ENERGY STORAGE COMPENDIUM

Batteries for Electric and Hybrid Heavy Duty Vehicles

CALSTART

MARCH 2010

Notice

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Energy Storage Compendium: Batteries for Electric and Hybrid Heavy Duty Vehicles

March 2010

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Prepared for:
U.S. Department of Transportation

Abstract

The need for energy storage solutions and technologies is growing in support of the electrification in transportation and interest in hybrid-electric and all electric heavy-duty vehicles in transit and the commercial vehicles. The main purpose of this document is to provide an overview of advanced battery energy storage technologies available currently or in development for heavy-duty, bus and truck, applications. The same set of parameters, such as energy density, power density, lifecycle and weight were used in review of the specific battery technology solution. The important performance requirements for energy storage solutions from the vehicle perspective were reviewed and the basic advantages of different cell chemistries for vehicle batteries were summarized. A list of current battery technologies available for automotive applications is provided. The compendium is intended to provide a snapshot of where the technology is currently, and a review of the current or prospective suppliers of heavy-duty vehicle batteries.

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Abbreviations and Acronyms

Ah – Ampere hours
°C – Degreed Celsius
DOE - Department of Energy
EDSP – Electric Drive Strategic Plan
EPA – Environmental Protection Agency
FTA – Federal Transit Administration
KW – Kilowatt (10^3 watt)
KWh – Kilowatt hours
Li –Lithium
Li-ion – Lithium ion
LFP – Lithium Iron Phosphate
LMO – Lithium Manganese Spinel
LTO – Lithium Titanate
MW – Megawatt (10^6 watt)
MWh – Megawatt hours (10^6 watt hours)
NCA – Nickel Cobalt Aluminum
NiMH – Nickel-metal hydride
V- Volt
VDC – Volt Direct Current
Wh – Watt hour
USABC – United States Automotive Battery Consortium

Acknowledgments

This compendium relied on the assistance and information sharing of many individuals. In collecting this information we benefited from conversations with battery manufacturers and hybrid system suppliers and we are grateful for all their input.

1. Introduction

The transit industry continues to move towards a greater degree of electrification as petroleum prices increase the drive for greater vehicle efficiencies and communities continue to look for better ways to reduce harmful criteria and greenhouse gas emissions. Electric drive technologies offer a pathway to reducing the energy consumption of transit operations and to significantly reduce vehicle emissions and transit offers an ideal platform for the validation and early adoption of advanced vehicle electric drive technologies. The commercial sector is also experiencing an increase in hybrid and all-electric trucks. To support the development and penetration of electric-drive technologies buses and heavy duty trucks will rely greatly on incorporation of advanced energy storage solutions into the new drive-lines.

2. Federal Transit Administration – Electric Drive Strategic Plan (EDSP) Goals and Vision

This energy storage compendium was motivated by the Electric Drive Strategic Plan (EDSP) of the Federal Transit Administration (FTA, 2008). The main purpose of the EDSP was to provide planning and guidance for research in electric-drive technologies -- a 20-year visions and 5-year plan for the related research and development activities. The following is a brief summary of the visions, goals and specific measures identified in the EDSP.

The transit electric drive research vision:
Commercial availability of zero and near-zero emissions, high-efficiency, affordable transit vehicles to transit agencies across the country by 2030 from domestic suppliers

The 2030 transit electric drive research goal is:
To advance electric drive and related technologies to enable commercially-viable transit vehicles with significantly higher efficiency, lower emission and superior performance.

Specific measures have been identified to include:

1) Tripling the fuel efficiency of 40-foot transit bus and rail transit systems
    - Achieve fuel economy greater than 12 miles per diesel equivalent gallon
2) Decrease transit vehicle tailpipe emissions
    - 50% improvement over 2010 EPA requirements for heavy-duty diesel engines
3) Achieve superior performance of new transit vehicles

- 10% increase in miles between road calls and 25% reduction of interior noise

3. Scope of the Energy Storage Compendium

The goal of the compendium is to provide FTA and transit agencies an objective source of the most recent information available for energy storage systems for electric and hybrid-electric buses and heavy-duty vehicles. The compendium focuses on batteries as the primary energy storage technologies and includes a survey of current battery technologies specifically designed for bus and heavy-duty vehicle applications. The main focus is on advanced batteries, mostly nickel-metal hydride (NiMH) and lithium-ion (Li-ion).

This compendium provides an overview of the battery companies with products for the transportation sector and especially those that have products specifically for heavy-duty vehicles. We attempted to collect information directly from the companies themselves whenever possible. While the list of companies included covers most of the battery companies, we are aware that the list may not be all-inclusive due to the fact that it is a very rapidly changing industry.

4. Energy Storage Needs of Buses and Heavy-duty Trucks

The main purpose of energy storage in electric and hybrid vehicles is to provide electricity to the electric motor for motive power and to capture regenerative breaking energy. The first generations of hybrid-electric buses employed lead-acid batteries followed by nickel-metal hydride (NiMH) batteries. More recently the shift has been to using lithium-ion (Li-ion) batteries which offer increased energy density, thus providing same energy storage at equal or lower weight, and longer cycle life.

In order to asses the needs and requirements from the vehicle side, we interviewed several bus and truck hybrid driveline manufacturers to collect information regarding the important parameters for electric energy storage. The following is a list of the main battery parameters identified as important for electric and hybrid-electric buses and medium and heavy-duty trucks and based on the input from the driveline manufacturers.

> ***Continuous power capability*** – is defined in kilowatts (KW) and is the ability of the battery to provide continuous power output. Higher continuous battery power rating is preferred. Continuous power is defined by the current flow and voltage rating of the battery and is largely limited by the heat effects that occur during current flow.

Peak power capability – in units of kilowatts (KW) is defined for a short duration, on the order of 10 seconds or so, and is defined by the system specifications on the battery pack level. Different peak power requirements are often defined for charging and discharging. Peak power needs for a battery are determined by the hybrid or electric-drive system specifications of the electric traction motor and inverter electronics driving the motor.

Battery life – is defined in terms of years but in reality depends on the specific duty or driving cycle of the vehicle. A more precise measure is the total energy throughput in megawatt hours (MWh) that a battery system or pack is capable of. Current expectations on lifetime for batteries in heavy-duty vehicles are 6 years. However, for future generation batteries the expectation is that they would last the lifetime of the vehicle. A defining factor in determining battery life is the particular cell chemistry used in the battery pack. In practical terms battery life, or lifecycle, will depend greatly on the specific vehicle driving or duty cycle.

Energy capacity – defined in kilowatt hours (KWh) depends on the specific application. Generally speaking, the total energy capacity of a battery pack for hybrid buses and heavy-duty trucks can range from 2 KWh to 10 KWh. For battery all-electric vehicles a much higher energy capacity, on the order of 80 KWh and higher, is needed.

Thermal requirements – wide range of performance in cold and hot climates is desirable. Ambient operating temperature requirements in the cold regions can go as low as -40°C (-40 °F) and in hot operating requirements up around 50°C (122 °F) for many heavy-duty applications. Batteries are expected to perform equally well in cold and hot environments.

Weight – is an important parameter for buses and heavy-duty trucks. Payload capacity for all heavy-duty vehicles is of high importance because the additional weight of the battery system and associated components can result in a decreased payload or passenger capacity. Therefore, the goal is to decrease the weight of the on-board battery system. Decreased total weight has been one of the principal advantages of advanced batteries, in particular Lithium-ion batteries.

Cost – lower cost for advanced batteries is another very important parameter. In fact, high cost of lithium-ion batteries is one of the main disadvantages of advanced batteries. Cost is usually given units of $ per KWh. According to Department of Energy (DOE) the current cost of advanced transportation batteries is around $1,000per KWh which is about three to five times too high. Expectations are that this number will drop to $500 per KWh by 2015. This approaches the long term goal of US Automotive Battery Consortium (USABC) of $300 per KWh at the consumer level and $150 per KWh at the OEM level.

5. Battery Pack – Module - Cell

Battery packs for vehicles in general consist of a combination of battery modules. Battery modules in turn consist of a number of individual cells. Generally speaking, each module contains from 6-12 cells packaged together either in series or parallel. A battery cell is the smallest unit and each cell generally speaking, ranges from one to six volts. In case of lithium-ion batteries, each module also contains a control or safety circuit to monitor any damage during charging and discharging. A battery pack is sized specifically for the design and requirements of the vehicle.

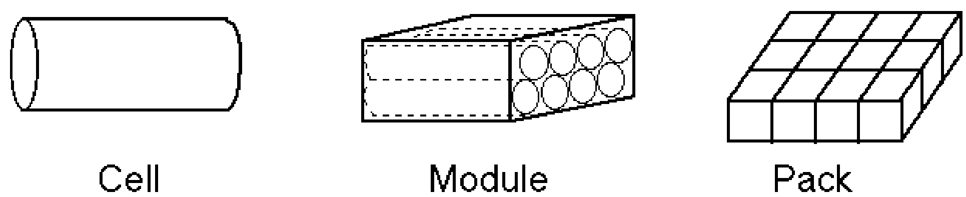


Figure 1: Cell, modules, and packs (Source: Gaines and Couenca, 2000)

Most common cell designs are cylindrical, prismatic, and pouch cells discussed below in more detail.

Cylindrical cells – are most common with the 18650 being widely known in household use. The number refers to the dimensions; 18 is the diameter and 650 the length in millimeters. Cylindrical cells offer high energy density and mechanical stability but do not use space very efficiently when packaged in modules. The cylindrical cell is used for all different cell chemistries.

Figure 2: Cylindrical cell

Prismatic cells – offer thinner geometry as main advantage. They are most commonly used in mobile phones and similar portable electronics. Prismatic cells are common for lithium-ion chemistries in particular the polymer battery is comes exclusively in this design. Packaging of prismatic cells is easier but manufacturing may be more expensive.

Figure 3: Prismatic cell

Pouch cells - avoid the use of metal casing but instead use a foil to house the battery elements which allows greater design flexibility. They may swell during charging and discharging and have lower mechanical stability.

Figure 4: Pouch cell

Relevant Parameters for Battery Modules and Packs

The characteristics for batteries used for transportation applications can include a long list of parameters depending on the battery type and final application. The choice of the most important characteristics for battery modules and packs applicable to heavy-duty vehicles was made based on the usual characteristics of automotive batteries and the needs and requirements of heavy-duty vehicles. Table 1 contains the list of characteristics we chose in the current review for battery modules and packs of the different battery technologies.

Table 1: Relevant Parameter for Battery Modules and Packs for Heavy-duty Vehicles

Property	Units
Battery Module	
Weight	Kg or lbs
Power Density	W/kg
Energy Density	Wh/kg
Voltage	V
Lifecycle	No. cycles
Temperature range	°C or °F
Charge rate (C-rate)	C/1, C/2, etc.
Battery Pack	
Peak Power	KW
Weight	Kg or lbs
Capacity	Ah
Voltage	V
Design life	No. of cycles

Most of the parameters listed are self-explanatory or were described and defined in an earlier section. The *C-rate* stands for charge or discharge rate equal to the capacity of the battery in one hour (1C rate or C/1) or two hours (2C or C/2). The C-rate is different for batteries with different capacities. Most manufacturers list different charge and discharge rates or maximum pulse rates for a shorter period of time.

6. Basics of Battery Chemistry

The characteristics of the final pack will depend on the characteristics and design of the battery cell units and on the battery chemistry. In fact, the manufacturers will often refer to the specific cell chemistry when describing the battery technology. To help with the different cell chemistry terminology, we provide a brief description of nickel-metal hydride batteries and an overview of the main lithium-ion cell chemistries in the section below.

Nickel Metal Hydride (NiMH)

The Nickel Metal Hydride batteries use an alloy as the anode (-), a nickel oxide as the cathode (+) and an alkaline electrolyte. The cell voltage in NiMH batteries is relatively low, 1.2 V. Main advantages of NiMH batteries is the potential for long cycle life and calendar life. They are safe and have good track record in terms of reliability and safety in electronics applications as well as automotive. A main drawback is their low energy density derived from the low cell voltage. The large amount of cells required in heavy-duty vehicle applications brings up issues of high weight of the total NiMH battery system which is a drawback for these types of batteries.

Lithium-ion Battery Types and Chemistries

A lithium-ion battery is not a single chemistry type like NiMH. However, all lithium-ion batteries work on the principal of exchange of the lithium ions between the two electrodes, cathode (+) and anode (-), via the electrolyte in-between them. The electrodes can be made of different types of materials. The *anode* material can be:

- Graphite
- Hard Carbon
- Lithium Titanate (LTO)

Most common is the use of graphite but several battery companies are choosing hard carbon and LTO as alternate cathode materials.

The material used for the *cathod*e varies between the different manufacturers. The choice of the material will affect greatly the end battery properties such as safety, energy, life cycle, and cost. Materials used for the cathode include:

- Lithium Iron Phosphate (LFP)
- Lithium Nickel Cobalt Aluminum (NCA)
- Lithium Manganese Spinel (LMO)

Finally, the choice of electrolytes includes:

- Liquid organic solvents
- Gels
- Polymers
- Ionic liquids.

The different types of automotive lithium-ion batteries can be grouped in five types shown according the different chemistries based on the material of the anode or the cathode (see Table 2). The different cell chemistries have certain advantages and disadvantages but no clear winner can be defined based on chemistry alone.

Table 2: Comparison of different lithium-ion battery chemistries

Chemistry	Energy Density Wh/Kg	Advantages	Disadvantages
Lithium Nickel Cobalt Aluminum (NCA)	170	Most Proven High Energy Density High Power	Safety Cost (Cobalt and Nickel) Life expectancy Range of charge
Lithium Manganese Spinel (LMO/LTO)	150	Cost	Life expectancy Safety Low Temperature Perform.
Lithium Titanate (LTO)	150	Safety Life expectancy Discharge time Range of charge	Cost vs. LMO Energy density
Lithium Iron Phosphate (LFP)	140	Safety Life expectancy Range of charge Cost	Low Temperatures Perform.

Adapted from: Global Market Research, Deutsche Bank, June 2008.

Lithium Nickel Cobalt Aluminum (NCA)

This is the most proven chemistry for the cathode. It also has a high energy density and high power capability. Some of the disadvantages include concerns over thermal stability, safety, as well as cost due to heavy use of cobalt and nickel. Johnson Controls Saft and Toyota (PEVE – Panasonic EV Energy Company) are two prominent leaders in this cell chemistry.

Lithium Manganese Spinel (LMO) and Lithium Manganese Polymer Cathodes

Manganese spinel cathodes are considered safer and more environmentally benign, compared to cobalt and nickel, and have a lower cost as an advantage. On the down side, their energy density is lower and safety and life expectancy are not fully proven out yet. LG Chem (Compact Power) and Electrovaya are two prominent leaders in

Lithium Titanate (LMO/LTO) Cathode/Anode

This is a combination of a manganese cathode coupled with a titanate anode. The advantages are a long life, wide charging range, more stable then LMO, and can charge quickly. Among the disadvantages is a lower energy density and operation at 2.4 V rather than 4.0 V. Appropriate applications for this cell chemistry are those that require very long life, low energy and high power. EnerDel, Altairnano are companies utilizing this approach.

Lithium Iron Phosphate (LFP) Cathodes

Safety is one of the biggest advantages of this cell chemistry with a very low possibility of thermal runaway and fire. Other advantages include lower cost and wide range of charge. A principal drawback is lower energy density and poor operation at lower temperatures. A123 is company utilizing this cell chemistry approach.

Another useful way to review the different battery chemistries for vehicle applications is using a chart that shows specific energy over specific power and the relative performance of various energy storage devices. Figure 5, shown below, includes lead-acid, NiMH batteries, lithium-ion batteries in comparison to internal combustion engine for light-duty vehicles.

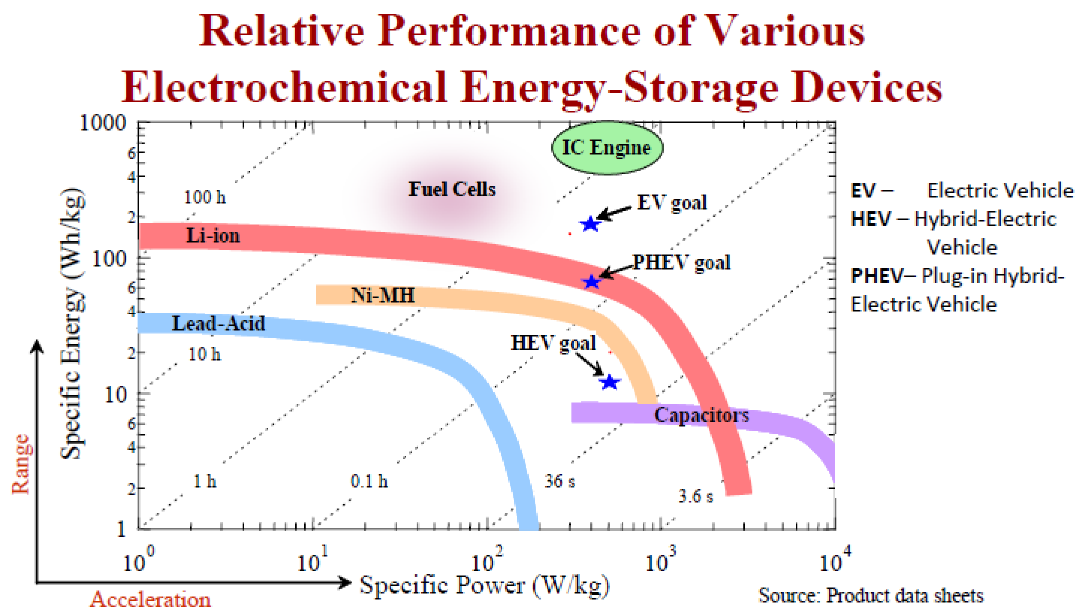


Figure 5: Potential vehicle applications for different battery chemistries (Source: Battery Workshop, Lawrence Berkeley Lab, Available at: /www.als.lbl.gov/als/workshops/workshopDocuments/Ross ALS battery wrkshp.pdf)

This chart contains the performance targets of light-duty hybrid, electric and plug-in electric vehicles. The chart shows that Li-ion chemistries have a wider range of performance compared to both NiMH and lead-acid and surpass them in specific energy and specific power. This in turn provides a lighter battery for the same application.

7. Compendium of Battery Technologies

The following pages contain an inventory of battery storage technologies with battery packs and modules relevant for the heavy-duty, bus and truck, vehicle sector. For each company we provide a description of the battery cell and, when available, an example of a module, and/or pack that would be appropriate for use in a heavy duty vehicle. It is important to remember that most, if not all these companies, build modules and packs in a variety of configurations for different applications, and can engineer systems for custom applications as well. This list is in not comprehensive but includes the main battery technologies currently on the market. In cases where we lacked specific information, a half page was included. The compendium is intended to provide a snapshot of where the technology is currently, and a review of the current or prospective suppliers of heavy-duty vehicle batteries.

A123
Altairnanto
Cobasys LLC – SB LiMotive
Compact Power – LG Chem
Electorovaya
EnerDel
E-One Moli Energy Corp
Firefly Energy
Gold Peak Industries
Hitachi
Imara
Johnson Controls Saft
K2 Energy Solutions
Kokam America, Inc.
Lithium Energy Japan
Magna Steyr
Nilar
Panasonic
PowerGenix
Quallion LLC
Thunder-sky
Valence Technology Inc.
Zebra / CEBI

A123

A123 produces Nanophosphate based lithium-ion batteries. The characteristics of this particular chemistry and design are higher power density and excellent thermal properties well suited for heavy duty systems. A stable chemistry and good safety record makes this battery technology a reliable choice. A123 Systems has a broad automotive class Lithium Ion cell portfolio ranging from high power cylindrical and prismatic cells with +5kW/kg performance for use in heavy duty and passenger hybrids to high energy prismatic cells with for use in plug-in and pure electric vehicles with industry leading usable energy in excess of 140Wh/kg. The company's energy solutions group can design systems to fit customer needs.

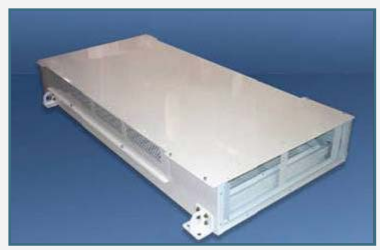
26650 CylindricalCell

<u>Heavy Duty Battery Module Properties</u>

Voltage: 40V
Lifecycle: Designed to meet heavy duty requirements
Temperature range: -40°C to +52°C
Charge rate (C-rate): 20C pulses

<u>Battery Pack Properties</u>

Peak Power: 200 kW
Energy: 11.39 kWh
Capacity: 18 Ah nominal
Voltage: 630 VDC
Design life: 6 years at a 16hr per day heavy duty profile



BAE System battery pack with A123 cells

www.a123systems.com **Contact: Roger Lin**
Arsenal on the Charles | 321 Arsenal Street | Watertown, MA 02472

Altairnano

Altairnano cells contain nano-structured lithium titanate in place of traditional graphite material anode material. Altairnano's products feature unique fast-charge, abuse tolerance, and extreme long life along with cold temperature charging. The cells are provided to manufacturers and established integrators in 11 Ah and 50 Ah configurations.

50 Ah Altairnano cell

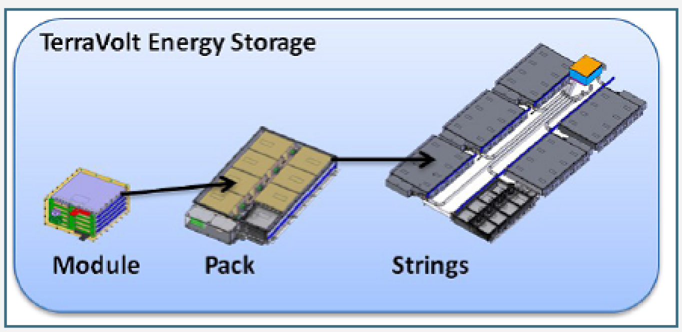
Proterra integrates these batteries into their ProDrive powertrain system for a complete vehicle solution.

Battery Module Properties

Weight: 21.9 kg/48.3 lbs
Power Density: 525 kW/kg
Energy Density: 56 Wh/kg
Lifecycle: >7000 cycles
Temperature range: -30°C to +65°C
Charge rate (C-rate): 6C

Battery Pack Properties

Peak Power: 58 kW
Energy: 9.75 kWh
Voltage: 184 VDC
Weight: 550 lbs / 250 kg
Design life: 6 years



Proterra TerraVolt modules and packs

www.altairnano.com **Contact : Jeff Yambrick**
Altair Nanotechnologies, Inc. | 204 Edison Way| Reno, NV 89502-2306
www.Proterraonline.com **Contact: Dale Hill**
Proterra LLC | 16360 Table Mountain Pkwy | Golden, CO80403

Electrovaya

Electrovaya designs and manufactures proprietary Lithium Ion SuperPolymer® battery systems. Electrovaya uses nano-structured materials to store more energy in less space. Using a platform technology, they can tailor design and chemicals to suit various applications. They offer products at levels from the module to systems level, and control systems.

35 Ah pouch cell

Battery Module Properties

Weight: Varies with module configuration
Power Density: 1800 W/kg for up to 10 seconds
Energy Density: 185 Wh/kg
Voltage: 15 V, 45 V and 48 V configurations available
Lifecycle: Varies with system design, load profile, temperature gradient.
Temperature range: -20°C to 55°C
Charge rate (C-rate): up to 10 C for regen braking

30 kWh battery module

Battery Pack Properties

Peak Power: 1800 W/kg for up to 10 seconds
Capacity: 5 Ah to 100 Ah sizes available
Voltage: Experienced with 48 V to 700 V systems
Weight: Varies with system size and packaging requirements
Design life: 10 years

www.electrovaya.com **Contact: Gitanjali Das Gupta**
107 Hermes Rd Suite 100 |Malta, New York 12020 | 518.899.7300

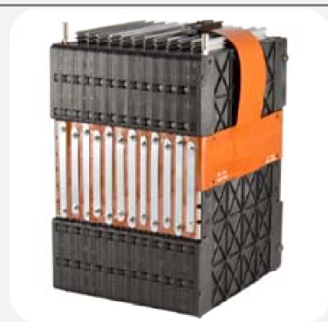
EnerDel

EnerDel produces lithium ion cells with different combination of anode / cathode materials – lithium-titanate, lithium manganese, hard carbon.
Products include battery cells and modules, as well as building battery packs that are scalable for all sizes of vehicles. Their flat pack designs offer significant advantages for packaging, with a chemistry that offers increased safety.

EnerDel prismatic cell

Battery Module Properties

Weight: 425 g / .9 lbs
Power Density: 4 kW/kg
Energy Density: 150 Wh/kg
Voltage: 4.1 V
Lifecycle: >1000 cycles
Temperature range: -25°C to + 52°C



EnerDel module design

Battery Pack Properties

Capacity: 74 Ah
Voltage: 400 V
Weight: 285 kg / 628.3 lbs
Design life: 10 + years

www.enerdel.com **Contact: Adam Hunt**
8740 Hague Rd | Indianapolis, IN, 46256 | 317-585-3456

E-One Moli Energy Corp.

Based in Taiwan and with production in the United States, E-One Moli produces Li-ion batteries with different types of cathode materials. The batteries for EV applications use lithium manganese spinel (LMO) cathodes.

Cylindrical, prismatic and high-power cells

Heavy Duty Battery Module Properties

Weight: 5.62 kg / 12.3 lbs
Power Density: 427 W/kg (30sec@8V)
Energy Density: 132 Wh/kg
Voltage: 7.20 V Typical
Lifecycle: 2000 cycles (4.0V-3.2V cycling)
Temperature range: -20°C to 60°C
Charge rate (C-rate): 98A(max)

EME253-H402 2S53P EV Module

Battery Pack Properties

Peak Power: 120 kW (30sec@8V, 50 modules)
Energy: 37.2 kWh (50 modules)
Capacity: 106 Ah (50 modules)
Voltage: 360V (50 modules)
Design life: 10 years

www.molicel.com
In North America: www.molienergy.com

Gold Peak Industries NA, Inc

Gold Peak Industries provides complete custom battery pack and charging solutions for portable applications. They specialize in custom battery solutions for a wide range of applications including: industrial OEM, emergency lighting, field instrument, consumer electronics, and hobby. Chemistries offered include Lithium Ion, Lithium Ion Polymer, Lithium Manganese, Nickel Metal Hydride, Nickel Cadmium.

Battery Module Properties

Weight: 20 kg / 44.1 lbs
Power Density: 500 W/kg
Energy Density: 52 Wh/kg
Voltage: 12 V
Lifecycle: >1500 cycles
Temperature range: 0 to +45°C
Charge rate (C-rate): /

Battery Pack Properties - NiMH
Peak Power: 350 kW
Capacity: 160 Ah
Voltage: 540 V
Weight: 1800/kg
Design life: >3 yrs

www.gpina.com/ **Contact: Patrick Huberty**
11235 West Bernardo Court | San Diego, CA 92127-1638 | 800 268-3416 | sales@gpina.com

Imara

Imara develops advanced lithium-ion battery cells and packs for high-power applications including HEV and PHEV traction batteries and specialty applications. Imara owns a unique cathode technology that can be applied to all lithium-ion chemistries to deliver more energy (runtime) at high power. The technology eliminates the need to use materials that trade off power with cycle life. Imara's cells offer a improved combination of run time and cycle life for high power applications. Imara is scaling production of 18650 high power cells and initiated development of large format pouch cells in 2009.

Cylindrical 18650 power cells

Cell Properties

Power Density: 3000 W/kg
Energy Density: 120 Wh/kg at 1000W/kg continuous power
Voltage: 3.7V nominal
Lifecycle: 1200 cycles at room temp, 100% DOD and 4C discharge
Temperature range: -20°C to 60°C
Charge rate (C-rate): 2C

Battery Pack Options
36V and 48V modules
Battery Management System for multi-module series and parallel configurations
Custom engineering solutions

www.imaracorp.com **Contact: Neil Maguire**
1555 Adams Drive | Menlo Park, CA 94025 | 650.543.6032

K2 Energy Solutions

K2 Energy Solutions, Inc. ("K2") has developed batteries and battery systems using lithium iron phosphate (LFP) technology, which provides increased safety and reliability over traditional lithium battery chemistries. K2's technology also provides improved weight, power, and cycle life performance versus traditional battery technology to competitively address high performance mobile applications. K2 manufactures both high energy and high power cells, batteries and battery systems.

K2 Cylindrical cells

<u>Battery K2 Module Properties for EV (see photo above)</u>
Weight: 3 kg / 6.6 lbs
Power Density: 700 W/kg
Energy Density: 96 Wh/kg
Voltage: 3.2V nominal
Lifecycle: +2000 cycles at 100% DOD and still retain over 80% of original capacity
Temperature range: -20°C to +60°C
Charge rate (C-rate): recommend c/5

<u>Battery K2 Pack Properties for EV</u>
Peak Power: 210 kW
Capacity: 90 Ah
Energy: 29 kWh
Voltage: 320 VDC
Weight: 300 kg
Design life: 10+ years


K2 LFP300HES Battery Pack

www.K2battery.com **Contact: Mark Stoker:**
1125 American Pacific Drive | Henderson, NV 89074 | mstoker@peakbattery.com

Kokam America Inc.

Kokam products are a combination of lithium-ion and lithium polymer technologies - Superior Lithium Polymer Battery (SLPB). SLPB products have the following merits: continuous automated cell assembly process, low cell impedance, high discharge rate up to 30°C continuous, flexible design resulting wide range of capacity – 25mAh to 240Ah, automation for better quality control.

100Ah lithium polymer

Battery Module Properties

Weight: 23.5 kg / 51.8 lbs
Power Density: 670 W/kg
Energy Density: 140 Wh/kg
Voltage: 51.8 V
Lifecycle: >1500 cycles
Temperature range: -20°C to + 60°C
Charge rate (C-rate): Max 2C

Battery Pack Properties

Peak Power: 31 kW
Capacity: 60 Ah
Voltage: 51.8 VDC
Weight: 51.7 lbs / 23.5 kg
Design life: > 1500 cycles

Battery modules - Kokam

www.kokamamerica.com **Contact: Mike Choi**
Kokam America Inc. | 2901 NE Hagan Road | Lee's Summit, MO 64064

Nilar

Nilar has developed a Nickel Metal Hydride (NiMH) battery utilizing the company's patented packaging technology. The result is a performance breakthrough in power and energy density and simplification in pack integration and control. The Nilar design offers significantly lower pack resistance and can be assembled with inexpensive cooling and battery monitoring systems resulting in lower cost for the customer. Nilar Power Systems delivers complete energy storage solutions for the heavy duty vehicle market.

PE15 MOD – 12V Power Module

The patented Nilar battery was developed in the USA. Production and development are located in Denver, Colorado.

<u>Battery Module Properties</u>
Maximum Power: 4 kW
Energy Density: 50 Wh/kg
Power Density: 845 W/kg
Voltage: 12 V
Lifecycle: 3.125 MWh
Temperature range: -10°C to 45°C
Charge rate (C-rate): 2C for full charge, 15C for Regen pulse

<u>Battery Pack Properties</u>
Peak Power: 129 kW
Weight: 220 kg
Capacity: 20 Ah
Voltage: 384 V
Design life: 5-7 Years, 95k 7% SOC Cycles
Design life: 1,000 full depth of discharge cycles

70kW Energy Storage System - Nilar

www.nilar.com **Contact: Joseph Heckel**
7388 South Revere Parkway, Suite 1001 | Centennial CO, 80112 | 303.662.8891

Quallion LLC

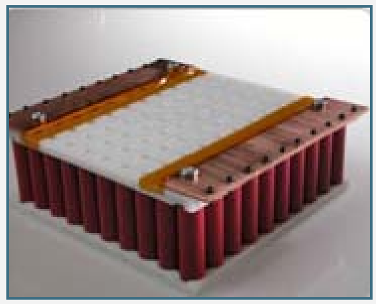
Qualion produces a number of primary and rechargeable cell and battery configurations for use in the medical, military, vehicle and aerospace markets, with revenues divided evenly across these market segments. Relevant chemistry experience includes Li ion (various species of $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$, LiCoO, LiMnCo, LiNiCoO), Li Polymer, Li Metal, CFx, SVO, LVO, and Li Air. Production capabilities range from high volume medical, military and vehicle batteries to unique custom-designed aerospace batteries. Cell designs range from the world's smallest conventional lithium ion cell (a cylindrical 1.8 mAh cell) for biomedical implants to 15 and 72 Ah prismatic cells.

18650 cylindrical cell

PHEV Battery

<u>Battery Module Properties</u>

Weight: 8.70 kg / 177.9 lbs
Power Density: 6.53 kW
Energy Density: 93 Wh/kg
Voltage: 51.80 V
Lifecycle: 2000 cycles
Temperature range: -30°C to +52°C
Charge rate (C-rate): 5.5C



Battery module - Quallion

<u>Battery Pack Properties – PHEV</u>

Peak Power: 45 kW
Capacity: 15.6 Ah
Energy: 5.66 kWh
Voltage: 363 V
Weight: 70 kg / 154 lbs
Design life: 15 years (calendar life), 2000 cycles

www.quallion.com **Contact: Paul Beach**
12744 San Fernando Road | Sylmar, CA 91342 | info@quallion.com

Valence Technology Inc

Valence cathode materials provide foundation in this cell technology solution. Valence offers systems with phosphate based lithium iron magnesium chemistry that has outstanding deep cycling ability, high energy density and safety stemming from not suffering from thermal runaway. Other properties include good shelf life and no memory effect.

Cylindrical cell

Heavy Duty Battery Module Properties

Maximum Power: 1920 W continuous and 384 W Peak
Power Density: 91 Wh/kg
Voltage: 12.8V
Lifecycle: >2,000 cycles
Temperature range: -10°C to +50°C
Charge rate (C-rate): C/2, max 2C Pulse

Battery Pack Properties
Peak Power: 180 kW
Capacity: 80 kWH
Voltage: 307 V
Design life: 9-10 years

U-Charge modules - Valence

www.valence.com Contact: Jonnie Hefty
12303 Technology Blvd. | Suite 950 | Austin, Texas 78727 | 1-888-VALENCE

Cobasys LLC

Cobasys recently became a subsidiary of Samsung Bosch Joint Venture, SB LiMotive. Cobabys has experience in nickel metal hydride batteries, and is focused on the electric vehicle market. Their patents are 700 strong, and claim several fundamental patents on NiMH technologies. The new joint venture will be developing and manufacturing both NiMH and Li-ion batteries for the automotive sector.

3740 Lapeer Road South, Orion, Michigan 48359 | 248-620-5700 | info@cobasys.com

Compact Power, Inc., LG Chem Ltd.

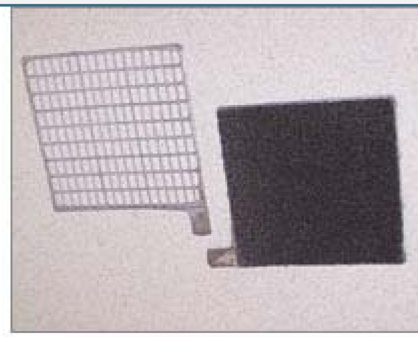
CPI / LG Chem produce Li-ion polymer batteries for automotive and non-automotive applications. The advantages cited are lightweight, compact design, high power and energy, and good safety record. They provide the total solution, battery modules, battery packs and management system. The unique package design offers a low cost, high quality and reliable cell that is designed for fail-safe performance.

Li-ion polymer cell

Battery pack

www.johnsoncontrols.com

Firefly Energy



Conventional lead grid (left).
Firefly carbon-graphite foam grid (right)

Firefly Energy has developed two significant technologies that will deliver advanced battery performance for an entire spectrum of uses served by lead acid, nickel, and lithium based chemistries. The two technologies involve the use of a porous three dimensional material in either flooded or VRLA (valve-regulated lead acid) battery designs. Implementation of this technology successively does away with the corrodible lead grids found in conventional lead acid battery design, and allows delivery of the full power potential of lead acid chemistry for energy storage. The resulting products possess performance parameters comparable to advanced materials (Lithium and Nickel-based) batteries, but at costs far below these high performance batteries.

www.fireflyenergy.com/ | 309.222.2600 |

Hitachi

Hitachi is one of the largest manufactures of lithium Ion batteries, and lays claim to a lithium-ion battery having the world's highest power density of 4,500W/kg. They are a high volume manufacture, having delivered over 600,000 units to automotive and railway customers.

Prismatic Li-ion battery cell

www.hitachi.com

Johnson Controls - Saft

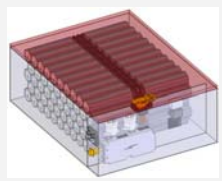
JCS is a joint venture between Johnson Controls and Saft for the purpose of developing and manufacturing NiMH and Li-ion batteries for hybrid, plug-in hybrid and electric vehicles globally. The cells are prismatic with nickel cobalt aluminum (NCA) cathode and graphite anode. JCS offers complete suite of products from cells, modules to battery packs with a battery management solution.

Cylindrical cells

<u>Battery Module Properties</u>

Liquid cooled-Air cooled-

Design life: expected 10 years and 150,000 mi


390 V -80kW-17kWh
Air Cooled


390V – 80kW – 17kWh
Liquid Cooled

www.johnsoncontrols.com

Lithium Energy Japan

GS Yuasa joined forces with Mitsubishi Corporation and Mitsubishi Motors Corporation to establish "Lithium Energy Japan" in December of 2007.

Lithium Energy Japan has lithium-ion battery "LEV50" which is based on GS Yuasa Group's state of the art technology and extensive experience in manufacturing large-scale industrial and small lithium-ion batteries.

Its excellent performance is brought by our latest technologies and most suitable for EV applications, and can unfold widely for other applications for energy storage etc.

www.lithiumenergy.jp | +81-75-312-040

Magna Steyr

Magna Steyr, an operating unit of Magna International Inc., is a battery system developer and battery system supplier for hybrid energy storage systems. The company is the link between the cell supplier and the OEMs. Magna Steyr launched a battery pack for a heavy-duty bus application (Volvo) using A123 batteries in 2009.

Battery Pack

The heavy-duty battery packs will range from 2.5-7 kWh and 60-180kW, and be built with the cylindrical cells. The 120 kW pack is first into production. 75 kW and 180 kW battery systems are in development and are targeted to be available in 2010.

http://www.magna.com
600 Wilshire Drive | Troy, MI 48084 | 248.729.2400

Panasonic

A leading OEM supplier of primary and secondary batteries, Panasonic satisfies the many needs of the market with one of the broadest lines of battery products including Lithium Ion, Nickel Metal Hydride, Lithium primary and rechargeable cells, Alkaline, and Valve Regulated Lead Acid.

Prismatic and cylindrical cells

www.panasonic.com/industrial/battery/oem/about/index.html

PowerGenix

PowerGenix's nickel-zinc (NiZn) technologies offer many compelling benefits for use in hybrid electric vehicles and other mobility applications. Nickel-zinc offers the high-power, high-cycle life and required energy density to meet the high torque and discharge demands of many of these vehicles at cost effective performance levels. Nickel-zinc also performs very well at both high and low temperatures, a key performance requirement for HEV's. Just as importantly, nickel-zinc is extremely safe, environmentally clean, and recyclable without any special handling needs.

Battery Pack

www.powergenix.com/hev.php **Contact: Franz Krueger**
10109 Carroll Canyon Rd| San Diego, CA 92131 | 858.547.7300 |info@PowerGenix.com

Thunder-sky

Thunder Sky Battery Limited is a producer of rechargeable Lithium-Ion battery with high capacity and high power. In cooperation with FAW, the leading Chinese automaker, TS will start in the year 2009 a production of e-buses for a annual output of 25.000 vehicles, to be used in major metropolitan areas in China.

Heavy Duty Battery Module Properties

Voltage: 278VDC ~ 472VDC

Lifecycle: >4,000 cycles

Battery Pack Properties

Peak Power: 283.0Kwh
Weight: 9.6 kg / 21.2 lbs
Capacity: 300 Ah
Voltage: 4.25 V
Design life: >4,000 Cycles

www.thunder-sky.com Contact: thunder@thunder-sky.com

Zebra / CEBI

Zebra produces sodium nickel chloride (Na Ni Cl) batteries. They use salt and nickel for electrode materials with a ceramic electrolyte. ZEBRA® batteries are intrinsically maintenance free and have a long life and high reliability. Their safety features make ZEBRA® batteries specially suitable for mobile applications like cars, vans and buses. ZEBRA Batteries are designed for electric and hybrid vehicles.

Sodium Nickel Chloride cell

Heavy Duty Battery Properties

Weight: 168 kg / 370.4 lbs
Power Density: 177.9 W/kg
Energy Density: 120 Wh/kg
Voltage: 170 V
Temperature range: -40°C to +50°C

www.cebi.com

8. References Cited

Federal Transit Administration (2008), "Electric Drive Strategic Plan," Draft Copy, September.

Gaines, Linda and Roy Cuenca (2000), "Costs of Lithium-Ion Batteries for Vehicles," Center for Transportation research, Argonne National Laboratory, May.

Global Market Research Company (2008), "Electric Cars: Plugged In," Deutsche Bank, June.