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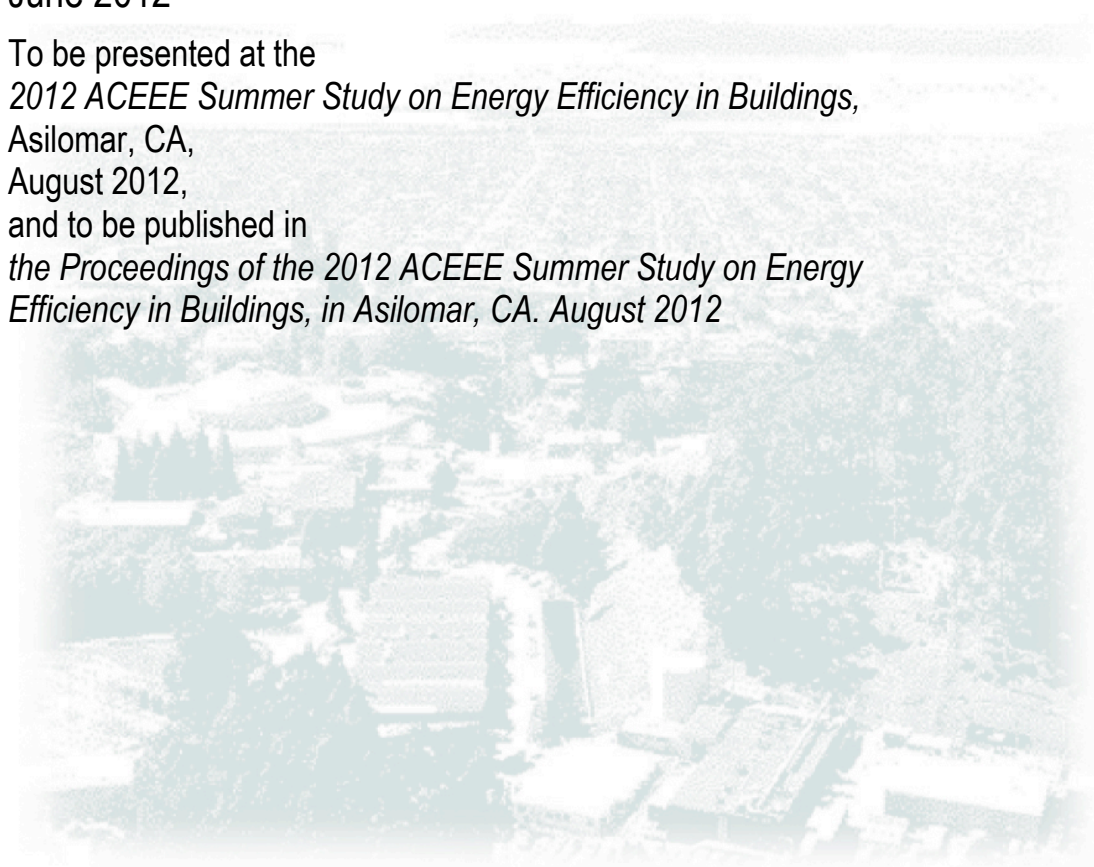
Achieving Extreme Efficiency: How to get  
the job done when energy is extremely  
expensive and scarce

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# **Achieving Extreme Efficiency: How to get the job done when energy is extremely expensive and scarce**

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## **ABSTRACT**

How far can we push cost-effective energy efficiency if power costs 10 times today's utility price and is extremely scarce? Many situations today operate under these conditions, generally in buildings or vehicles that generate their own power, such as military forward bases, disaster response centers, remote, off-grid sites, and hospitals or other critical facilities operating on backup power. This paper examines these applications as a unified "market," where 80-90% energy efficiency improvements are not only cost-effective but can help these facilities better carry out their mission. Clear advantages of high efficiency include longer operation between fuel and battery resupply, longer vehicle ranges, and ultimately the ability to operate autonomously using locally available renewable energy sources.

We first summarize the energy use characteristics and operational needs of several applications that would benefit from such extreme efficiency. We then identify ultra-efficient design options for a wide variety of equipment used in such facilities, including lighting, space conditioning, water heating, cooking and cleaning appliances, electronics, pumps and motors. Savings of 50-90% are possible using technologies that are either commercially available or close to production, and further savings are possible using advanced technologies that are still in development. Several cross-cutting strategies apply to a wide range of equipment, including electronic lighting, heat pump technology, power management, variable-speed drives, sensors and controls, and high-efficiency motors. By designing products to meet the efficiency needs of extreme applications, this market niche can be used as a market transformation strategy to bring these advanced technologies into broader commercial production much sooner than traditional building applications.

## **Introduction**

The concept of energy efficiency is inextricably linked with that of cost-effectiveness, i.e., from an economic perspective, it pays to invest in more efficient products only to the point where incremental purchase price is paid off by the energy bill savings (and possibly maintenance and/or replacement savings) over some reasonable time period. Including social and environmental costs improves the cost-effectiveness. Given relatively low energy prices in the U.S., however, this means that only modest, incremental efficiency improvements have met this cost-effectiveness test. Advances in the efficiency level of new products has increased gradually due to energy efficiency standards and other forces taking the lowest-performing products off the market, while the upper end of the market has moved proportionately through the efforts of voluntary standards like ENERGY STAR and utility programs. All of these programs, however, are targeted to the "most common denominator," which is defined by average energy use in conventional situations. Extreme efficiency takes a fundamentally different approach. Rather

than designing to the average conditions and gradually improving over time, extreme efficiency targets the edge cases where energy is scarce, and therefore very expensive. Moreover, extremely efficient products can provide additional benefits through the fact that they require less supporting infrastructure, generate less heat, and other types of co-benefits that come with lower energy use. Because energy services are very valuable in these edge cases, in many cases the additional cost of extremely efficient products is hardly a consideration in the purchase decision. If a product better serves its main purpose—while using less energy—it will be the preferred product. Previous work on this topic includes Goldstein (2008) and the Rocky Mountain Institute’s Factor 10 engineering ([www.rmi.org/10xE](http://www.rmi.org/10xE)).

This paper is mainly a thought piece, to explore the conditions under which extreme efficiency might make sense. We only consider electricity end-uses (although in many of these applications electricity is generated directly on-site from liquid fuels, so saving electricity directly reduces use of fossil fuels, primarily petroleum). Our hypothesis is that niche applications where extreme efficiency is both cost-effective and necessary can provide sufficient market pull to bring ultra-efficient technologies and products into the market, for eventual application in mainstream markets. In this paper we identify research questions and begin to identify program elements to promote extreme efficiency.

## **Expensive and Scarce Power**

Applications that require extreme efficiency have many common characteristics, primarily that they tend to be situations where energy is scarce—therefore expensive—yet people expect or require “modern” energy services. These often are situations where people from wealthier, urbanized areas travel to austere areas of the developing world (generally for either military or humanitarian missions), or to remote areas of their own countries beyond the reach of the modern energy system.

### **Candidate Applications**

**Expeditionary military.** When the military conducts training or operational missions, they rely on transportable facilities that can be relocated to wherever the mission occurs, to provide functions such as command centers, sleeping quarters, medical services, food services, vehicle maintenance, and other support functions such as storage and recreation. These facilities are usually powered by many inefficient diesel generators that rely on fuel that is trucked or flown to the base. The transportation of this fuel also creates vulnerable supply lines that have frequently been attacked in Iraq and Afghanistan, causing loss of life and jeopardizing the military’s ability to carry out its mission. Reducing this energy use has become a priority for the military.<sup>1</sup>

### **Medical services.**

- *Developing world medical clinics and hospitals* that either lack electricity entirely or lack reliable electricity. The World Health Organization estimates that between 200,000 and 400,000 health clinics worldwide lack electricity or lack reliable electricity (WHO 2011).

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<sup>1</sup> General John R. Allen, USMC, recently stated “A military force that reduces its fuel consumption becomes more agile and insulates itself from logistics-related disruptions.” [http://energy.defense.gov/Memorandum\\_Supporting\\_The\\_Mission\\_with\\_Operational\\_Energy.pdf](http://energy.defense.gov/Memorandum_Supporting_The_Mission_with_Operational_Energy.pdf)

To maximize impact it is more cost effective to provide more facilities with smaller electricity systems aimed at providing the most critical services first (e.g. task lighting for surgical and medical procedures rather than ambient light; blood bank and vaccine refrigeration, not general refrigeration; and electricity for high value diagnostic equipment and emergency communications). Because of their critically high value, all of these are excellent candidates for extreme efficiency.

- *Emergency medical response* (e.g. Doctors without Borders) deliver medical care in relief situations where the power grid is often degraded or non-existent, making power from emergency generators often the only option.
- *Traveling medical delivery units* (e.g. Smile Train, cataract surgery, mobile clinics in rural parts of the U.S.) are usually self-contained due to their mobile nature, relying on periodic grid connections or portable generators.

**Disaster and other humanitarian response.** In addition to medical applications described above, lighting and communications are critical for operations such as Federal Emergency Management Agency (FEMA) response centers, Peace Corps projects, disaster relief and refugee camps, orphanages, schools, and community centers.

**Rural off-grid.** These conditions are found in remote areas of the developed world, such as Alaskan villages, and areas of the developing world (both rural and urban) where the centralized electricity grid has not been built. These areas often have some type of local generation, usually small to medium diesel generators. For applications that are close to an existing electric grid, there is a decision about whether to extend the grid or not. Extreme efficiency widens the range over which extending the grid turns out to be the less cost-effective choice. Note that there are some situations, such as in Hawaii and other islands, where a central grid exists but power prices are high because of expensive generation fuel (de Figueiredo & Snell 2000). We consider these areas to be candidates for extreme efficiency, even though they are technically grid-connected.

**Unreliable grid power.** This situation covers locations served by grid power that need to run on backup power for long periods. There are two main variants of this situation: areas of the developing world with extremely unreliable power, and critical services (hospitals, emergency services, telecommunications) in the developed world. In the former situation, backup generators tend to run for long periods of time and in extreme cases are used nearly all the time (i.e., the sites are essentially off-grid<sup>2</sup>). In the latter case, outages are very infrequent, but when they occur the sites need to be able to maintain services for extended periods of time that may extend beyond typical backup-fuel storage capabilities. Even in these intermittent cases, the backup power is usually very expensive, and can itself be unreliable (e.g. diesel generators can fail if run at low load for extended periods). In unusual situations, outages can be very lengthy, such as in Juneau, Alaska when an avalanche severed the city's main transmission line and the city was forced to rely on diesel generators for several months, with a 5-fold increase in electricity prices. In some cases diesel generators are not utilized even when they are installed because the fuel supply is intermittent, too costly, or the generator is unnecessarily large to provide the critical service needed (e.g., sized for a hospital but only needed for one night-time surgery).

**Mobile.** There are many mobile applications, such as autos, long-haul trucks, recreational vehicles, and boats, where electricity is produced either by the main engine or an auxiliary generator, resulting in very expensive power. These applications can sometimes use grid power (e.g., an RV plugged into a campsite outlet), but probably only a minority of the time.

### Typical power costs

All of the applications mentioned above experience a cost of electric power that is much higher than typical utility prices for residential and commercial customers in the U.S. (4-15¢/kWh). The most common power source in the applications described above is a small to medium-size diesel or gasoline-powered generator (capacity less than 100 kW). Even under favorable conditions in urban areas in developed countries, considering only the marginal fuel cost for generation leads to a power cost of 30-40¢/kWh.<sup>3</sup> Including the capital cost of the generator, maintenance costs, generator lifetime, and other costs can increase these levelized power costs by 50% or more. In rural areas of Alaska, the cost is 75¢/kWh or greater (Milkowski 2009). In remote areas, the higher cost to transport fuel and equipment, as well as higher installation cost, can easily double the cost of power. A recent record-setting winter in Nome, Alaska required shipping emergency fuel via frozen seas, with numerous delays (Yardley 2012).

The most extreme example of transportation costs is military operations, where fuel transportation requires complex logistics and added security costs. Including these transportation and security costs—especially in the remote areas of Afghanistan—can add \$10 or more per gallon (\$3/liter) to the “fully burdened” cost of fuel (Erwin 2010), with the resulting electrical power costing \$1 to \$3 per kWh (again assuming a generation efficiency of 10 kWh per gallon of fuel). For mobile applications such as automobiles, power costs are approximately \$1/kWh (Thomas et al. 2008). The most extreme power costs are found in mobile applications that use disposable batteries, such as a flashlight being run on typical AA alkaline batteries. Assuming a cost of

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<sup>2</sup> For instance, it is estimated that 60% of the Dominican Republic's GDP is produced by industries powered mostly or entirely by local diesel generators, due to the unreliability of grid power (Murphy 2012).

<sup>3</sup> Assuming a fuel cost of \$3-4/gallon and a generation efficiency of 10 kWh/gallon of fuel.

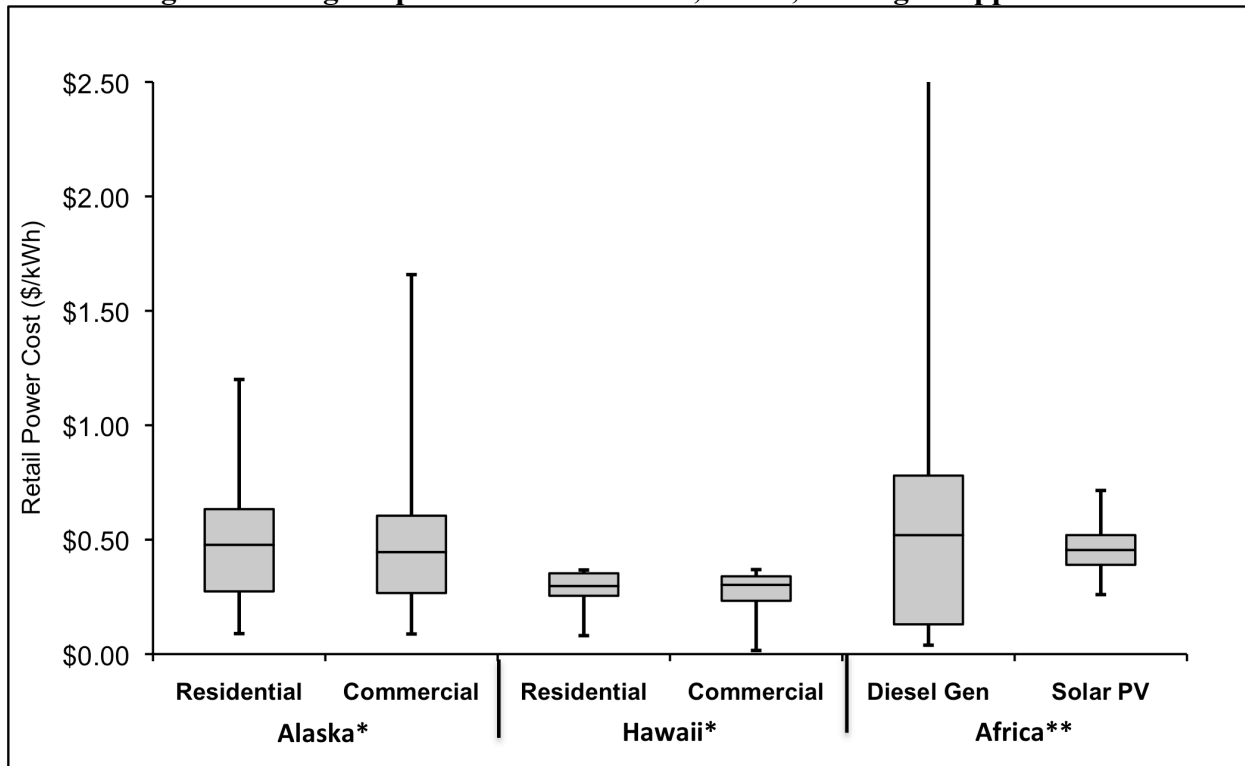
\$0.80 per battery and 2.2Ah capacity at 1.5V, the cost of electricity is \$242/kWh, which explains the rapid adoption of very high-cost LED lamps in this application long before this technology was cost-effective for general-purpose lighting. Figure 1 summarizes the range of power prices found in these situations, as of 2010.(although with the increase in petroleum prices in the last two years, these power prices, other than PV, are probably 30-40% higher now).

It is important to note, however, that diesel generators are generally most efficient at full load, and the load-efficiency curve can be strongly peaked. If the generator is operating at a small fraction of full load, the marginal power cost can be quite high and become even higher with only a small reduction in load. Under these circumstances, some efficiency measures may not be cost-effective. Ultimately, proper right-sizing of the generator is required to maintain efficient operation.

### Typical Energy Services

To analyze the energy efficiency opportunities in the applications described above, we first need to understand what energy services are required and what types of products and devices typically deliver these services. In areas with relatively more expensive and scarce electric power, the energy services are targeted more at basic human needs—such as clean water, medical care, and essential communications and lighting—while areas with more abundant power will usually have additional services—such as refrigeration, comfort conditioning, and ambient lighting. While not exhaustive, Table 1 describes the types of services that are commonly found in each application.

**Figure 1: Range of power costs in remote, island, or off-grid applications**



\*Source: U.S. EIA 2010. Data are average utility-wide prices by customer class.

\*\*Source: Szabo et al. 2011. Cost distributions are inferred from detailed power-cost maps.



**Table 1: Common Energy Services Found in Extreme-Efficiency Applications**

Energy Service		Application					
Category	Function	Military	Medical	Disaster/ Humanitarian	Off-grid	Intermittent Grid	Mobile
Water & sanitation	Pumping	X		X	X	X	
	Purification	X		X	X		
	Water heating	X	X		X	X	
	Clothes washing	X	X		X	X	
Lighting	Task	X	X	X	X	X	X
	Ambient	X	X		X	X	X
Refrigeration	Medical	X	X	X	X	X	
	Food	X			X	X	X
Comfort	Ventilation & Air movement	X	X		X	X	X
	Heating	X		X	X	X	X
	Cooling	X		X	X	X	X
Medical equipment		X	X	X	X		
Electronics	Communications	X	X	X	X	X	X
	Computing	X	X	X	X	X	X
	Entertainment	X			X		X

X= Energy service is present in a given application

### Secondary Attributes

Much of the equipment and products used in the applications described above, in addition to providing their primary energy service (e.g., lighting or refrigeration), must do so in remote and rugged conditions. Equipment used in these situations must meet demanding requirements in order to adequately deliver their energy services. These “secondary” product attributes include:

- Transportability (minimal weight and size),
- Durability (able to withstand impact, penetration, etc.),
- Portability (able to be packaged and human transported, or with minimal material handling equipment),
- Tolerant of extreme conditions (temperature, water, dust, etc.),
- Usability (e.g. ease of use, universality of connector and other component),
- Maintainability (availability of parts and repair expertise, with a minimum of required maintenance).

These secondary attributes are not the main focus of this paper, but in considering energy efficiency options it is important to recognize that these product requirements are a major factor driving the low efficiency levels that are seen in these applications, and often serve as a major barrier to improving efficiency. On the other hand, there may be situations where higher efficiency helps better serve these other requirements, such as reduced waste heat can improve the lifetime and reliability of electrical components.

## Super-Efficient Technologies

Some key technologies are potentially applicable to a broad range of end-uses and energy services. These technologies may be in early stages of development and/or deployment, but are potentially well suited to extreme efficiency applications. Some examples are provided below, and a more complete discussion is available in Desroches & Garbesi (2011).

### Technology Examples

**Pumps.** The main efficiency potential in most pumping systems is to “right-size” the system and to include variable-speed operation. Many pumping systems are designed to handle the maximum anticipated flow or head, and yet the efficiency curve of the pump is often sharply peaked. As a result, the system is typically operating away from its most efficient conditions. Variable-speed designs can substantially improve pumping efficiency in all applications with varying loads. New pump designs are already commercially available, and can reduce energy consumption by approximately 40%. Pumping efficiency can also be improved through the use of super-efficient motors, such brushless DC permanent magnet motors, which can reduce total pumping energy consumption by 75% or more in small pumping applications.

**Water Heating.** Most water heating applications globally utilize either a natural gas burner or electric resistance to heat water. Super-efficient water heaters utilize heat pumps, which can reduce energy consumption by 50% or more. The current best-on-market heat pump water heaters in the U.S. have an energy factor (EF) of 2.4-2.5, depending on size. There are many technologies available to improve the efficiency of heat pumps (see below), including the use of CO<sub>2</sub> as a refrigerant (which requires high pressurization but is non-toxic with low global warming potential). CO<sub>2</sub> heat pump water heaters are already available in Japan, and can reduce energy consumption by nearly 70% (an EF up to 3.0) compared to electric resistance water heaters.<sup>4</sup> Ground-source systems are also super-efficient, though they generally require the installation of a ground loop and may not be suitable for all applications.

**Clothes Washing.** Energy-efficient clothes washing technologies use cold (or unheated) water. Specialized low-temperature detergents can be used, in addition to ozone, to maintain washing performance similar to washing at higher temperatures. High efficiency washing machines also use less water, which saves the energy used to pump and treat that water.

**Lighting.** There are a number of promising lighting technologies that are in advanced development or just becoming commercialized. These include light-emitting diode (LED) bulbs, organic LED (OLED) lighting fixtures, ceramic metal halide lamps, and high-efficiency plasma (electrodeless) lamps. All have the potential to reduce lighting energy consumption by approximately 50% over the current efficient technologies (such as fluorescent and non-ceramic metal halide lamps), and many are expected to reach 150 to 200 lumens per watt. The recent winner of the Department of Energy’s L-Prize ([www.lightingprize.org](http://www.lightingprize.org)), an energy-efficient design contest to replace the standard 60W incandescent bulb, is a LED bulb that is now

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<sup>4</sup> General Electric and Oak Ridge National Laboratory are currently designing a residential CO<sub>2</sub> heat pump water heater for the U.S. market. See: [http://www.ornl.gov/info/press\\_releases/get\\_story\\_tip.cfm?ID=148](http://www.ornl.gov/info/press_releases/get_story_tip.cfm?ID=148)

commercialized. Another very promising technology is the use of quantum dots. Quantum dots are nearly perfect absorbers and emitters of light. The output spectrum is highly tunable (depends on the dots' physical size, easily controlled during manufacturing) and very regular. This enables the use of very efficient monochromatic light sources (e.g., blue LEDs) that can be transformed into a much more pleasing color distribution, with almost no losses.

**Refrigeration.** Refrigerators are a collection of many individual components, and as such, there are a variety of super-efficient technologies that can be used in parallel to reduce the energy consumption of refrigeration systems. These include high-surface-area heat exchangers, variable-speed compressors (e.g., linear compressors), vacuum-insulated panels, aerogels (as insulation), and DC cooling fans. Where possible, refrigerator and freezer compartments can be separated and operated with separate compressors, using optimized refrigerant temperatures for each compartment. For permanent installations (e.g., laboratories, hospitals), ground-source systems improve heat transfer efficiency. Combining many of these technologies potentially reduces energy consumption by 50% or more. Technologies that are still in research and development, but show promise, include magnetic refrigeration and thermoacoustic refrigeration. Magnetic refrigeration is already used in specialized ultra-low-temperature laboratories.

**Comfort.** This category generally includes a broad range of equipment used for ventilation, space heating, and space cooling, including a variety of super-efficient components and designs. For air conditioners and heat pumps, there are some similarities to refrigerators, since all rely on some form of the refrigeration cycle. Many of the same super-efficient technologies can be used here (e.g., high-surface-area heat exchangers, variable-speed compressors, ground-source systems). When waste heat is available as a resource, the absorption cycle provides efficiency gains, as does the adsorption cycle (without needing toxic chemicals). Adsorption (as opposed to absorption) relies on desiccant materials to complete a refrigeration cycle. Adsorption chillers are commercially available today. Oil-free, magnetic-bearing, variable-speed chillers with a centrifugal compressor are efficient vapor compression systems. In arid or semi-dry locations, evaporative cooling very energy efficient, but may require more water than is available. Variations on evaporative cooling include direct, indirect, indirect-direct, and evaporative pre-cooling (before using a traditional air conditioner). For dehumidification applications, desiccant wheels, liquid desiccants, and multiple small-plate dehumidifiers are all energy-efficient technologies. Finally, with respect to air handling, DC motors and airfoil fan blade design can significantly reduce energy consumption. Considering all of these possible technologies, energy consumption reductions of 50% or more are easily achievable with ventilation, space heating, and space cooling equipment.

**Electronics.** Electronics are rapidly evolving, and because of mobile consumer applications, there is already a strong incentive for efficiency in order to maximize battery life. Nevertheless, significant efficiency gains are still possible. For display applications (e.g., monitors), OLED screens will not only be more efficient, but thinner, lighter, and flexible in the near future. Quantum dots can also be used to improve the efficiency of displays. Solid-state drives are already available on some devices, and significantly reduce the energy consumption of data storage and access. Power management at the chip level (including clock gating) reduces energy consumption when the system is in idle, not actively processing any commands. Network

protocols such as proxying or energy-efficient Ethernet ([www.ieee802.org/3/az/index.html](http://www.ieee802.org/3/az/index.html)) allow computer systems to remain “live” on a network, with full presence, while allowing the network port and/or computer itself to sleep when not being used. The consolidation of functions onto a single chip improves waste heat management and allows for smaller form factors. These, and many other technologies, are rapidly advancing into the market.

**Load Management and Controls.** One general theme applicable to most of the above end uses is the ability of systems to respond in real-time to changes in demand. Inherently “variable-speed” systems can adjust output based on need, nearly always resulting in lower overall energy use over a typical duty cycle. This is especially true if the device or equipment remains on and fully powered when not in use. The load management can occur at a mechanical level with continuous response (e.g., DC motors, linear compressors) or at an electronic level with discrete states (e.g., sleep modes for electronics). All these cases require well functioning sensors and control mechanisms to take full advantage of the energy-reducing potential. As an example, occupancy sensors can be connected to lighting systems and electronic displays to shut them down when not needed and when no one is present. Energy reductions of 50% or more are possible in many instances.

**Integrated Design.** In some applications, combining several end uses together into an integrated system can reduce overall energy consumption. The output of one system can be used as the input to another. Space cooling and water heating are natural integrated system. Other technologies perform best with waste heat (e.g., adsorption cooling).

### **Technology Costs**

Many of the technologies outlined above are relatively new, and either in the early stages of commercialization (with small market shares) or are in late stages of development. As a result, it is difficult to assign specific costs to any one technology, especially since the true cost is likely to substantially change during initial market adoption. Nevertheless, some estimates of the cost of high-efficiency appliances do currently exist. The U.S. Department of Energy analyzes the life-cycle cost (initial purchase price plus operating expenses) of various efficiency levels as part of its Appliance and Commercial Equipment Standards program.<sup>5</sup> Furthermore, McNeil & Bojda (2012) summarize the cost of conserved energy for a variety of high-efficiency residential appliances. While the technologies considered in these analyses are not “extreme” as envisioned in this paper, the results are nonetheless informative.

In Table 2 we summarize the costs of conserved energy from McNeil & Bojda (2012). The costs are generally lower than even some average state utility rates, let alone the extreme energy costs described above. These high-efficiency appliances would certainly be cost-effective in those applications. Extreme-efficiency appliances and equipment, in contrast, are likely to have a cost of conserved energy that is significantly higher, though there is plenty of margin before those costs reach parity with extreme energy costs.

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<sup>5</sup> [http://www1.eere.energy.gov/buildings/appliance\\_standards/](http://www1.eere.energy.gov/buildings/appliance_standards/).

**Table 2: Cost of Conserved Energy for High-Efficiency Residential Appliances**

Appliance	Reduction in Energy Use from Baseline Products	Cost of Conserved Energy (\$2010/kWh)
Refrigerators	35%	\$0.15
Room AC	18%	\$0.09
Central AC & Heat Pumps	24%	\$0.11
Electric Water Heaters	53%	\$0.08

Note: Values are averaged over major product classes for each appliance and represent the highest efficiency level analyzed by DOE for appliance standards. Water heaters include heat pumps. Source: McNeil & Bojda (2012).

### Real-World Example

As an example of the technologies and applications described above, consider the LED lamps used with WE CARE Solar’s “Solar Suitcase.”<sup>6</sup> The PV-powered Solar Suitcase is designed to be very rugged for portability to remote regions and for use in extreme environments inside medical facilities. The need for ruggedness and portability imposes strict system size limits (particularly if packaged with PV panels), and results in a very high cost of power (~\$30/W).<sup>7</sup> To be able to power both lighting and other critical medical loads (communications and medical equipment) each device must be very high efficiency. These facts together justified the use of custom-designed LED lamps (the most critical load) that cost approximately \$70/lamp, with an efficiency of about 70 lumens per watt. By comparison, basic LED bulbs generally have efficiencies no greater than 60 lumens/W and can cost as little as \$20. Assuming an output of approximately 850 lumens (roughly equivalent to a standard 60 W incandescent light bulb), the custom-designed lamp draws 12 Watts whereas the standard LED bulb draws 14 Watts. The \$50 cost difference is therefore justified by the 2 Watts of power savings when power costs \$30/W (and is easily justified based on improved battery life). These systems are currently used in off-grid and grid-intermittent medical facilities to provide power for maternal health applications (labor, delivery, and surgery) in the developing world. The systems have also been deployed for disaster relief in Haiti. Similar power systems have been developed for military applications for which extreme efficiency would be equally attractive, and high cost even less of a barrier.

### Research and Program Agenda

Realizing the potential of ultra-efficient technologies will require a combination of new technology developments, product designs, and programs to encourage market adoption. We discuss here some initial ideas that the efficiency community might pursue to make extreme efficiency more achievable.

#### Market Research

A basic question that needs to be answered is whether the premise of this paper—that several different applications that would benefit from extreme efficiency—can indeed be addressed as a

<sup>6</sup> [http:// www.wecaresolar.org](http://www.wecaresolar.org).

<sup>7</sup> Compare this to an installed cost of \$6/W for net-metered photovoltaics (Barbose et al., 2011).

unified market and thereby achieve some level of market transformation. A first step in this is to identify characteristics that are common to all extreme efficiency applications, such as zero standby energy use (i.e., “hard off” controls), the ability to load shift, easily usable controls, etc. To do this, we need to better understand what energy services are needed in each application, how products are typically used, etc. It is also important to know where split incentives exist, or other types of market barriers that make it harder to realize the benefits of ultra-efficient products. Another issue is how to make products that are broadly applicable across many applications, so as to achieve the greatest market scale possible. An aspect of this research would involve better understanding the trade off purchasers make between capital costs, energy operating costs, and other product attributes such as weight or size. This will help inform where to put design emphasis. Similarly, it is important to know how components or products designed for extreme applications make the jump to traditional, grid-connected applications. A possible first step in conducting market research in this area is to conduct an extreme efficiency workshop, which would gather people from many of the applications listed above to identify where there are common product requirements that can be bundled together into a larger “unified” market. Eventually there should be a detailed mapping of technologies to applications (i.e., a much more detailed version of Table 1) to inform technology and market development efforts in this area. This analysis should also develop some scenarios that assess avoided power costs in specific applications, identify the technologies currently in use, and assess the economic viability of available higher efficiency technologies for those applications.

### **Enabling-Technology Research**

Fundamentally, ultra-efficient systems require highly efficient components. Today’s component technologies need to be further refined, particularly for components that are used in a wide variety of products, such as electric motors, refrigeration compressors, pumps, heat exchangers, and lighting. These components then need to be integrated properly into ultra-efficient systems. This integration challenge could possibly be overcome with the help of design tools for ultra-efficient systems (e.g., decision support tool to help trade off a product’s secondary attributes). Developing methods for context-appropriate design can also help with tailoring a product’s energy services to the context in which it is meant to be used (e.g., in the developing world context a product’s design may not need to be quite as comprehensive or delivered with the same level of reliability). Another area of research is in designing integrated products (like “smart appliances”) that present as attractive a load as possible to the grid, through load-limiting, demand response capability, energy storage, and power-factor correction. In fact, within the energy system it is possible that extreme efficiency applied to locations with on-site generation may lead to excess power supply at certain times. This will lead to a question about what to do with the excess power. In locations that already have excess generation capacity, it is possible that efficiency improvements translate into little or no reduced fuel consumption (reduced load may just shift the generator to a lower-load, less-efficient point on the generator efficiency curve). In this situation, proper design and sizing of the overall power system (generators *and* loads) is important to realizing the savings from ultra-efficient products. Finally, standard user and network interfaces are needed to allow efficient operation.

## Conclusion

There are a variety of situations today – remote or off-grid towns, islands, and military outposts – where power costs three to four (or even ten) times the cost of average grid power in the U.S. These places have many common energy end-uses, which would suggest that a new class of extremely efficient energy-using equipment and buildings could be developed to cost-effectively reduce the consumption of this expensive power. Based on a review of previous work looking at maximum-available technologies, we find there are many technical options available that go well beyond today’s best available products. Furthermore, it appears that today’s best available products for residential appliances save electricity at a levelized cost well below the power prices currently paid in these extreme applications. These findings suggest that there may be a potential market to be developed in extreme-efficiency products, and further attention is justified to learn more about the energy needs in these applications, as well as the market and technology development needed to realize this opportunity.

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