into the power architecture. Although a detailed cost analysis has yet to be conducted, it is estimated that the cost of developing and fielding such a system pales against the logistics and operational costs associated with the system today.

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