Accounting for Every **Kilowatt**

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Modern warfare relies on electrical generators at base camps. While the associated fuel costs are well understood, we cannot explain where our kilowatt-hours (kwh) are going. Reducing demand without reducing our capability requires appliance-level feedback, which current smart-meter technology does not provide.

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Enter the Deployable Nonintrusive Load Monitor (DepNILM, pronounced "deep" NILM) system in development at the Massachusetts Institute of Technology (MIT). Field tests on base camps at Fort Devens, Mass., and Fort Polk, La., show DepNILM can provide accountability of individual load consumption, forewarning of maintenance problems, and awareness of human activity based on electrical activity.

Functionality

The system measures voltage and current at the generator or electrical panel 8,000 times per second using off-the-shelf sensors. When custom software is used to process the data, subtle changes in power begin to stand out. Every electrical device has distinct features similar to a human fingerprint. Once you program software to recognize those features, every heater, refrigerator, pump or light turning on or off is a detectable event.

Accountability

Soldiers need appliance-level feedback to reduce electrical consumption. Specifically, they need to know what loads are currently on and how much power each load uses. When the cost and behavior of each individual appliance is understood, facility managers have the information they need to make smart decisions. DepNILM permits users to distinguish between mission-critical loads, quality-of-life loads, expendable loads and even wasted energy.
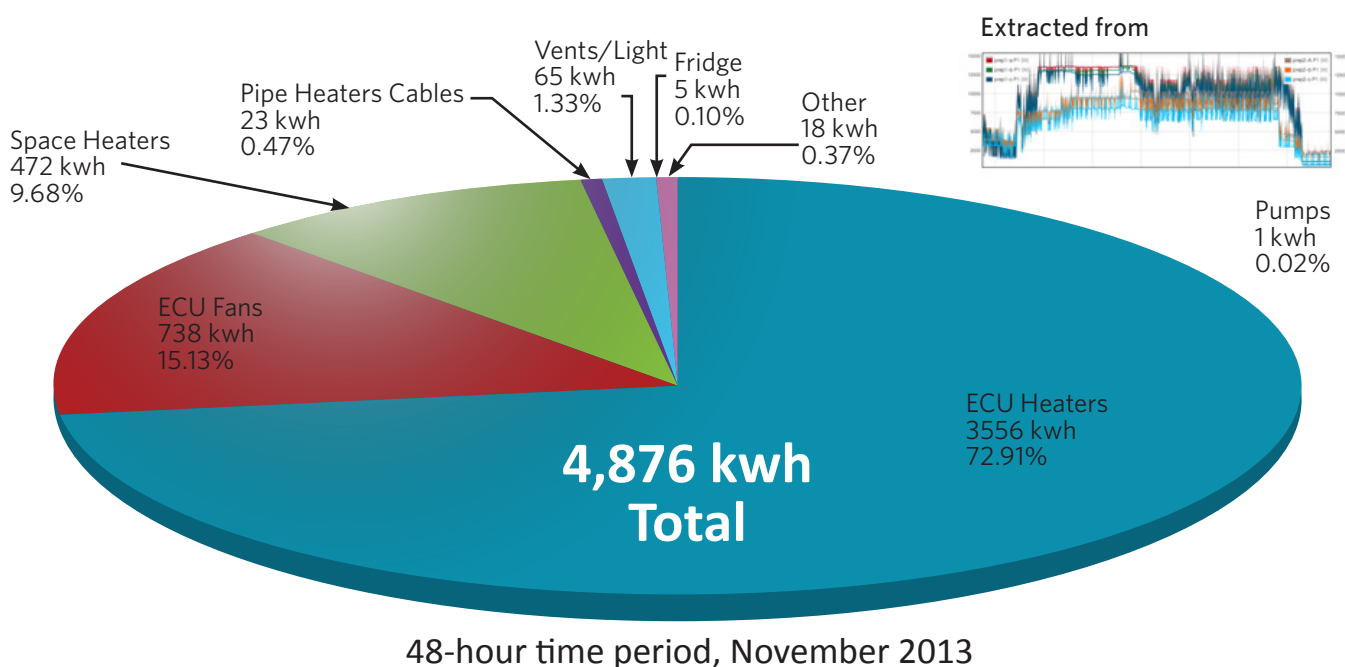
Forward deployed soldiers live at base camps like the Force Provider 150 (FP-150) standing at Fort Devens. The camp at Fort Devens is a fully functional research and training facility, which includes living tents, latrines, showers, laundry and

a kitchen. The following timeline provides some context for the top plot in Figure 1. Ninety infantry soldiers came to Fort Devens on a Friday. Around 9 p.m., they washed and went to bed. Saturday morning at 5 a.m., they woke, shaved, ate breakfast and departed for the weapons range around 7 a.m. At 4 p.m., they returned to the base, ate, cleaned their weapons and showered before retiring around 10 p.m. On Sunday, they arose at 6 a.m., packed their things and departed by noon.

DepNILM itemized the power consumption of the largest loads over the weekend (Figure 2). Seventy-three percent of the energy over the weekend went toward Engine Control Unit (ECU) heating coils. If the supply fan, which circulates the inside air across the heating coils, is considered part of the heat system, 88 percent of the cost over the weekend is attributed to 11 ECU machines. Adding in the smaller space heaters (and the window unit air conditioners), used in the showers, latrines and kitchen, 98 percent of the total cost came from keeping the rooms at a desirable temperature. The refrigerator, vents, pipe heater cables, pumps, lights and all other unaccounted for loads consume negligible power in comparison to the heaters.

Appliance-level detail enables important comparisons. Although only two soldiers were left behind, all heaters in all tents remained on while the rest of the unit went to the range. Figure 3 shows the effect conservation efforts would have. The top plot of Figure 1 shows an unoccupied consumption graph during those nine hours. When unoccupied, only the rooms with water service are heated. Actual use from 7 a.m. until 4 p.m. was 913 kwh. The unoccupied consumption of a similar-temperature day during the same nine hours was 209 kwh. This translates to 14 percent of the total weekend energy cost

Figure 1. Power Consumption (kwh) During the Training Weekend

Extracted from

Space Heaters
472 kwh
9.68%

Pipe Heaters Cables
23 kwh
0.47%

Vents/Light
65 kwh
1.33%

Fridge
5 kwh
0.10%

Other
18 kwh
0.37%

Pumps
1 kwh
0.02%

ECU Fans
738 kwh
15.13%

ECU Heaters
3556 kwh
72.91%

**4,876 kwh
Total**

48-hour time period, November 2013

(704 kwh) going toward heating unoccupied living quarters. With absolutely no loss of comfort or mission readiness, the cost could have been 14 percent less.

$$\Delta E \times \frac{1}{\rho_{diesel}} \times \frac{1}{\eta} = Gallons_{diesel} \quad (1)$$

The conversion from kwh to gallons of diesel fuel is Equation 1. One estimate of the energy density of diesel fuel (ρ_{diesel}) coupled with the efficiency (η) of a 60-kilowatt generator operating at full load is 11.76 kwh per gallon. Using the energy savings of 704 kwh for the energy savings (ΔE), the cost of waste in this example equates to 60 gallons of fuel for this 48-hour period.

A rational operator will not knowingly waste energy. However, running equipment in ignorance of the cost allows perpetuation of inefficient behavior. DepNILM clarifies the cost of doing business down to the appliance level. Targeted conservation efforts will have the greatest effect when soldiers know what they are using and how much it costs.

Figure 2. Power Use Itemized by Device During a Winter Weekend
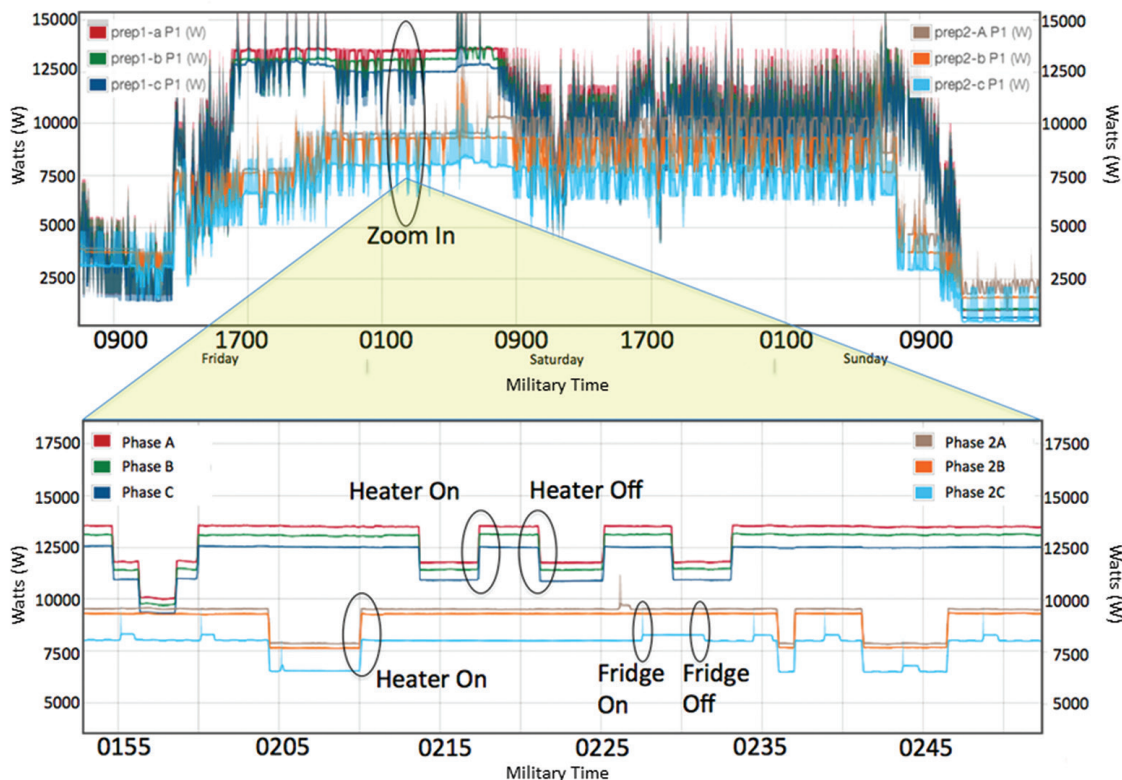
Figure 3. Potential Kilowatt Savings From Not Heating Empty Tents
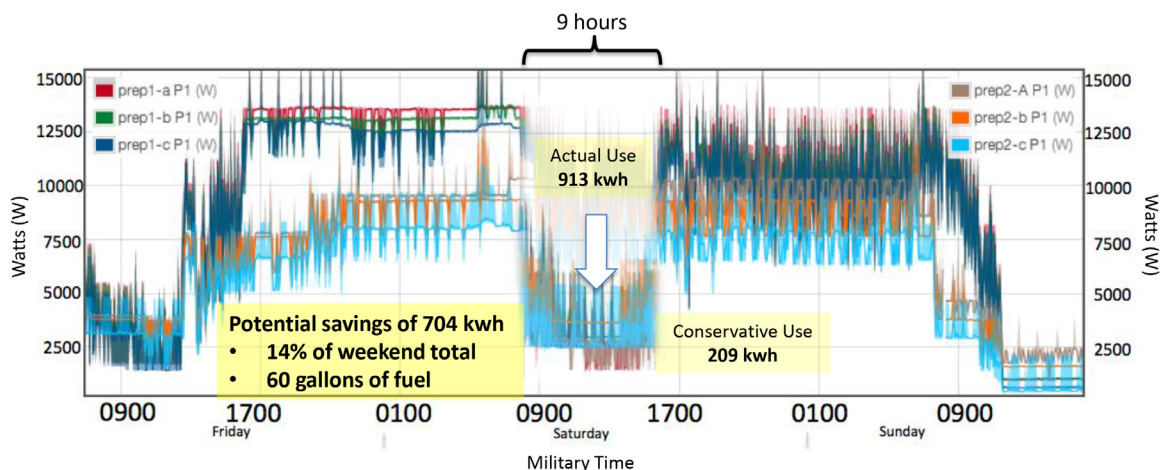
Condition-Based Maintenance

Signs of machine wear and dysfunction are detectable through their electrical signals. Observable with DepNILM's high-resolution data, subtle details of machine transients can signal anomalies in the sequence of operations and trigger alarms.

Fort Polk, home to one of three Army Combat Training Centers, has several Forward Operating Bases (FOBs) built to emulate conditions in current theaters of operation. DepNILM monitored a portion of one FOB during a training rotation, including sleeping quarters and two headquarters buildings. The organic loads consisted only of lights and environmental control.

When one A/C unit stopped behaving normally, DepNILM caught it. After hours of regular 12-minute cycles, the compressor turned on and stayed on for more than 12 hours straight. Afterward, the supply fan ceased to function. We detected the fault by comparing the bad ECU (Compressor 1) with a good ECU (Compressor 2). First, the power draw of Compressor 1 after the 12-hour runtime was consistently about 0.3 kw less than before, dropping from about 3.3 kw to just 3 kw. This difference is about how much the supply fan uses. Second was the distinct absence of the "fan off" fingerprints from all future cycles (Figure 4). The fan is supposed to turn off one minute after the compressor does (right side of top plot). Third, a comparison of the run times between Compressor 1 and Compressor 2 indicated significant likely differences in future operation. During a five-hour period, the hottest part of that day, the broken unit ran more than twice as long as the good one, using almost 2.5 times as much power.

With appliance-level resolution, equipment malfunctions can be identified and targeted efficiently. Through any Web interface, the DepNILM system permits the users to access highly detailed data regarding the electrical network, even in a bandwidth-constrained environment. To quantify the reduced data-transfer requirements, we remotely accessed, analyzed and diagnosed electrical consumption data from Fort Polk using a mobile third-generation—relatively common and slow—WiFi hotspot from AT&T collocated with the three DepNILM systems. Over the following weeks of analysis, total data transfer among all three DepNILMs was less than 2 gigabytes. Most of the preceding accountability and maintenance examples were identified from our desks at MIT. Tech support can be anywhere and do the same.

Human Activity

DepNILM provides awareness of human activity within a network. Each device has an electrical fingerprint, and specific devices imply associated human actions. When electrical activity is detailed enough to tell when appliances cycle, experience and intuition can extract meaning.

Figure 4. Power Signature: Working vs. Malfunctioning
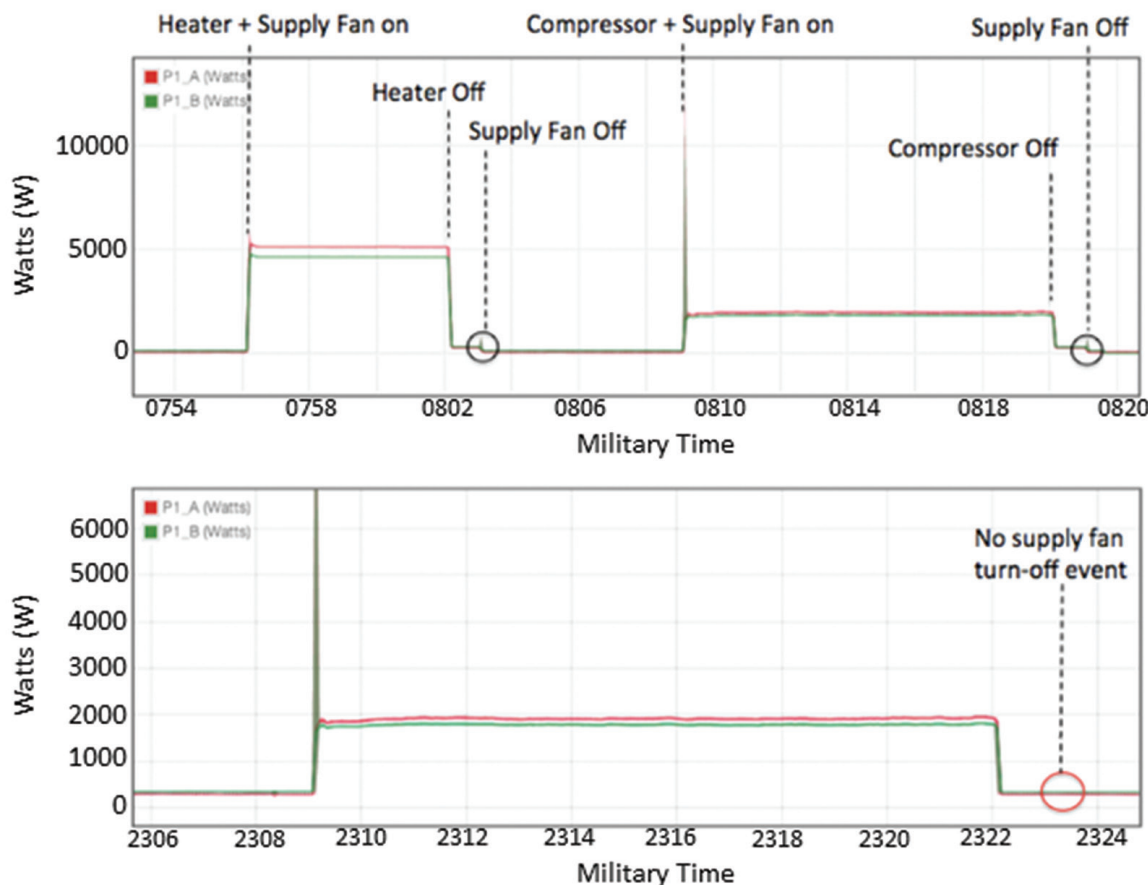
We monitored a Combat Support Hospital unit powered off mobile generators. The loads in the hospital are numerous and technical, but three in particular shed light on human behavior and schedule. Hypothermia, common among trauma patients, is treated with a Bair Hugger, which pumps warm air under a blanket. Cycling six times per second, it has a distinct fingerprint. The Pressurized Oxygen Gas System, which harvests medical-grade oxygen from the air, is run continuously for patients requiring ventilation or respiration. It has a distinct periodic wave form that ramps up and drops off every 30 seconds. These two appliances are good indicators of the arrival of new casualties. The third device is the ubiquitous coffeemaker. Its signals clearly stand out and feature repeated 45-second bursts of power use followed by 15 seconds of rest. In the sleeping quarters, where the hospital staff rested, a small coffeemaker started most mornings shortly after 6 a.m., corresponding to the 12-hour shift changes at 7 a.m.

Finally, we show an example of a refined human activity product based on discrete machine cycles. Pump events correspond to times when soldiers are using water, namely the latrines and showers. Figure 5 shows pump event times overlaid with the training timeline milestones. A general understanding of when the troops are asleep or awake is possible by observing when pump events are not happening, including Friday night (between 10 p.m. Friday and 4:59 a.m. Saturday and Saturday night (from 10:22 p.m. Saturday to 5:56 a.m. Sunday). Conjectures are possible about when the base is occupied or minimally manned. Normal use during occupied times

shows pump events approximately every 25 minutes. Periods of heavy pump use indicate washing and showering times.

Detailed electrical measurements permit another means of confirmation of human activity. A skilled analyst accustomed to looking at electrical data may be able to recognize specific equipment simply from experience if actual loads are unknown.

The Way Forward

DepNILM offers a unique, accurate and inexpensive method to infer human activity from electrical activity, gain accountability of individual load consumption and be forewarned of looming maintenance problems.

The benefits of the DepNILM system scale well. Forward bases, no matter how large, are composed of essentially modular base camps like the FP-150. At the height of the War on Terror, more than 200,000 soldiers lived at base camps on

Top: Connection to a generator during unit field training at Fort Polk, La.

Left: Force Provider tents at Base Camp Integration Lab, Fort Devens, Mass.

Photos by Mark Gillman

foreign soil. From the previous example at Fort Devens, saving 60 gallons of fuel per FP-150 per weekend is strategically significant—40,000 gallons per day.

These savings are possible when users have the right information to base decisions on. Figure 6 presents our design for the user feedback display, what we think the average FOB manager needs to know to make energy-conscious decisions. Live data are still being collected at Fort Devens to test and improve the system. This vision is clear: Actionable feedback leads to cost savings (and a whole lot more). &

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Figure 5. Occupancy-Related Energy Usage
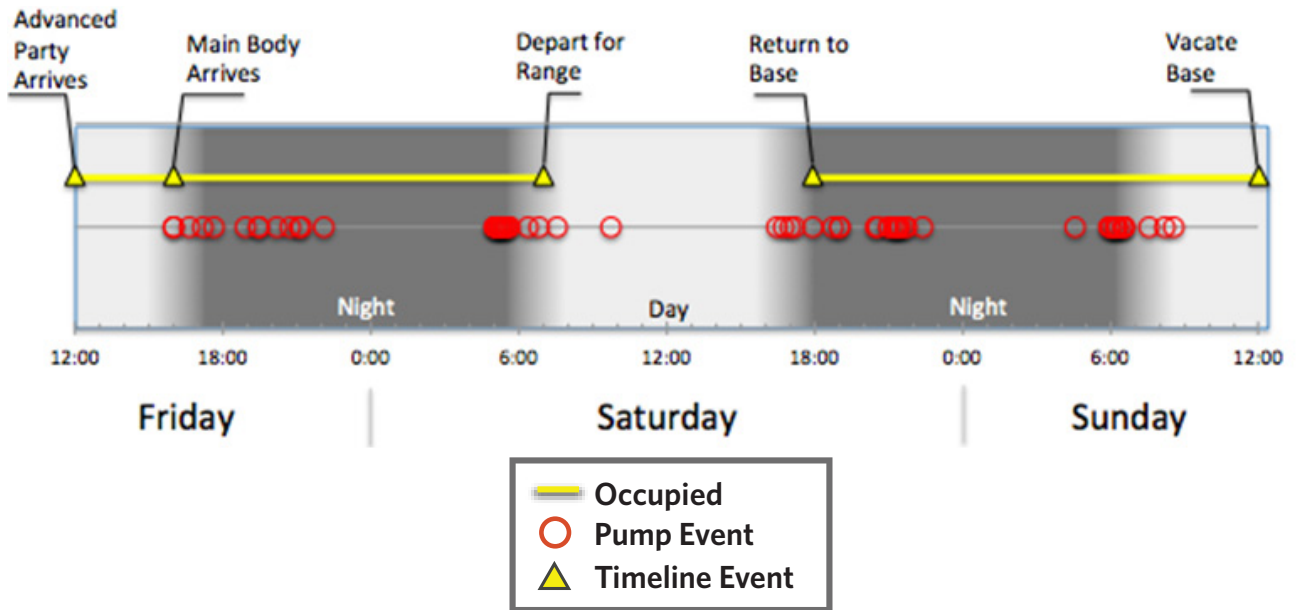
Figure 6. Design of User Feedback Display