

**:: EXCERPT (January, 2011) ::**

**Carrying the Fire**

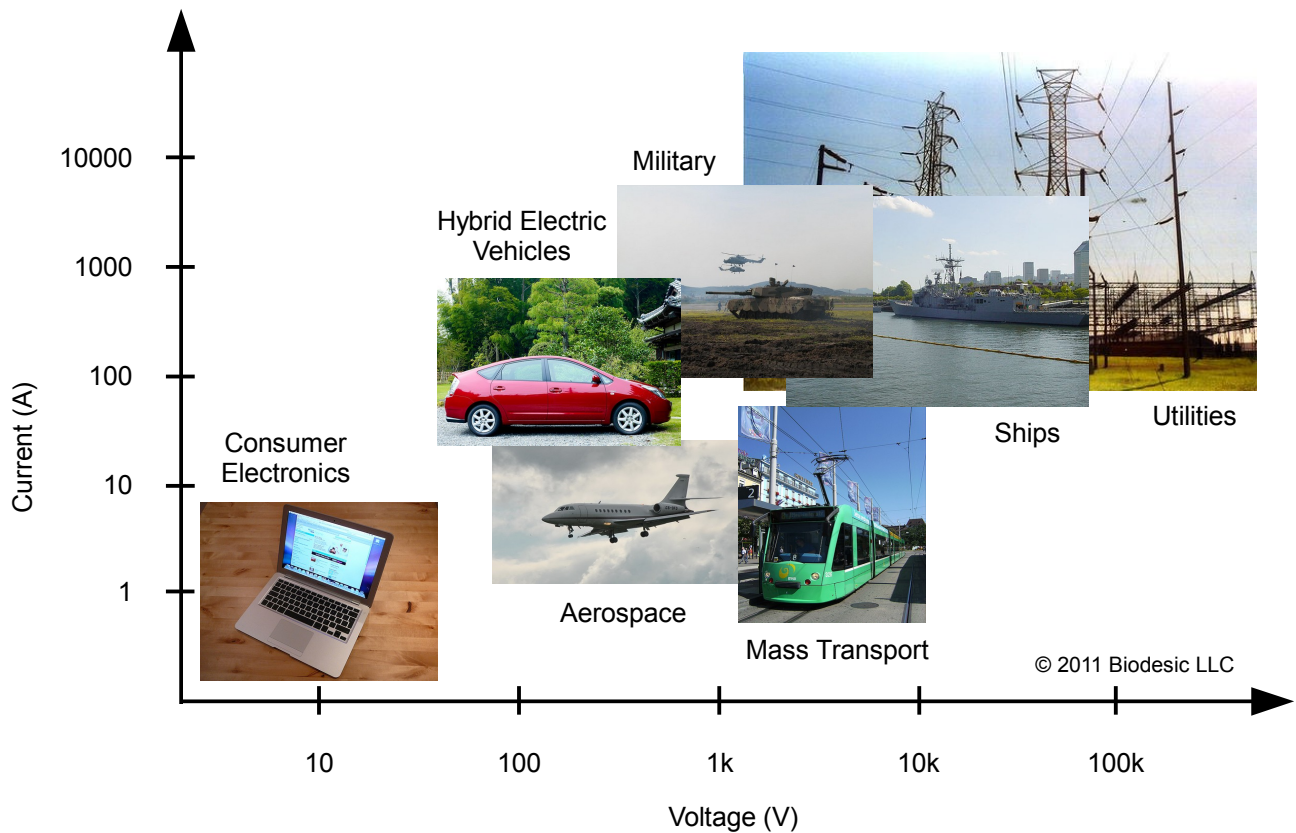
High Density Energy Storage Technologies For Grid, Transportation, and Mobile Power Applications.

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*Domains of Power Demand*

**Synopsis**

Power generation is often not matched to power demand. As generation and consumption both increase, the magnitude of mismatches increases, as does the need to provide temporary storage solutions. This document is a brief introduction to the technical, economic, and regulatory aspects of high density energy storage (HDES). This short excerpt necessarily cannot include technical analyses for particular power storage options.

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## About the Authors:

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Rob is a Principal at Biodesic, LLC, an engineering, design, and consulting firm in Seattle, WA. At the broadest level, Rob is interested in the future role of biology as a human technology. He has worked to develop new biological technologies in both academic and commercial environments, focusing on molecular measurement and microfluidic systems. Dr. Carlson earned a doctorate in Physics from Princeton University in 1997.

### Rik Wehbring



Rik is a Principal at Biodesic, LLC. Rik has a broad technical and entrepreneurial background developed at several start-ups and his own consulting firm. His technical expertise includes all aspects of modern electronic hardware development including high-speed PCB design, ASIC & FPGA design, HDL coding and synthesis methodologies, and design-for-manufacturing and -test. He has worked for startups, founded two companies, and most recently ran his own engineering consulting firm. Rik earned a BA Physics with Distinction and an MEng in Electrical Engineering, both from Cornell University.

## Introduction

Power generation and demand are distributed unevenly in both time and space. Overall power demand may at times exceed overall power production. Large scale production is often located at a distance from population centers, and—in the case of hydro, geothermal, and wind power—may be geographically or geologically constrained. Wind power, the fastest growing source in the U.S., Europe, and China<sup>1</sup>, may peak at times different than that of power consumption. The demand for power sources is increasing rapidly around the world to serve needs ranging across utilities, transportation, communication, and computation. Consequently, energy storage technologies will see increasing global demand to shift power to where, and when, it is needed.

Various power markets—existing or emerging, mobile versus stationary—have very different requirements with respect to discharge power, discharge time, energy density, and power density. Mobile applications, such as laptops and cellphones, are sensitive to overall weight, but typically do not require more than a few tens of watts. Weight is immaterial when balancing loads across a grid, but 500 MW or more of power is required. The diversity of applications makes straightforward comparisons of applications difficult. A logarithmic plot such as Figure 1 captures the wide range of power applications as a function of their power storage and time requirements. The figure is further divided into Quadrants to facilitate the matching of applications with appropriate power storage technologies, as described in the next section.

High density energy storage (HDES) is not just a technical requirement to provide a buffer between supply and demand; there are serious economic drivers. For example, a one-time wind power generation fluctuation in Texas in February of 2008 reduced capacity by 1,200 MW in ten minutes; only widespread load shedding by industrial customers avoided crashing the North American power grid.<sup>2</sup> What is the cost of taking America off-line for one day? Similarly, a 2004 study from Lawrence Berkeley Lab estimated U.S. losses from power outages and blackouts at \$80 billion annually.<sup>3</sup> Significant market opportunities exist to reduce these costs.

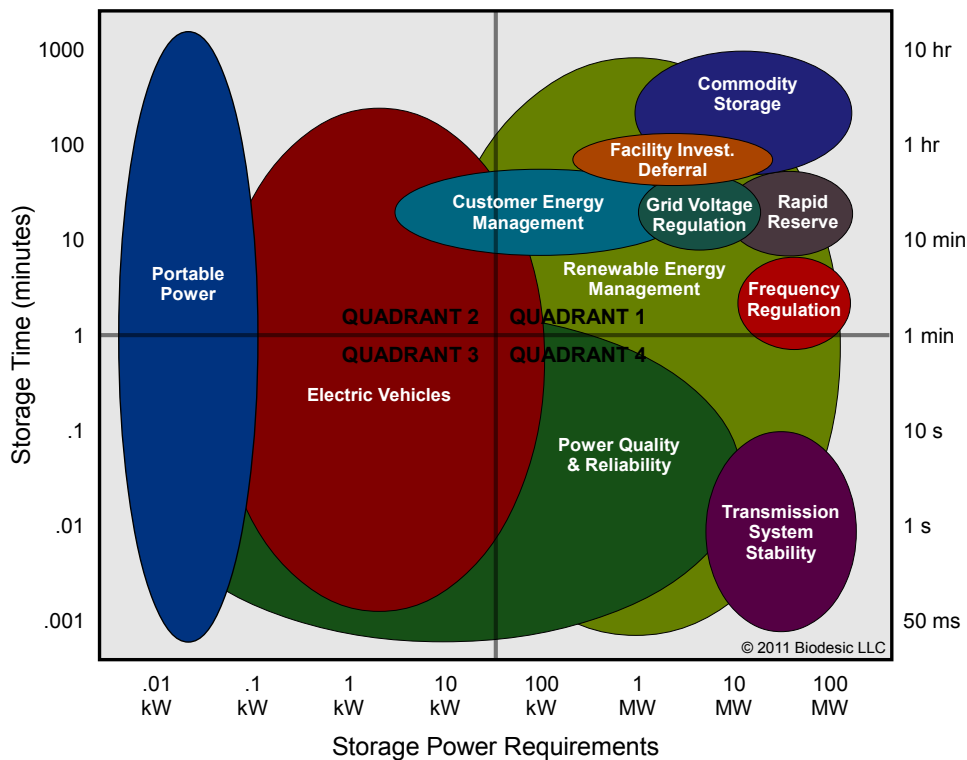


Figure 1: Selected demand-side drivers for HDES

1 "US and China in race to the top of global wind industry", Global Wind Energy Council, February 2, 2009.  
 2 "Energy Storage Applications for the Electric Grid", Imre Gyuk, Presentation at GE, October 23, 2008.  
 3 "Understanding the Cost of Power Interruptions to U.S. Electricity Consumers", Kristina Hamachi LaCommare and Joseph H. Eto, Energy Analysis Department, Ernest Orlando Lawrence Berkeley National Laboratory, September 2004, <http://certs.lbl.gov/pdf/55718.pdf>

## What is High Density Energy Storage (HDES)?

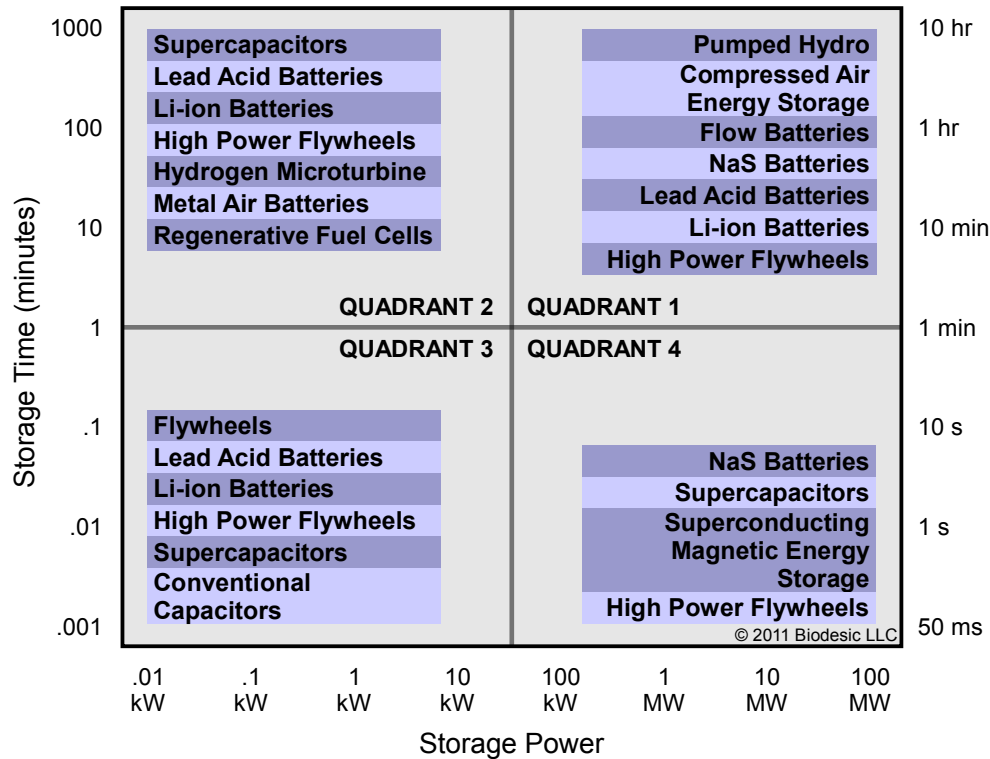


Figure 2: Available HDES technologies mapped by demand Quadrant.

Given the diverse nature of power demand it is not useful to adopt a single definition for HDES, nor a single figure of merit to describe the “best” technology. Consequently, hereafter we match storage technologies to demand across various requirements—principally storage power and storage time. Storage technologies suitable for use in the following applications are summarized in Figure 2, organized according to Quadrant.

### Application Segments

**Bulk energy storage on the grid** will require the capability to discharge between 10 and 1,000 MW for 1–10 hours, which will in turn require a storage capacity of between 10 and 10,000 MWh. Example applications are load leveling, power arbitrage, spinning reserve, and power banking, with matching storage technologies found in Quadrant 1 of Figure 2.

**Distributed generation on the grid** will require the capability to discharge between 100 and 2,000 kW for 0.5–4 hours, which will require a storage capacity of 50–8,000 kWh. Applications include peak shaving and transmission deferral, with matching storage technologies found in Quadrants 1 and 4.

**Power quality management on the grid** will require the capability to discharge between 0.01 and 10 MW for 1–30 seconds, which will require storage capacity of up to 85 kWh. Example applications include managing end-use power quality and ensuring reliability, with matching storage technologies found in Quadrants 3 and 4.

**Distributed storage on the grid** will require the capability to discharge between 0.1 and 100 kW for 1–12 hours, which will require a storage capacity of between 0.1 and 1,200 kWh. Example applications include uninterruptible power supplies (UPS) and residential power storage, with matching storage technologies found in Quadrants 1 and 2.

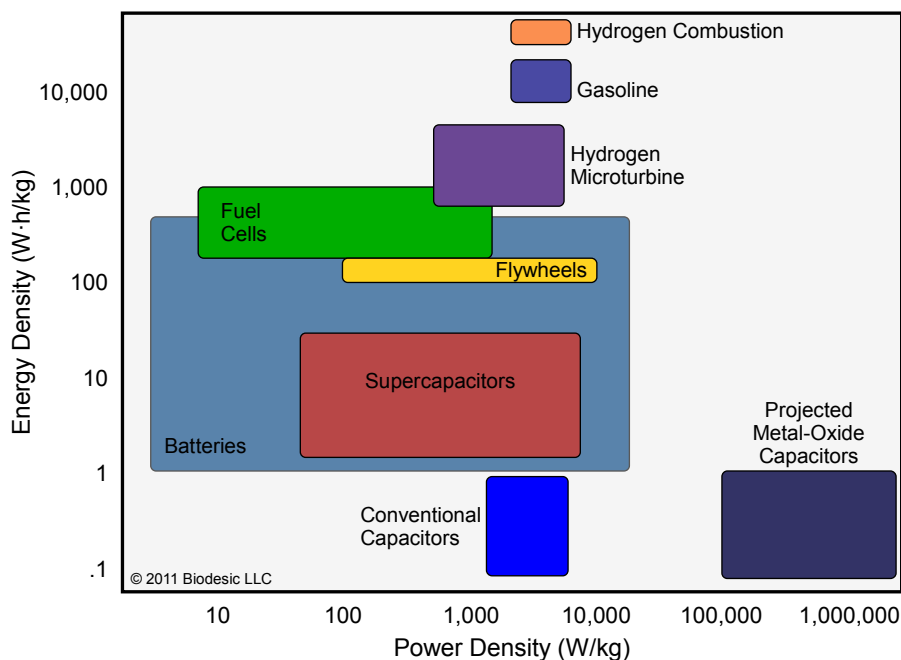
**Power storage for transportation** will require a discharge capability of 0.1 to 100 kW for 0.1–12 hours, which will require a storage capacity of 0.01–1,200 kWh. Applications include replacing starter batteries with capacitors, providing accessory power, and main drivetrain power supply.

**Portable power applications** will typically require from a few milliwatts up to 100 W for between a few minutes and 10 hours, which will require a storage capacity between 0.001 and 1 kWh. Applications include communications, computation, and entertainment. Storage technologies useful for transportation and portable power applications are in Quadrants 2 and 3.

## Technology Evaluation Overview

High density energy storage may be accomplished through a variety of means. Relevant technologies store energy in five forms: gravitational, electromagnetic, chemical, and potential and kinetic mechanical energy. These different forms of storage are implemented using technologies that range in size from nanometers to kilometers, and that employ widely different physical principles and materials. The diversity of characteristics is a challenge to comparing technologies.

For example, it is straightforward to compute the energy and power density of a battery or capacitor—these are objects with finite size and mass. It is more difficult to assign an energy density to pumped hydroelectric or underground compressed air energy storage (CAES) because they include “tanks” composed largely of geologic features which contain variable masses of water and air. Furthermore, the power generating capacity of both hydroelectric and compressed air facilities can depend on the total mass stored, which changes as water or air is released. In applications where the actual mass of the storage medium is important, such as portable power and transportation, technologies suitable for HDES are often compared using a Ragone chart (Figure 3), on which the axes are energy density and power density.



The Ragone chart may be viewed as a *map of energy supply*; the vertical axis describes how much energy is available, while the horizontal axis describes how quickly it can be delivered.

Figure 3: Ragone Chart

A wide variety of technologies implies a broad range of costs. The spread in HDES costs is related both to physical scale and to the fact that many technologies suitable for storage are at different stages of development. Using excess power to pump water into reservoirs is an old, but very large scale and capital intensive, technology; in contrast, commercial regenerative fuel cells can be built at many scales and price points but are a relatively young storage technology. The various forms of supercapacitors, flow batteries, and regenerative fuel cells may be expected to become less expensive and more capable in the coming

decade, whereas, in all likelihood, pumped storage has already reached its maximum technical and economic efficiency.

## Regulatory Influences

Beyond market demand and technical feasibility, policy makers will have a major impact on the pace of power storage capitalization and roll out. In 2010, the California Air Resources Board increased the Renewables Portfolio Standard (RPS) requirement for the percentage of the state's power derived from renewable sources by 2020 from 20% to 33%<sup>4</sup>. The RPS will likely be met by a combination of wind, photovoltaic, and solar thermal generation. However, as these sources are not only intermittent but also produce power over a range from hundreds of watts to hundreds of megawatts, the consequent supply requires a variety of storage solutions. Therefore, the RPS implies a mandate for heavy investment in power storage if new sources of renewable power are to be utilized effectively. The implied mandate is not reflected in budget estimates, which represents both a risk of cost overruns for renewable power projects and a market opportunity for storage providers.

In concert with the RPS, the reductions in greenhouse gas emission required by the California Global Warming Solutions Act<sup>5</sup> are likely to further drive investment in storage so that existing fossil-fueled generation can be retired. In 2007, the CEO of the California Independent System Operator (ISO) reported the feasibility of "maintaining reliable electric service with the expected level of intermittent renewable resources associated with the current 20 percent RPS, *provided* that existing generation remains available to provide back-up generation and essential reliability services."<sup>6</sup> In other words, integrating adequate renewable power generation to meet even the 20% RPS requires the continued availability of fossil-fueled power generation, which is in conflict with the mandated greenhouse gas reductions. Therefore, increasing the RPS requirement to 33% will create an even larger demand for HDES technologies to accommodate both increased renewable production *and reduced back-up and reliability services previously provided by fossil-fueled generators that are retired to decrease emissions*.

### Policy considerations that affect markets for HDES

***So-called "Congressional risk" could continue to affect investment:*** The cycle of expiration and renewal of investment and production tax credits has historically had a dramatic impact on the planning and roll out of renewable energy production. If generating facility construction is in doubt, this will affect the demand for energy storage. Over the long term, the cost of renewable production may fall so far as to lessen the impact of this risk.

***Renewable Portfolio Standards should increase the demand for storage:*** State and national standards for the production of power from sources that are intermittent will increase the demand for storage applications such as power quality and system stability.

***The establishment of carbon markets will boost the demand for storage:*** The establishment of a price on carbon emissions will alter the price of power in favor of renewables and will create a market for storage to replace fossil-fuel generation used for regulation and stability.

***Prioritization of infrastructure in stimulus spending:*** Economic stimulus actions that favor energy projects to create manufacturing and construction jobs would be expected to benefit both renewable production and storage.

***Federally mandated shifts to high voltage DC (HVDC) transmission will recover power that can be stored:*** Efficiency gains from the installation of DC transmission can be "banked" using storage facilities. Higher efficiency HVDC transmission will also increase the "round-trip" efficiency of large-scale grid-tied storage such as pumped hydro and CAES.

*(continued on next page)*

4 "Calif. Raises Renewable Portfolio Standard to 33%", Colin Sullivan, *The New York Times*, 24 September, 2010, <http://www.nytimes.com/gwire/2010/09/24/24greenwire-calif-raises-renewable-portfolio-standard-to-3-24989.html>

5 Assembly Bill 32: Global Warming Solutions Act, <http://www.arb.ca.gov/cc/ab32/ab32.htm>

6 "Integration of Renewable Resources", California Independent System Operator, Letter from the CEO, 2007.

**State and federal policies favoring electric transportation will increase demand for storage:** The widespread adoption of electric or hybrid-electric vehicles—spurred by tax rebates—would substantially alter the market for HDES. Greater use of electric vehicles would be expected to increase the need for smaller storage installations used for rapid charging. Grid-connected hybrid vehicles could themselves also serve as smaller, distributed power generation and storage capacity. The market for batteries and supercapacitors would be expected to grow substantially.

**Regulatory recognition of storage as a market component will enable a “power banking” niche:** Federal and state recognition of storage as a sector will differentiate storage providers based on application segment and quality and will facilitate the creation and use of instruments for energy trading that are analogous to the instruments used in financial services.

**Regulatory recognition of graded values of storage depending on speed of response will segment the storage market:** Because the value of storage depends on speed of response and capacity, updating regulations to acknowledge this difference should enable higher margin businesses via market segmentation.