

Towards Multi-Modal Army Base Energy Management Systems: The Arctic Resilient Intelligent Integrated Energy System (ARIIES) Case

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I. Executive Summary:

This white paper advocates for the development of Multi-Modal Army Base Energy Management Systems (M²ABEMS). As an example, it describes the Arctic Resilient Intelligent Integrated Energy System (ARIIES) project which is currently ongoing at the Thayer School of Engineering at Dartmouth (Hanover, NH) as part of a subcontract from the Cold Regions Research and Engineering Laboratory (CRREL). The ARIIES project is developing a real-time multi-modal energy management system that optimizes the supply, demand, and storage of energy for an Arctic military base's operations. Unlike other energy management systems found either in electric microgrids or district heating systems, this system is multi-modal. It provides a systems understanding of energy needs and flows in Arctic bases and key control levers to increase energy services and reliability per unity of energy consumed. It identifies system integration opportunities and challenges so as to enable energy managers to lower costs, increase reliability, and increase energy services in response to the needs of a calibrated force posture in recognition of the degraded and often hostile conditions of the extreme Arctic climate.

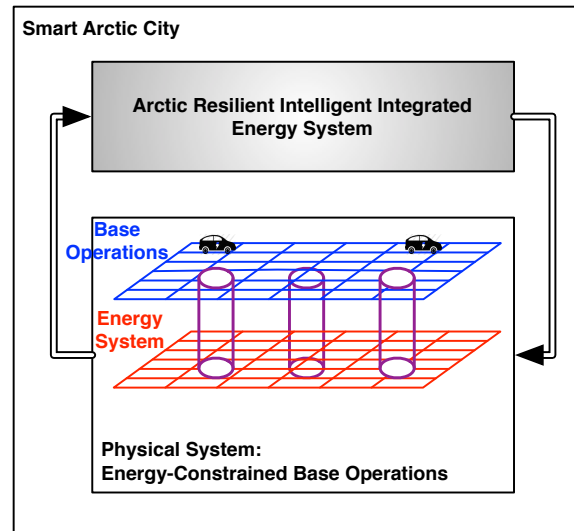


Figure 1. The ARIIES provides a multi-modal energy management system that directly enables base operations.

I. Introduction & Motivation

Military bases sit at the heart of the Army's modernization strategy to conduct *multi-domain operations*¹. They are the start and end points of missions; be they on land, sea, or in air, space, or cyber-space. These multi-domain operations are built upon three tenets: 1.) calibrated force postures, 2.) multi-domain formations, and 3.) convergence that enables the highly integrated and rapidly reconfigurable projection of force. Furthermore, these complex operations must be executed and sustained for longer periods of time in often degraded and hostile conditions. Furthermore, such multi-domain operations must exist within a broader context of flat Army budgets.

Such multi-domain operations are not possible without a similarly *integrated view of a military base's energy system*; be it "within the fence" or projected through mobile applications well-beyond. Indeed, a military base's energy system is its life-blood. All land, sea, air, space, or

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cyber-space missions have an energetic footprint. Consequently, the secure and reliable delivery of heat, electricity, and mobility services is integral to all critical functions of the base's mission.

Furthermore, the *three tenets of multi-domain operations* have their energetic equivalents. A military base's *energy posture* must be calibrated to not just the time of day or season but also the mode of operation; be it normal, emergency, battle, or recovery. The base's multi-domain formations immediately imply *heterogeneous multi-modal energy management systems* that deliver the necessary heat, electricity, and mobility services. Finally, the convergence of multi-domain operations means that these heterogeneous energy services must be *increasingly integrated* so as to reliably support the rapidly reconfigurable projection of force. Enhancing the performance of individual energy technologies neglects the *high potential for their system-wide coordination*.

The energetic footprint of multi-domain operations is further exacerbated by the *degraded and often hostile conditions of extreme climates*. Two climates stand out; not just for their thermodynamic severity but also for their strategic relevance to the nation's security. Hot and arid desert climates such as those found in the Middle East place heavy demands for air conditioning and chilled water. Often scarce potable water may need to be transported to the base or even desalinated from nearby seas and oceans. The presence of sand and humidity near seacoasts further demands robust air quality management systems. In the meantime, the Arctic region presents unique technical challenges to the design, planning and operation of energy systems. Extreme cold temperatures amplify the demands for heat and electricity while simultaneously complicating the reliability of battery-operated equipment. In the winter months, the scarcity or even absence of daylight renders solar power generation ineffective and encourages the storage of energy in its many forms. In both of these extreme climates, the military base's energy system must be resilient so as to continue operation despite a wide variety of potential disruptions. For example, the reliance on fossil fuels with long supply chains like diesel fuel, propane, and natural gas presents a system wide vulnerability. Consequently, it is imperative that a military base's energy system be designed and optimized for the multi-modal delivery of heat, electricity, and mobility.

The budgetary context of multi-domain operations implies that a military base's multi-modal energy system similarly *respect economic realities*. Whereas in battle mode, such an energy system must be operated so as to project a calibrated force posture, a normal operating mode must, in contrast, demonstrate energy frugality. Such an intelligent switching has the additional benefit of extending mission capability. If stored energy quantities (e.g. fuel, chilled water, hot water, etc), are used efficiently between fossil fuel shipments in normal operations, they are likely to last much longer when they are urgently needed in active conflict.

This white paper advocates for the development of *Multi-Modal Army Base Energy Management Systems (M²ABEMS)*. As an example, it describes the *Arctic Resilient Intelligent Integrated Energy System (ARIIES)* project which is currently ongoing at the Thayer School of Engineering at Dartmouth as part of a subcontract from the Cold Regions Research and Engineering Laboratory. M²ABEMS, and more specifically the ARIIES, enable the multi-domain operations at the heart of the 2019 Army Modernization Strategy. Furthermore, the development of M²ABEMS, as a measure to *modernize base facilities, minimizes infrastructure risks* and

prevents their propagation into compromised readiness in the field. It also sits squarely within two *Army priority research areas: disruptive energetics and artificial intelligence.*

The remainder of the white paper is organized as follows. Section II provides some relevant background literature for the development the ARIIES and M²ABEMS more generally. Section III explains the ongoing work of the ARIIES project. Section IV concludes the white paper.

II. Relevant Background Literature

The concept of multi-modal army base energy management systems (M²ABEMS) is built upon significant technological maturity in the area of microgrid energy management systems (MEMS)ⁱⁱ; both in the academic literature as well as in practical application in civilian and military contexts. These MEMS allow a relatively small electric power system to operate in coordination with a larger power grid, entirely independently in an “off-grid” setting, or in a semi-islanded fashion where the microgrid connects and reconnects in response to grid conditions^{iii,iv}. In the context of forward operating bases, microgrids can often be deployed as “turn-key” solutions in a relatively short period of time; often relying on solar PV generation or diesel gensets. More established army bases; either domestically or in allied nations, often build their bases on an electric power systems that has the ability to operate in an islanded mode although it may be utility-grid tied in normal operation.

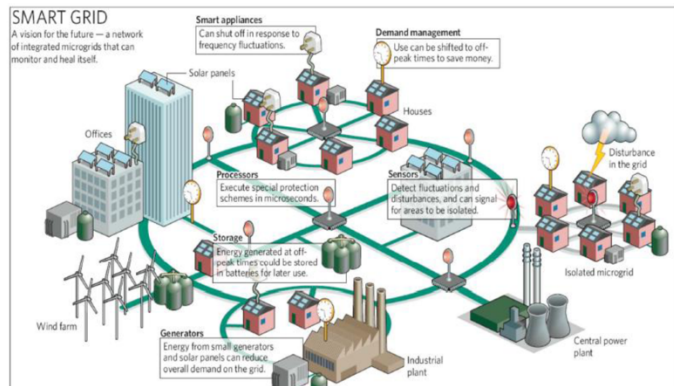


Figure 2. Conceptual Representation of an Electrical Microgrid.

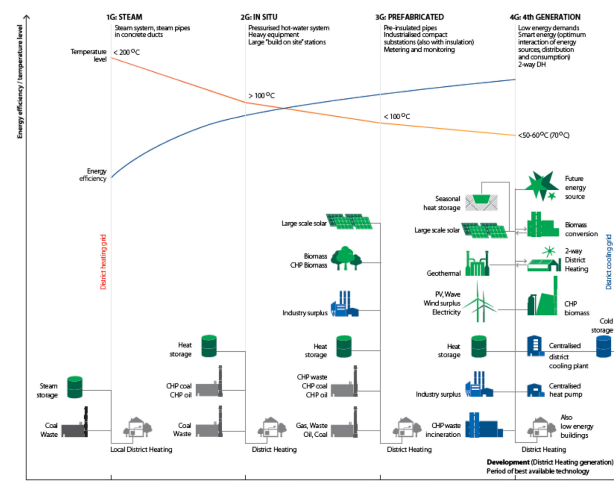


Figure 3. Illustration of the concept of 4th Generation District Heating in comparison to the previous three generations.

has recognized the potential for “4th Generation District Heating Systems” that integrate electric power grids, district heating/cooling systems, and “smart” energy management systems. Such a

While electric microgrids have the potential to coordinate electricity supply, storage, and demand, they do not address other modes of energy consumption. Of the 101.2 Quads that Americans used in 2018, only 38.2 were used by the electric power system. Consequently, a truly holistic energy management system must look beyond electricity as an energy carrier to other modes of energy transport. In that regard, district heating and cooling systems provide a centralized thermal service, often from a single central heating/cooling plant^{v,vi}. Thermal transport in the form of hot or cold water has viable applications in commercial, industrial, academic, and military contexts. More recently, the district heating and cooling system literature

view, however, is fundamentally multi-disciplinary because the two modes of energy transport are governed by entirely different engineering physics.

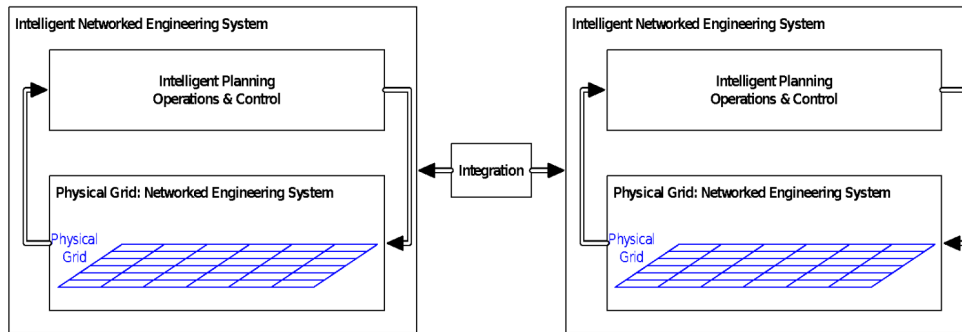


Figure 4. A Class of Engineering Systems: Two physical networks with their respective dynamics and multiple layers of control and decision making are integrated.

The Laboratory for Intelligent Integrated Networks of Engineering Systems (**LIINES**) has specialized in the design, planning, and operations of engineering systems where one physical network that has multiple layers of control and optimization is integrated with another physical network of entirely different function that has its own multiple layers of control and optimization. It has made many contributions to this class of engineering systems. With respect to the energy-water nexus, it has produced the first model of its engineering physics^{vii, viii} and developed optimal methods for its operation^{ix, x, xi}. Furthermore, it has developed the first model of a transportation-electricity nexus^{xii} composed of road-traffic and electric power dynamics and then used it simulate a hypothetical test case^{xiii} and conduct the first full-scale electric vehicle integration study^{xiv, xv}. This work was further extended to microgrid-enabled mass-customized production systems^{xvi}. This last work is particularly relevant because the operations research literature has found that an arbitrary service system such as a military operation can be expressed with mathematical equivalence to a mass-customized production systems. All of these applications rely on a newly developed “hetero-functional graph theory” that facilitates the mathematical modeling and simulation of an arbitrary number of networks connected arbitrarily^{xvii}. Furthermore, they demonstrate the strong theoretical and methodological foundation for the integrated development of multi-modal army base energy management systems.

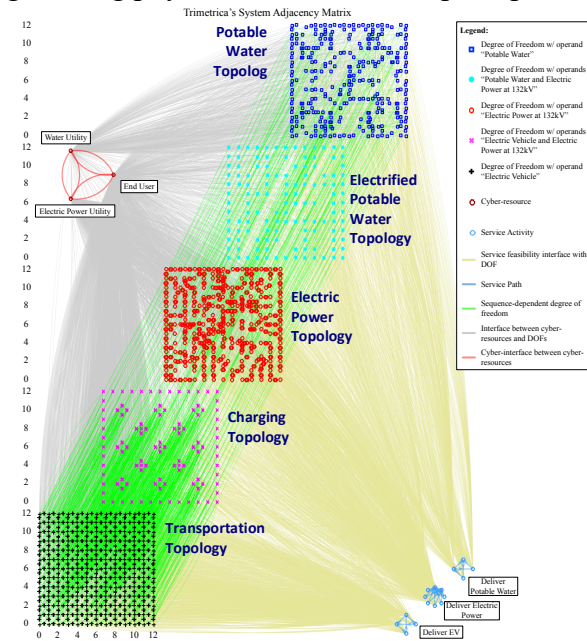


Figure 5. A Hetero-functional Graph Representation of the Trimetrica Smart City Test Case

III. The ARIIES Project

The ARIIES is best understood as a real-time, multi-modal, energy management system software that optimizes the supply, demand, and storage of energy for a military base’s operations. In this regard, it is analogous to the energy management systems found in (exclusively electric) microgrids or those found in (exclusively thermal) district heating systems. Because the ARIIES is designed with resilience, integration, and intelligent decision-making specifically in mind, the ARIIES can enhance the effective utilization of existing physical energy assets. Furthermore, depending on the chosen energy optimization objective, it presents a significant **five-point opportunity** for operational efficiencies that can extend mission capabilities by as much as 30%. so as to directly extend mission capability by as much as 30%.

- First, military bases have the opportunity to custom-design and reconfigure their energy systems for the delivery of their specific mission. Therefore, we can design an **integrated** multi-modal energy system that not just includes electricity, heat, and mobility but also recognizes that the multiple modes of energy delivery support resilience through multiple modes of base operation (i.e. normal, emergency, battle, or recovery). In effect, an integrated energy system can provide the right levels of flexibility and redundancy to extend mission capabilities.
- Second, the **integrated** design of these multiple energy modes opens the door to thermodynamic and cost efficiencies that are otherwise infeasible. For example, heating loads can be served by a combination of electricity (e.g. heat pump) and fossil fuel (e.g. furnace) technologies.
- Third, military bases can deploy **intelligent** decision-making so that the supply, demand, and storage of multi-mode energy can simultaneously adhere to potentially limited energy inflows (e.g. solar, wind, and fossil fuel shipments) and prioritize the criticality of military base functions potentially months into the future.
- Fourth, military bases have the potential to make **intelligent** energy management decisions because they can link to most of their most energy intensive activities to the **time-dependent** activities of their operations. In short, when we deeply understand the “**why**” of energy consumption that the “**how**” of energy delivery can be most effective.
- Finally, Arctic military bases have the opportunity to improve their **resilience** by diminishing their reliance on expensive fossil fuels with highly vulnerable and long supply chains.

Consequently, the Arctic Resilient Intelligent Integrated Energy System (ARIIES) seeks to capitalize on the five-point opportunity described above with five points of novelty and innovation.

- The ARIIES’ focus on **integrated** multi-modal energy management sets it apart from other solutions. Whereas electric energy management systems are well-developed for electrical microgrids, to our knowledge, the ARIIES will be the first real-time multi-modal energy management system. Its energy management system will require a newly developed dynamic model of a military base’s energy system.
- The ARIIES’ focus on **integrated** multi-modal energy management also allows trade-off decisions between electricity, heat, and mobility services that could not be achieved by optimizing electricity alone. For example, when heating loads are served by a combination of electricity (e.g. heat pump) and fossil fuel (e.g. furnace) technologies, the ARIIES has

the potential to decide the optimal balance between these two energy sources. Such a decision is even-more valuable when deciding between renewable energy generation (e.g. solar PV and wind turbines) and conventional thermo-electric facilities (e.g. natural gas turbines or diesel gen-sets). Consequently, we believe that the ARIIES' algorithms will find thermodynamic and cost efficiencies that are otherwise infeasible. The ARIIES' newly developed dynamic energy system model will also facilitate the development of its model predictive control (MPC) algorithms.

- The ARIIES' use of *intelligent* MPC means it can “look ahead” over potentially lengthy time horizons to be ready for potentially limited energy inflows (e.g. solar, wind, and fossil fuel shipments). In purely electrical applications, such algorithms have proven their ability to maximize the utilization of battery technologies. In this multi-modal context, it can find the right balance of batteries and fossil fuel shipments.
- The ARIIES' *intelligent* energy management decisions will also characterize the military base's energy demand in terms of the *services* they enable in the military base's mission. One consistent weakness in the (electric) “demand response” literature in the power systems engineering field is that it often characterizes electricity demand purely in terms of kWh; neglecting that the *value* of a kWh depends on *how* and *when* it is consumed. In contrast, a recent control system design of a navy ship's chilled water system understood that in “battle mode” chilled water needs to be routed exclusively to weapons and propulsion systems! In short, optimizing energy service delivery is a far more effective means of extending mission capability than simply optimizing energy quantity.
- The ARIIES' *resilient* energy management decisions mean that it will systematically prefer the consumption and storage of local (and relatively cheap) renewable energy. Such a preference optimizes fossil fuel shipments and reserves its use to the highest priority and most demanding modes of operation.

The value of the ARIIES lies in its ability to make use of the optimization opportunities underlying the energy management trade-off decisions at an Army base. Some of these are conventional and exist at just about any army base; still others appear when the Army base possesses a greater diversity of on-site energy resource. There is the choice between on-site electrical generation of potentially varying economies-of-scale and the import of electricity from utilities. In the meantime, the vary nature of army base operations means that the value of consumed energy is different from one energy service to another. During constrained modes of operation (e.g. battle, emergency, restoration), there will be a natural preference towards safety-critical functions. These opportunities are expanded further by the presence of onsite renewable energy generation (e.g. solar PV and wind). In energy abundant times (sunny and/or windy days), these energy resources can be systematically preferred over those that consume from fossil fuel shipments. Such a operational decision leaves these fuels ready for constrained modes of operation. Similarly, heating setpoints can be adjusted to pre-heat or pre-cool buildings during these energy-abundant times. These options grow still with the presence energy storage in its various forms; be they batteries or thermal storage. In short, the ARIIES makes optimal use of the multi-modal energy resources on the base and gains further value as new and more diverse energy resources are installed.

In order to develop the science and technology of ARIIES as a base-wide state-of-the-art energy management system, the LIINES is working with Cold Regions Research and Engineering Laboratory (CRREL) to develop a collaborative relationship with U.S. Army base. In this relationship, we seek to deeply understand a base's mission and work to understand how energy is a critical factor to its success. We plan to engage the base's leadership to identify operational priorities and work with technical staff to gain an on-the-ground understanding of the base's energy resources. The development ARIIES requires operational data collection. In some cases, this data is a part of the standard good practice of facility operations. In others, it may require electricity, fuel, gas, and/or water meters to gain a better understanding of operational challenges. As we develop the ARIIES, we hope to identify significant opportunity for operational efficiencies that can extend mission capabilities by as much as 30% or reduce costs without hampering current mission effectiveness.

IV. Conclusion

In conclusions, military bases sit at the heart of the Army's modernization strategy to conduct multi-domain operations. They are the start and end points of missions; be they on land, sea, or in air, space, or cyber-space. The success of these multi-facted missions, however, equally requires a multi-domain approach to energy. The three tenets multi-domain operations means that army bases must have 1.) energy postures calibrated to their force posture 2.) hetero-geneous multi-modal energy management systems to support multi-domain formations, and 3.) increasingly integrated energy systems that enable the highly integrated and rapidly reconfigurable projection of force. The ARIIES project provides an opportunity to develop multi-modal army base energy management systems (M²ABEMS) in the degrade and often hostile condition of an extreme cold climate. Finally, the M²ABEMS respect the economic reality that such multi-domain operations must exist within a broader context of flat Army budgets.

About the Author: Prof. Amro M. Farid leads the [LIINES](#) and maintains an expertise in the enhancement of sustainability and resilience in intelligent energy systems. Unlike many power systems engineering laboratories, we specialize in energy systems where one physical engineering system with its associated layers of decision-making and control interacts with another fundamentally different physical engineering system with its own layers of decision-making and control. This specialization has consistently produced novel mathematical models, simulation software and optimization algorithms across five relevant research themes: 1.) smart power grids, 2.) energy-water nexus 3.) electrified-transportation systems, 4.) microgrid-enabled production systems, and 5.) interdependent smart city infrastructures. This expertise provides us a unique insight in the development of ARIIES as an intelligent energy system that superimposes military base operations as one physical engineering system upon a multi-modal energy system as another. Prof. Farid is an American Citizen born in Brooklyn, NY. He has received from the US Congress a Certificate of Merit for Exceptional Community Service.

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