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TECHNISCHE UNIVERSITÄT WIEN

DIPLOMARBEIT

Analysis of rechargeable energy storages for hybrid electric vehicles

ausgeführt zum Zwecke der Erlangung des akademischen Grades
eines Diplom-Ingenieurs des Wirtschaftsingenieurwesens - Maschinenbau
unter der Leitung von

O. Univ. Prof. DI Dr.techn. Adolf Stepan
Institut für Managementwissenschaften E330
Abteilung für Industrielle Betriebswirtschaftslehre und Wettbewerb

eingereicht an der Technischen Universität Wien
Fakultät für Maschinenbau und Betriebswissenschaften

von

Friedrich Alfred Födermayr
0226268
A-1080 Wien, Hamerlingplatz 4

Wien, im März 2008

Kurzfassung

Energiespeicher bilden einen wesentlichen Bestandteil eines Hybridfahrzeugsystems. Die Auslegung des gesamten Systems richtet sich nach der Beschaffenheit dieser Speicher. Die vorliegende Arbeit behandelt ausschließlich wiederaufladbare Energiepeicher mit Schwerpunkt auf elektrische Hybridfahrzeuge. Hydraulische Systeme werden kurz angerissen.

Die Arbeit ist im Wesentlichen in drei Teile gegliedert:

Im ersteren Teil wird ein breiter Überblick über verschiedene Energiespeichertechnologien und den derzeitigen Stand der Technik gegeben. Theoretische Grundlagen sowie die Auswahl von Speichern für weitere Beobachtungen werden erläutert.

Im zweiten Teil wird von ca. 250 abgerufenen Webseiten von Batterie-, Superkondensator- und Schwungradherstellern eine Menge von Herstellern zur Aufnahme von deren Datenblättern ausgewählt. In weiterer Folge werden einheitlich definierte Kennzahlen und Ziele vom U.S. Advanced Battery Consortium (USABC) adaptiert und geringfügig abgeändert. Herstellerdaten werden auf diese Kennzahlen bezogen, wobei vorerst Ungleichheiten betreffend verschiedene Definitionen seitens USABC und den Herstellern eliminiert werden müssen. Als wesentlicher Unterschied fällt die Festlegung über den Lade- bzw. Entladewirkungsgrad auf, der in allen weiteren Schritten berücksichtigt wird, indem USABC Ziele umgerechnet werden.

In der anschließenden Analyse der gewonnenen Daten werden zwei Lithium-Ionen Technologien identifiziert, die den Großteil der an sie gestellten Anforderungen erfüllen bzw. überragen. Schwungräder erfüllen die Anforderungen und Graphit Doppelschicht Kondensatoren erreichen die an sie speziell gerichteten Ziele. Erstere könnten jedoch aufgrund der komplexeren Bauweise und daraus resultierenden höheren Kosten wiederum als ungeeignet gelten.

Im dritten Teil dieser Arbeit wird auf die Selektionsumgebung von Batterieherstellern, insbesondere auf Lithium-Ionen Technologie eingegangen, als auch auf die besondere Stellung der AVL List GmbH, Auftraggeber dieser Arbeit. Der relevante Markt von Batterien für elektrische Hybrid- als auch Elektrofahrzeuge wird betrachtet und als hochkonzentriert befunden. Weiters ist anzunehmen, dass die aktuell marktbeherrschende Nickel-Metallhydrid-Technologie sukzessive von der Lithium-Ionen Technologie verdrängt wird. Geographisch gesehen dominieren japanische Anbieter den globalen Markt. Bezüglich Kostensenkung werden Materialkosten als hauptsächlicher Kostenverursacher identifiziert. Potential für Skaleneffekte ist hinsichtlich Lithium-Ionen Technologie durchaus bezüglich mehrerer Punkte gegeben. Forschungs- und Entwicklungscluster werden in den Vereinigten Staaten und in Japan eruiert.

Abstract

An energy storage is a core part of a hybrid vehicle. The design of the entire system has to be adjusted to the performance and the characteristics of the storage. The following work solely deals with rechargeable energy storages and in first line storages are observed concerning the usage in hybrid electric vehicles. Brief excursions are made to hydraulic systems.

This thesis is structured into three major parts:

In the first part, a broad overview is given about the state-of-the-art of various storage technologies. Theoretical and fundamental basics are indicated and the focus on which further discussion is put is explicated.

In the second part, from about 250 different accessed websites of battery-, supercapacitor- or flywheel suppliers, product data was collected from a sample of them. In order to compare data on a common basis, definitions of several characteristics as well as goals are adopted from the U.S. Advanced Battery Consortium (USABC). Some modification of these definitions and goals is necessary. Based on these modified characteristics, data is calculated from the suppliers' datasheets. A major difference regarding data provided by suppliers and goals set by USABC is energy efficiency concerning the charge and discharge of a storage. This discrepancy is assessed to qualify any benchmarking and thus is considered in all further calculations.

In the data analysis, two lithium-ion technologies turn out to meet or even outperform most characteristics. Carbon Electric Double Layer Capacitors meet their respective goals. Flywheels also meet the goals but their usage may be qualified by their complex design and probable high cost.

In the third part, the selection environment of battery manufacturers concerning the Hybrid Electric- and Electric Vehicle battery market and the role of the AVL List GmbH is observed. The relevant battery market is evaluated as highly concentrated. Lithium-ion technology is assessed to displace Ni-MH technology gradually. Currently (i.e., in 2008), the market is dominated by Japanese suppliers. Furthermore, material cost is identified as the main cost driver. Regarding the manufacturing process of lithium-ion batteries, economies of scale are expected. Most R&D activities are detected in the USA and Japan.

Acknowledgement

First and foremost, I would like to express my sincere gratitude to my supervisor O. Univ.-Prof. DI Dr. Adolf Stepan, head of the Institute of Management Sciences and the Department of Industrial Business Administration, for his support, long-sighted expertise and constructive feedback, as well as to my supervising tutor at AVL List GmbH, Graz, Austria, Dr. Bernhard Kortschak, for his extensive and expert support during my stay in Graz and for further extensive efforts in guiding and reviewing this diploma thesis.

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Table of contents

List of figures

List of tables

1 Introduction

‘Innovation Management’ includes all activities to market launch of a product or service as indicated in Figure 1.1. ‘Research and Development Management’ is an early part of it and ranges from fundamental research to development whereas ‘Technology Management’ focuses on stages of applied research and predevelopment. *(Vahs, Burmester, 2005)*

This work should contribute to the technology management of AVL List GmbH, Graz, Austria (www.avl.com) to assess current (2008) hybrid vehicle technology and in particular energy storage technologies of hybrid vehicles.

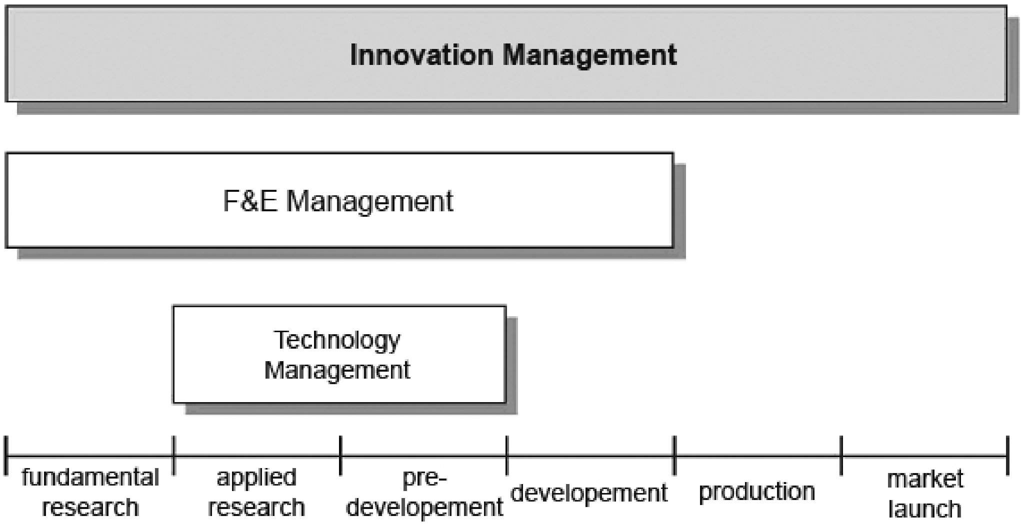


Figure 1.1 technology management (source: compare Vahs, Burmester, 2005, fig. 2.2)

According to UN ECE Regulation No. 85, Amendment 4, a hybrid vehicle is defined as “*a vehicle with at least two different energy converters and two different energy storage systems (on vehicle) for the purpose of vehicle propulsion.*” *(UNECE, 2005)*

Recently, several different forms of hybrid vehicles exist. In the following, a brief introduction is given.

By the degree of hybridization, it can be distinguished between **Micro-**, **Mild-**, **Full-** and **Plug-In** - Hybrids and by construction in **Series**, **Parallel** and **Series/Parallel** types. *(Reik et al, 2006)*

Primary goals of Micro and Mild Hybrids are higher fuel economy and lower emission of greenhouse gases. *(Reik et al, 2006)* Full hybrids, sometimes also called ‘Strong Hybrids’ *(Anderman, 2006)*, already allow electric drive, whereas Plug-In hybrids offer higher ranges and can be plugged to the grid in order to store electric energy. *(USDOE-EERE, 2008)*

Fuel economy results from engine stop/start maneuvers, recuperation of braking energy and, concerning Full and Plug-in hybrids, from **electric driving** as indicated in Figure 1.2. *(Reik et al, 2006)*

An **Engine Stop/Start** is performed, when the car stops e.g. at a crossing: The engine is shut down until the passenger activates it again by e.g. pressing the gas pedal or engaging a gear. *(Bosch, 2008)*

During **recuperation of braking energy** or also called 'regenerative braking', e.g. the drag torque of a coupled generator or inertial moments of a kinetic storage decelerate the vehicle and in turn convert braking energy to energy stored within a storage. *(Reik et al, 2006)*

Fuel economy regarding **electric driving** of Full- (approximately 4%, *Reik et al, 2006*) or Plug-In hybrids results from shutting down the combustion engine at low operating efficiency. Various shut downs and starts of the engine may occur during a usual drive. *(Reik et al, 2006)*

Moreover, efficiency results from downsizing the engine: Usually combustion engines operate most efficiently at higher load curves close but still beneath full load curve. Downsized engines have to operate at higher load curves to carry the same amount of load but in turn at higher efficiency. The deficit on power capability of downsized combustion engines is paid back by the additional hybrid propulsion system: the electric engine. *(compare Bosch, 2008)*

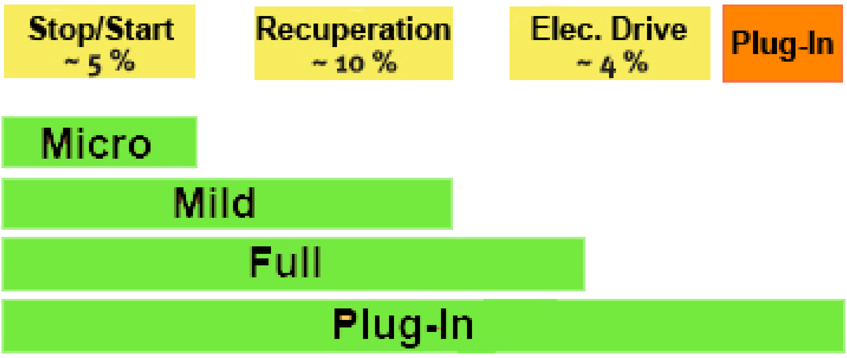


Figure 1.2 Various degrees of hybridization (source: compare Reik et al, 2006)

Recent efforts in Plug-In hybrids are made, in order to store electric energy supplied by the grid. Particularly in the USA, this strategy is considered to reduce dependence on foreign oil. Recently, the bigger part of electricity is recently consumed at the moment when it is produced. Storage capabilities are limited. Particularly, when electricity consumption is low, e.g. at night, or electricity is stochastically available, P-HEVs plugged to the grid could offer storage capabilities to store electricity when it is available but not consumed otherwise. *(Stieler, 2007)*

Regarding the construction of HEVs as indicated in Figure 1.3, in a ‘Series Hybrid’ the engine is coupled in series with a generator converting mechanical energy steadily to electricity. Electricity produced by the generator in turn powers an electric machine which operates as motor. Regarding recuperation of braking energy, the electric machine acts as generator and recharges the battery. *(Reik et al, 2006)*

In a ‘Parallel Hybrid’, a power split transmits power to the wheels via a gearbox as well as to an electric machine, which can be used as additional motor or as generator regarding recuperation of breaking energy. *(Reik et al, 2006)*

A combination of both types is the ‘Series/Parallel Hybrid’. *(Reik et al, 2006)*

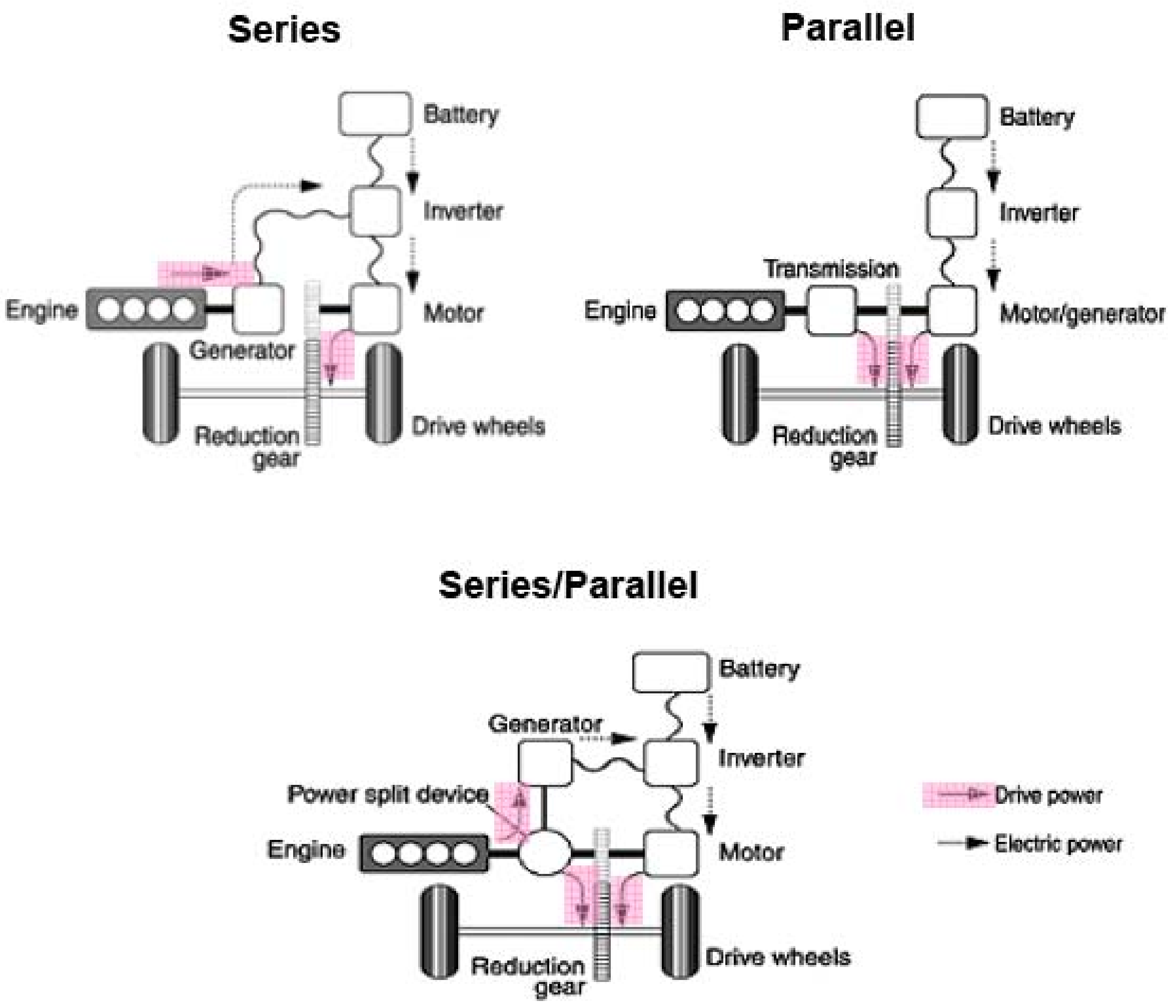


Figure 1.3 principal types of construction of HEVs (source: UNECE, 2007)

In 2006 total sales of Hybrid vehicles, regardless of which type, are stated between more than 246.600 *(EDTA, 2008)* and 384.000 *(Anderman, 2006)*. According to *EDTA, 2008* sales increased to more than 33.000 in 2007.

Stimulating factors are increasing oil prices due to increasing oil consumption and passing peak of oil production at the same time, efforts of ‘first world countries’ to reduce dependence on foreign oil and environmental issues as reduction of greenhouse gases in order to limit global warming. *(compare Bush, 2006)*

2 Overview of energy storage technologies - theoretical and fundamental basics

2.1 Definition of an energy storage

An energy storage is defined as a device storing secondary energy according to which a desired amount can be drawn upon at any time in a rational manner for a certain duration Such electrochemical and mechanical devices are also called accumulators. *(Meyers Lexikonverlag, 2007a).*

Secondary energy is defined as "*energy used by final consumers for residential, agricultural, commercial, industrial and transportation purposes*". *(CANMET Energy Technology Centre – Varennes, Canada, 2007)*

Because in many cases the form of energy stored is not the same as the one delivered the energy storage device may include the function of an energy converter, which converts energy from one form to another *(Meyers Lexikonverlag, 2007b).*

Energy converters can also exist separate from a storage, e.g. when considering a fuel cell and a hydrogen tank or a thermoelectric converter and a battery. For further investigations an outline of storages from pure converters is done where it's useful. In these cases it is only focused on storages.

Furthermore it has to be distinguished between rechargeable systems and non rechargeable systems. In respect to regenerative energy storing in hybrid vehicles only rechargeable systems are considered further in this work.

The aim of this chapter is to give a broad overview about existing energy storage technologies. Fundamental basics are sketched and applications in hybrid vehicles are evaluated. Focusing on some types is necessary considering the tremendous variety of energy storage technologies which differ in many factors as scale and subsequently in fields of application as motive or stationary ones. This should not be interpreted as a selection process to favor some technologies. The purpose of this work is to serve as a basis for further considerations and decisions respectively for a selection process.

2.2 Classification

A first classification of current storage technologies can be done by distinguishing between different forms of energy stored in storages. Most forms of energy appear in potential form, which is stored in a force field. In such fields a special form of force acts. *(Lugner, P., 2002)* Hence, regarding considerations in this work we use the following force related classification:

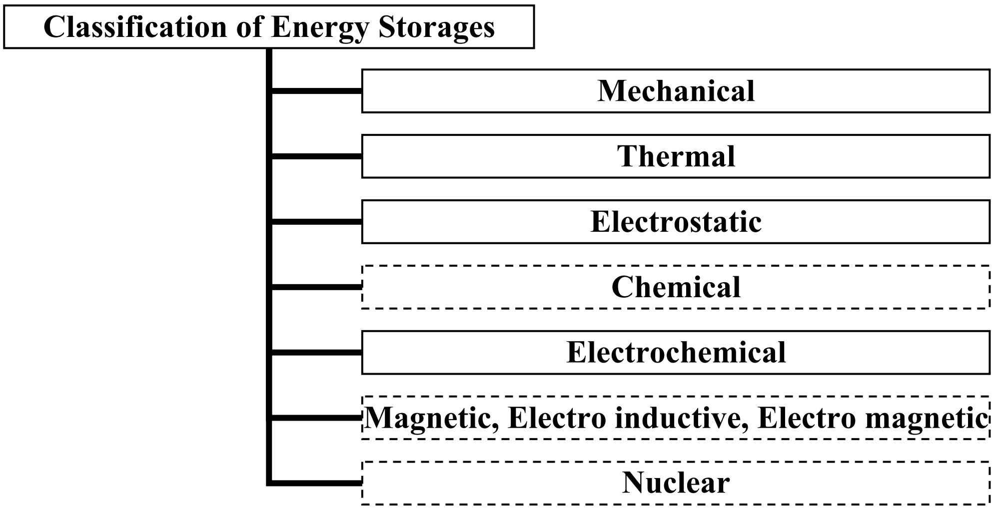


Figure 2.1 Classification of energy storages

Boxes with dashed lines represent types of storages, which are only investigated in chapter 2 of this work. No appropriate commercial storages of these types were found.

2.3 Mechanical storages

Mechanical storages include kinetic ones and those based on mechanic potentials such as gravitational storages, stress based storages (springs) or pressure storages (compressed fluids) as indicated in Figure 2.2.

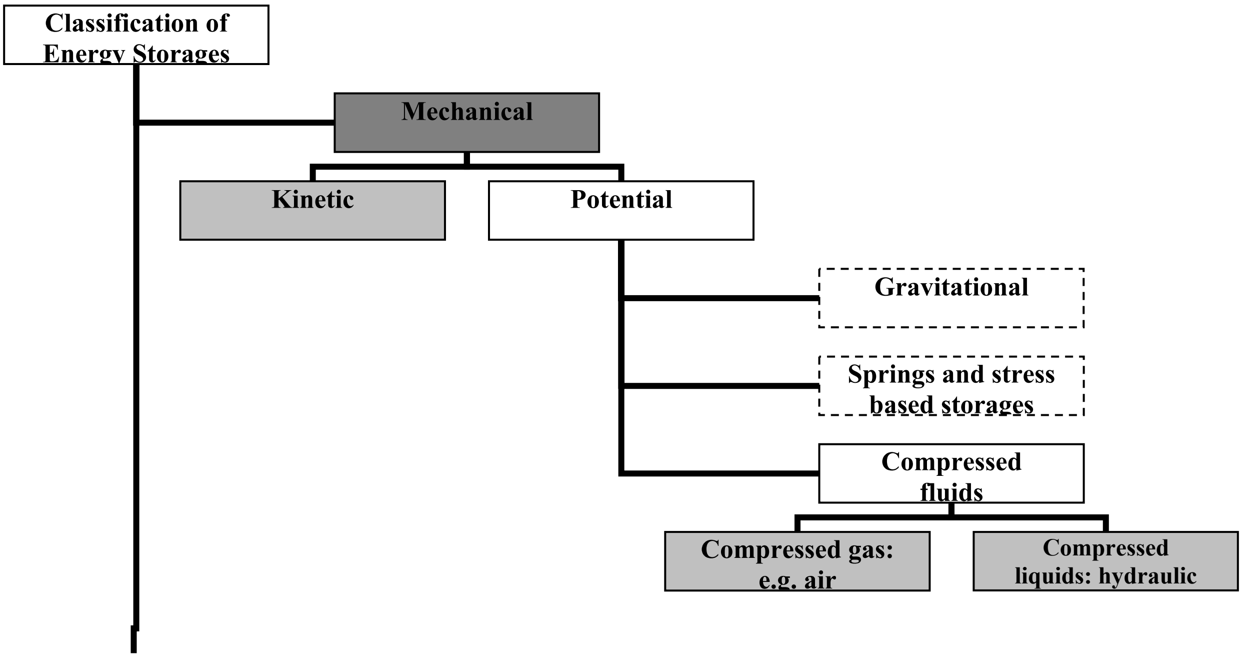


Figure 2.2 Classification of mechanical energy storages

Regarding motive applications we focus on kinetic and pressure storages.

As done in Figure 2.1, in all diagrams which categorize storages, dark grey coloured boxes highlight a group of storage types, which are just discussed in the particular chapter whereas light gray boxes indicate ancillary storages of the particular group, which are subject of further considerations in this chapter 2.

2.3.1 Kinetic energy storages, flywheels

Kinetic energy storages use the principle of inertia to store energy of an accelerated mass in a rotational motion. Kinetic storages with a cylindrical rotor are called flywheels.

Rotational energy E_{rot} is the half of the sum of all products of points of mass times the square of the distance point - axis r times the square of rotational speed ω^2. In mathematical terms

$$E_{rot} = \tfrac{1}{2} \times \omega^2 \times {}_{M}\!\int r^2 \times dm \quad \text{or} \quad E_{rot} = \tfrac{1}{2} \times \omega^2 \times J$$

J stands for the moment of inertia of the rotor. This means that energy increases by the square of rotational speed. Concerning a homogeneous cylinder as rotor, the momentum of inertia I is $I = r^3 \pi h \rho$ (r…radius, h...height, ρ...density). It increases cubic with the radius *(Rummich, 2004)*.

In most motive applications, achieving high specific energy and energy density, respectively is one of several main issues *(Flybrid Systems LLP, 2008)*. Thus, considering all parameters in order to achieve high energy storage capacity as mentioned before, rotational speed is the only parameter independent from volume and mass and therefore it is pushed to the feasible limits.

In first line these limits are given by the design of the bearings, which have to carry the loads of the rotor and have to fit to its revolution speed. Arising loads are the weight and the considerable high gyroscopic forces *(Flybrid Systems LLP, 2008)* which result from the rotational motion of the rotor: Like a gyroscopic compass every rotor tends to retain its rotating axis and torques occur when it is tried to change it.

Thus, at this stage, it is important to distinguish between storages which rotors' axis is fixed to the vehicle (chapter 2.3.1.1) and storages with rotors, which are suspended like a gyroscopic compass with three angular degrees of freedom (2.3.1.2).

2.3.1.1 Fixed case

In the fixed case, gyroscopic forces cause two major problems *(Ellis, Pullen, 2006)* for mobile applications:
On the one hand the bearings have to carry the considerable loads enforced by the gyroscopic torques when the rotating axis of the rotor is changed.

On the other hand, gyroscopic torques affect the total system - the vehicle. This has an effect on drivability when passing a hill or a curve. By installing the rotor in a configuration so that its axis is vertical, effects in curves can widely be avoided; actually it supports traction in curves. To eliminate effects on the vehicle completely, two similar rotors *(Ellis, Pullen, 2006)* with opposite sense of rotational direction with a common suspension between housing and vehicle have to be installed. Also multiples of two rotors are imaginable.

However, regarding rotors with opposite senses of rotational directions, the total effect on the vehicle can be eliminated but the forces in the bearings of course can't. Considering mechanics *(Lugner 2003)* it can be deduced that they are proportional to the change of the rotor's vector of angular momentum (L); stated in mathematical terms: $\sim dL/dt$. This means that fast changes of the rotors axis (e.g. when driving up a hill or in a curve quickly) result in high gyroscopic torques and therefore in high loads in the bearings. Moreover, the definition of the angular momentum $L = \omega \times {}_{M}\int r^2 \times dm$ implicates that gyroscopic loads are proportional to the rotational speed (measured to the horizontal plane) of the rotor's axis.

Therefore, concerning the fixed case in mobile applications, the right choice of bearings is essential. There exist different possibilities of choices for bearings used in flywheels/ kinetic storages: conventional hydrodynamic or magnetic and super conductive magnetic bearings *(Brown, Parker, 2003), (Burg, 2003) and (Ellis, Pullen, 2006).* As bearings do, they all differ regarding complexity, maximum load capability, maximum revolution speed, lifetime, friction and heat development. Magnetic and super conductive magnetic bearings are often not capable to carry high loads but they are the most common choice in combination with convential bearings concerning static applications *(Brown, Parker, 2003). They* minimize friction and enable self centering of the rotor's shaft. Conventional hydrodynmic bearings have the disadvantage of higher friction and heat generation which leads to higher self discharge of the storage.

2.3.1.2 Gyroscopic suspended case

In this case the axis of the rotor is not tried to change. Using a suspension of three angular degrees of freedom the axis always retains its position relative to the inertial system's axis and changes it to the vehicle when driving up a hill or in a curve *(Magnet Motor GmbH, 2007).*

Thus for a frictionless suspension, it can be concluded that gyroscopic forces do not occur. The disadvantages are the complexity of implementation of the suspension into the vehicle, that it is more volume consuming and the fact that there occur problems regarding energy transfer considering the motion of the storage *(compare Magnet Motor GmbH, 2007).*

2.3.1.3 Revolution speed

Generally, for both cases, the fixed and the suspended case, the revolution speed is limited by three major factors: The type and design of the bearings, burst speed of the rotor and critical revolution speed *(Burg, 1996).*

Critical speed is a term which is equal to the eigenfrequencies of a spinning system. The system can oscillate normal to the turning axis as well as around it. When an eigenfrequency equals rotational speed, resonance occurs and a resonance catastrophe and the destruction of the application can be the cause. Therefore, it is tried to avoid that a flywheel passes this speed. Flywheels, operating under the first critical speed are called subcritical and those working over are called supercritical. *(Burg, 1996)*

Burst speed is reached when centrifugal forces induce stresses equal to the maximum stresses of the rotor's material. For supercritical flywheels carbon fibers *(Burg, 1996)* are suited to withstand high tensile stresses and therefore are used often.

In spite of achieving high specific energy and energy density a tradeoff has to be made between the design of the bearings, dimensions and used materials.

2.3.1.4 Couple

To charge/discharge the storage, two possibilities are observed: either the rotor is coupled with an energy converter like an electric machine converting kinetic energy to electricity *(Magnet Motor GmbH, 2007)*, *(Compact Dynamics GmbH, 2007)* or it is coupled with a continuously variable transmission (CVT) *(Ellis, Pullen, 2006)*, *(Anonymous, 2007a)* of the vehicle to transmit kinetic energy direct to the wheels.

In the first case, the electric machine operates as motor to accelerate the rotor during charge and as generator to decelerate the rotor during discharge. Because a gyroscopic suspended storage changes its rotating axis, it's difficult to couple the storage with a CVT. In this case the serial connection of storage and electric machine solve this problem *(compare Magnet Motor GmbH, 2007).* Fixed storages coupled with a CVT may be coupled by a magnetic fluid couple *(Ellis, Pullen, 2006).*

2.3.1.5 Rotor design

Another key issue is the design of the rotor. As already mentioned special materials are used to withstand stresses in the material which are caused by the centrifugal forces. But in particular, when considering the high amounts of kinetic energy stored in the motion of the rotor and the vast destructive forces occurring at a break of the storage, safety plays a major role. Therefore the rotor is packed in a housing. In case of break the instable rotor material is destructed before it destructs the housing of the storage *(Burg, 1996)*. The rotor of supercritical flywheels is made of fiber reinforced plastic or a compound of fiber reinforced plastic and steel *(Flybrid Systems LLP, 2007)* which is instable in case of break *(Ellis, Pullen, 2006)* whereas subcritical flywheels with low revolution speeds are just made of steel.

A further effort represents minimizing the friction between rotor and housing, which is a consequence of turbulent air flow. Thus for high speed flywheels the housing is evacuated.

This can be achieved by a vacuum pump but regarding automotive applications, the housing is already evacuated at the manufacturing process.

2.3.1.6 State-of-the-art products:

Examples of several different realizations were found during research of this work and should be presented briefly. Information about the qualifying factor, cost, was not available because products are currently in developement.

Representatives of a gyroscopic suspended kinetic storage with serial connected electric machine which are intended as applications in public transit buses or just as static UPS are the 'Magnetdynamische Speicher (MDS)' offered by the company MagnetMotor GmbH, Starnberg, Germany *(Magnet Motor GmbH, 2007)*. MDS' cylindrical rotor is constructed of wound carbon fibers and is installed vertical in buses. To avoid friction in the bearings, the majority of the loads is carried by magnetic forces. The housing is evacuated. According to the manufacturers homepage the MDS K3 series is used in diesel-electric public transit buses since 1988. Starting from 1992, twelve trolley buses equipped with MDS were used in the Swiss City Basel.

The company 'Proton Motor fuel cell GmbH' also integrated MDS in a fuel cell bus.

A representative for a fixed mounted storage but also coupled in series with an electric machine is the product 'Dynastor' from the neighbored company Compact Dynamics GmbH, Starnberg, Germany. This storage is observed more detailled in chapter 3.3.

A fixed mounted storage coupled with a CVT is developed for instance by a corporation of three companies in response to the new 2009 formula 1 regimentations *(FIA, 2006)* where kinetic energy recovery systems (KERS) are permitted. Also commercial systems are planed: The motor sport company Flybrid systems LLP, Silverstone, UK is developing the kinetic storage which is coupled with a CVT developed by Xtrac Limited, Thatcham, UK. *(X-trac Limited, 2008)* Xtrac is licensed to integrate and enhance the CVT with a small ancillary transmission called 'toroidal variator' from Torotrak plc, Leyland, UK . The toroidal variator is an 'infinitely variable transmission' (IVT) because of the range of its ratio, which is not provided by a system of gears with stepped ratio, as found in a common CVT, but by a variator which consists of a set of discs and rollers for a full range of ratio. This is essential regarding charging and discharging the storage. Moreover there is no torque limitation. *(Torotrak plc, 2008)* Details about the connection of the flywheel with the IVT were not yet available when consulting the respective companies' websites. However, it was stated that it should be a direct mechanical one. Charging and discharging is managed by the IVT by changing the transmission ratio. Furthermore the number of flywheels of the fixed installation to overcome gyroscopic forces was not yet clear. Flybrid has filed various British technical patents (application number GB0709085.5 'High speed flywheel' - lodged 11 May 2007, GB0709456.8 'High speed flywheel containment' - lodged 17 May 2007, GB0708665.5 'High speed flywheel seal' - lodged: 04 May 2007) but patents are pending. On Flybrid's homepage it is announced that the flywheel is made of high-strength steel and composite material and runs in a vacuum. Engineering efforts "*would be focused on the transmission system and the bearings*" *(Flybrid Systems LLP, 2007).*

Another manufacturer working on a KERS for Formula 1 is Zytek Group Ltd, Fradley UK (www.zytekgroup.co.uk). Zytek won a two year contract to develop and supply Kinetic Energy Recovery Systems for the 2009 season *(Zytek Group Ltd, 2007)*.

Together with the Imperial College London, Department of Mechanical Engineering, UK the Californian company HyKinesys Inc, (www.hykinesys.com) is developing KERS for the use in both Formula 1 and commercial cars *(Ellis, Pullen, 2006)*. Like the Xtrac-Torotrac-Flybrid system the axis of the kinetic storage is fixed and coupled with an IVT, which was invented and patented by one of the company's associate (British Patent in force, patent number GB2405129 (GB0318765.5), Christopher W. H. Ellis, 11 Aug 2003, Kinetic Energy Storage System, Infinitely Variable Transmission). The composite material of the flywheel is carbon fiber epoxy. The couple between flywheel and transmission is a magnet-fluid one.

American Flywheel Systems – Trinity (AFS-Trinity Inc.), Livermore, California, USA (www.afstrinitypower.com) - a company specialized on uninterruptible power sources (UPS) - also announced on its website to intend developing KERS for Formula 1. However, in the company's new business field of commercial hybrid car development, in their design study 'XH (extreme hybrid) -150' they decided to use supercapacitors *(see chapter 2.5)* instead of a kinetic energy storage *(AFS-Trinity, 2008)*.

There also exist a large number of manufactures of flywheels designed for applications of uninterruptible power supplies (UPS) which may detect the emerging automotive market as attractive to enter it in the next future. Referring to this, it has to be mentioned that flywheels as UPS differ essentially from such made for automotive applications regarding complexity and cost (compare Brown, Parker, 2003): In first line, UPS systems use superconductive magnetic bearings to minimize friction what demands cooled superconductive materials and therefore a refrigeration system. Efforts are made to use high temperature super conductive

(HTSC) bearings. Purchasing cost vary from \$100/kW to \$300/kW. The lower end of the range represents larger and/or lower rpm models, while smaller and/or higher rpm models will have higher per kW costs. Installation is relatively simple and inexpensive, typically running about \$20/kW to \$40/kW, including an allowance for electrical connections for US citizens. *(Brown, Parker, 2003)*

The following list provides a brief overview of UPS manufacturing companies:

Active Power Inc.
Austin, Texas, USA
www.activepower.com
Product: Flywheel-based UPS; direct current (DC) flywheel energy storage

AFS Trinity Power Corporation
Livermore, California, USA
www.afstrinitypower.com
Product: DC flywheel energy storage

Beacon Power Corporation
Wilmington, Massachusetts, USA
www.beaconpower.com
Product: DC flywheel energy storage, Flywheel-based UPS

Caterpillar, Inc.
St.Peoria, Illinois, USA
www.CAT-ElectricPower.com
Product: Flywheel-based UPS

EATON Powerware
Rd.Raleigh, North Carolina, USA
www.powerware.com
Product: Flywheel-based UPS; DC flywheel energy storage

Flywheel Energy Systems, Inc.
Nepean, Ontario, Canada
www.magma.ca/~fesi
Product: DC flywheel energy storage

GE Digital Energy
Atlanta, Georgia, USA
www.gedigitalenergy.com
Product: Flywheel-based UPS with generator

Optimal Energy Systems
Torrance, California, USA
www.optimalenergysystems.com
Products: Flywheel-based UPS; DC flywheel energy storage

Pentadyne Power Corporation
Chatsworth, California, USA
www.pentadyne.com
Product: DC flywheel energy storage

Piller Power Systems GmbH
Osterode, Germany
www.piller.com
Product: DC flywheel energy storage, Flywheel-based UPS, Flywheel-based UPS with generator

Powercorp
Berrimah NT, Australia
www.pcorp.com.au
Product: high speed flywheel, wind/diesel automation marketing containerized flywheel

Precise Power Corporation
Bradenton, Florida, USA
www.precisepwr.com
Product: Flywheel-based UPS

Regenerative Power and Motion
www.rpm2.8k.com
Product: DC flywheel energy storage

SatCon Power Systems
Burlington, Ontario, Canada
www.satcon.com
Product: Flywheel-based UPS with generator

Tribology Systems
Warminster, Pennsylvania, USA
www.tribologysystems.com/
Product: solid-lubricated bearing technology

Urenco Power Technologies
Washington DC, USA
www.uptenergy.com
Product: DC flywheel energy storage

Vycon
Yorba Linda, California, USA
www.vyconenergy.com
Product: durable high-speed flywheel systems

2.3.2 Hydraulic storages

Conventional hydraulic storages, also just referred to as accumulators *(Meyers Lexikonverlag, 2007c)*, are used for leakage compensation, energy storage and damping in hydraulic systems *(compare EATON Hydraulics Operations, 2007)*.

In vehicles, which are already equipped with a hydraulic system as for instance trucks, tractors or generally heavy duty applicatins, the conventional system may be enhanced to a hybrid system enabling start-stop, regenerative braking or regenerative energy recovery from lifting *(Anonymous, 2006)*. In the USA, these efforts are supported by the '21st century truck partnership' within the D.O.E's vehicle and fuel program *(Anonymous, 2006)*. EATON, Cleveland, Ohio, USA as a partner of this program offers hydraulic systems for start-stop applications or for series-hybrids *(EATON, 2007)*.

Due to the considerably high fraction of freight and heavy duty vehicles on total oil consumption of the transport sector *(Anonymous, 2006)*, the degree of potential energy savings when using hydraulic storage systems might be high. Detailed investigations of hydraulic systems would go beyond the scope of this work which deals primary with hybrid electric systems. Therefore, only basics of hydraulic storages are discussed in this work.

Generally, common accumulators are hydro-pneumatic ones as the bladder-, the diaphragm- and the piston accumulator *(EATON Hydraulics Operations, 2007)*. They store energy in form of oil under pressure. Due to the, as generally known, extreme low compressibility of hydraulic oil (almost incompressibility of fluids), it can't store much energy itself. Therefore, energy is stored by compressing inert gas (in most cases nitrogen), which is stored in a bladder (bladder-type, Figure 2.3), in the space between a diaphragm and the shell (diaphragm type, Figure 2.4) or between a sealed piston and the shell of the accumulator. (piston type, Figure 2.5) *(EATON Hydraulics Operations, 2007)*.

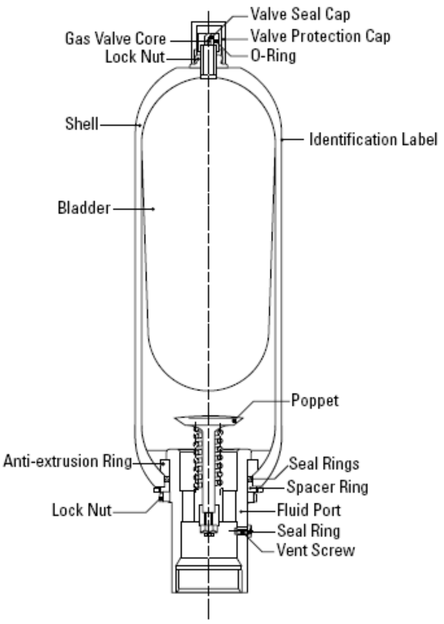


Figure 2.3 Bladder accumulator
(Source: EATON Hydraulics Operations, 2007)

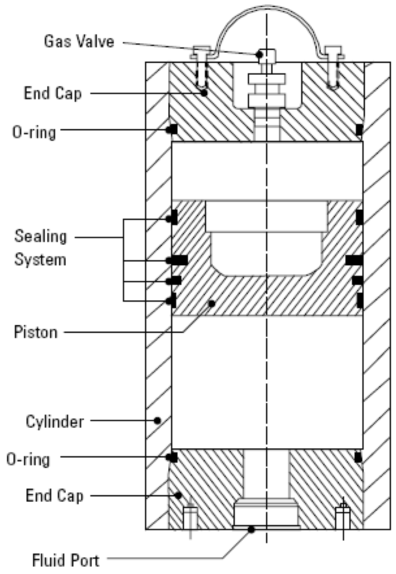


Figure 2.4 Piston accumulator
(Source: EATON Hydraulics Operations, 2007)

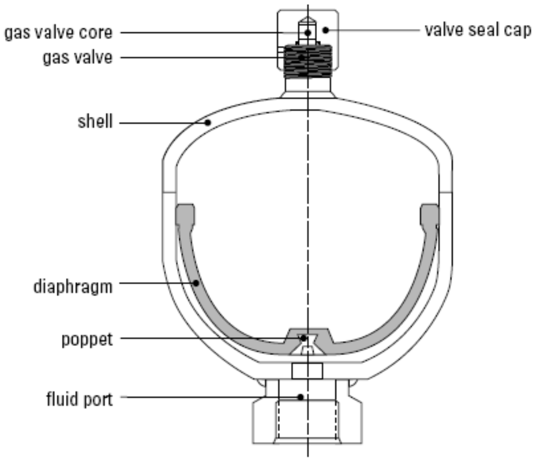
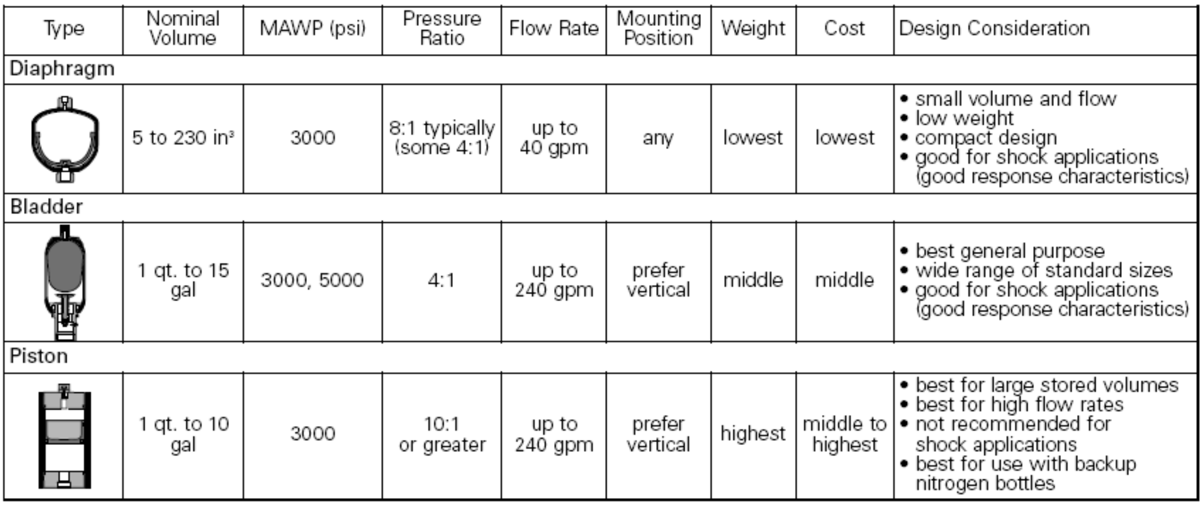


Figure 2.5 Diaphragma accumulator (Source: EATON Hydraulics Operations, 2007)

Characteristics of these three types are summarized in Table 2.1.



Type	Nominal Volume	MAWP (psi)	Pressure Ratio	Flow Rate	Mounting Position	Weight	Cost	Design Consideration
Diaphragm								
	5 to 230 in³	3000	8:1 typically (some 4:1)	up to 40 gpm	any	lowest	lowest	• small volume and flow • low weight • compact design • good for shock applications (good response characteristics)
Bladder								
	1 qt. to 15 gal	3000, 5000	4:1	up to 240 gpm	prefer vertical	middle	middle	• best general purpose • wide range of standard sizes • good for shock applications (good response characteristics)
Piston								
	1 qt. to 10 gal	3000	10:1 or greater	up to 240 gpm	prefer vertical	highest	middle to highest	• best for large stored volumes • best for high flow rates • not recommended for shock applications • best for use with backup nitrogen bottles

Table 2.1 Comparison of Standard Accumulators (Source: EATON Hydraulics Operations, 2007)

A disadvantage of these conventional storages when considering ideal gas law is the dependence of pressure on the compression rate of the inert gas (hyperbolic-relation). Thus pressure is not constant during discharge and power gradually decreases. This may be avoided by a variable limiting of pressure.

A non conventional accumulator which almost avoids this effect is the metal below accumulator shown in Figure 2.6 *(Senior Aerospace, 2008)*: In first line pressure results from the tension of a spring when the storage is charged. According to Hooke's Law, force and thus pressure is proportional to the change of the spring's length by the spring rate. The spring rate can be designed low in order to achieve approximately constant pressure. The spring has to be preloaded adequately to attain acceptable pressure from the beginning on *(compare Senior Aerospace, 2008)*.

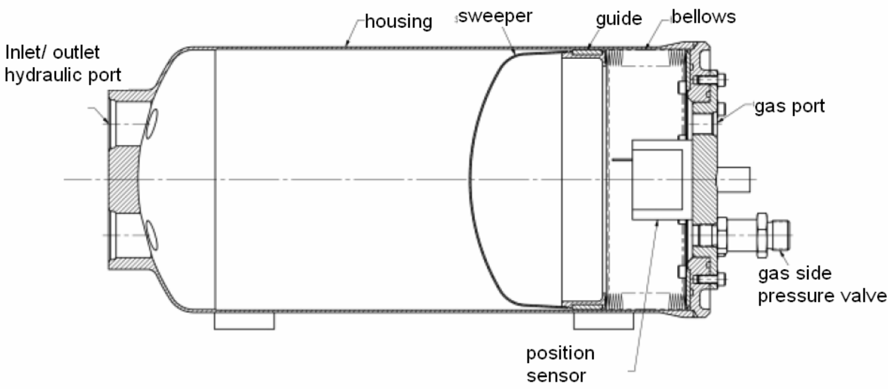


Figure 2.6 metal bellows (source: Senior Aerospace, 2008)

2.3.3 Compressed Air Technology (CAT)

To propel a vehicle, compressed air can be used either in combination with fuels or separate *(MDI, 2008)*:

In the first case, energy needed for propulsion is drawn from the decompression of air and the combustion with fuel (e.g. gasoline or compressed natural gas - CNG).

In the latter case, only the decompression of gas propels a vehicle's engine *(MDI, 2008)*.

Regarding combustion in combination with fuels, air is compressed in order to increase the amount of oxygen enabling more efficient combustion as well as higher peak power *(Geringer, 2005)*. Usually in cars the needed compressed air is delivered by a supercharger driven by the exhaust or directly by the crankshaft *(Geringer, 2005)*. It seems that a need for an energy storage in form of a compressed air tank is not given because air can compressed anytime when it is needed. A case when storing might make sense is to regenerate power by regenerative braking. *(see Anonymous, 2007b)*

Therefore, a mechanically coupled compressor or the engine (as engine brake) *(Anonymous, 2007b)* could be modified to pump air in a tank during braking. Scuderi Group, LLC, West Springfield, Massachusetts, USA (www.scuderigroup.com) developed an engine where a 4 stroke process of an engine's piston is divided on 2 pistons each using a 2-stroke process. *(Anonymous, 2007b)* The principle of this engine is shown in Figure 2.7.

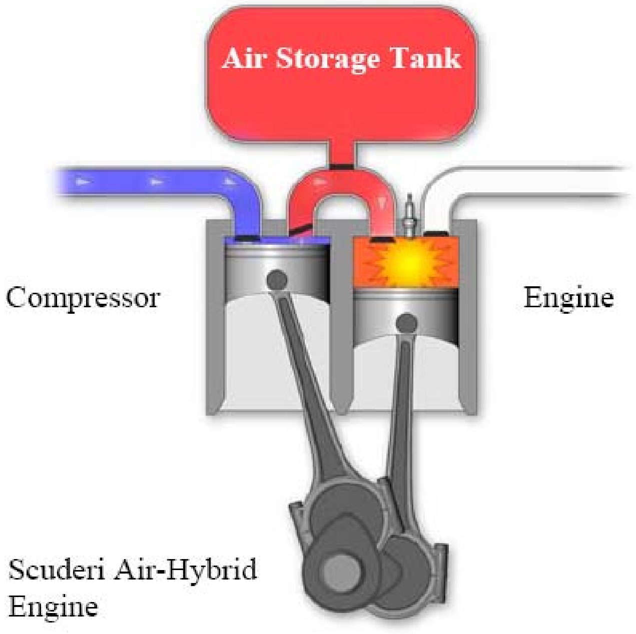


Figure 2.7 Scuderi air-hybrid engine (see Anonymous, 2007b)

The left (cold) piston in Figure 2.7 is considered only for the strokes of suction and compression whereas the right (hot) one is used for the strokes of work and exhaust. Both cylinders are connected by a transfer port. Fuel is injected in the right cylinder. During regenerative breaking the engine is used as motor break pumping sucked air into a tank. When the tank is opened it operates as a supercharger floating the right cylinder with compressed air.

However, success of this engine is limited and present realizations work less efficient than conventional combustion engines. Reasons are low volumetric efficiency in respect to low pump power capability and low thermal efficiency resulting from various problems of charge changing in the right cylinder. *(Scuderi Group LLC, 2008)* Moreover overheating of the right (hot) cylinder, losses of flow in the transfer port or to the storage might cause problems. Cost would be higher due to the double number of pistons and con rods.

The air hybrid engine is not investigated further.

The other possibility - using a conventional supercharger for regenerative braking - is limited. A conventional supercharger as for instance a 'Roots'-charger at an operating point of 70% efficiency, delivers approximately 1000m3/h (EATON, 2008) which equals 556l air in a 2 seconds braking time, but with a pressure ratio of only 1,9.

Assuming an ideal adiabatic reversible (=isentropic) compression, it holds

$$p_1 V_1^{\kappa} = p_2 V_2^{\kappa}$$

whereas index 1 indicates the initial state and index 2 the compressed state. p stands for pressure, V for volume and kappa for the isentropic coefficient. For air, kappa can be assumed with 1,401. Compressed air of 556L in the uncompressed state would still need 351 L in the compressed state. Considering such a low pressure ratio, air is not compressed sufficiently enough because the tank is far too big.

A similar application is to couple the clima compressor of a car to the gearbox during regenerative braking and to store compressed refrigerant in a tank. The latter can be used, when the engine is shut down during a stop/start. However, no documentation about such efforts was found.

Another application of compressed air in order to propel a car is the combination of an air tank and an air engine *(MDI, 2008)*. The air engine is propelled only by the decompression of air, which is stored in a tank. Recent efforts are made by an air car developing company called Motor Development International (MDI), Carros, France (see Figure 2.8). The latter signed an agreement with Tata Motors ltd. *(Tata Motors, 2007)*, Mumbai, India envisaging Tata's supporting for further development and refinement of this technology and granting Tata application and licensing for India.

Figure 2.8 MDI's MiniCat (source: MDI, 2008)

However, it is unclear how to provide an area-wide compressed air infrastructure for 'air cars' in the next future and which energy source should be used to compress air. Range and power may problems, which the air car faces. *(Millikin, 2007a)* Efficiency and ecological considerations are general problems of compressed air technology: Using electricity to compress air, efficiency may suffer from heat generation whereas efficiency of charging batteries, when plugged to the electric grid, is up to 97% at low charge rates (see chapter 3.2.6).

Furthermore, energy density of air is low: Assuming an ideal adiabatic reversible (=isentropic) compression as in previous considerations, work and maximal energy content is determined by

$$\mathrm{W} = \frac{-p_1 V_1}{\kappa - 1}\left[1 - \left(\frac{V_1}{V_2}\right)^{\kappa-1}\right]$$

Index 1 indicates initial state and index 2 compressed state, p stands for pressure, V for volume and kappa for the isentropic coefficient. Concerning air, kappa can be assumed as 1,401. For a given volume of 300l air at 25°C and 1,013 bar ambient pressure with a density of 1,2 kg/m^3 and a compression pressure of 30M Pa (MDI air car tank pressure), *(Air Car Factories S.A., 2008)* and considering that

$$p_1 V_1^{\kappa} = p_2 V_2^{\kappa}$$

approx. 5 liter result for the compressed volume V_2 and work of isentropic compression is approximately 86 Wh. This is equal to an energy density of 16 Wh/l which is less than the half of a Ni-MH battery's energy density.

However, in this work only rechargeable systems are considered. Air engines working as both, motor and recuperating pump where not detected during research of this work. The MDI's air engine only works as motor. *(MDI, 2008)* Therefore, we do not investigate the air propelled car further.

2.4 Thermal storages

During research of this work no thermal storage was found which is capable to propel a car but ancillary components (air conditioning, thermal management system of battery, etc.). Therefore, they are mentioned briefly. Figure 2.9 shows a classification. Boxes with dashed lines refer to groups which were not investigated further. Grey boxes might be appropriate as heat storage for applications in HEV.

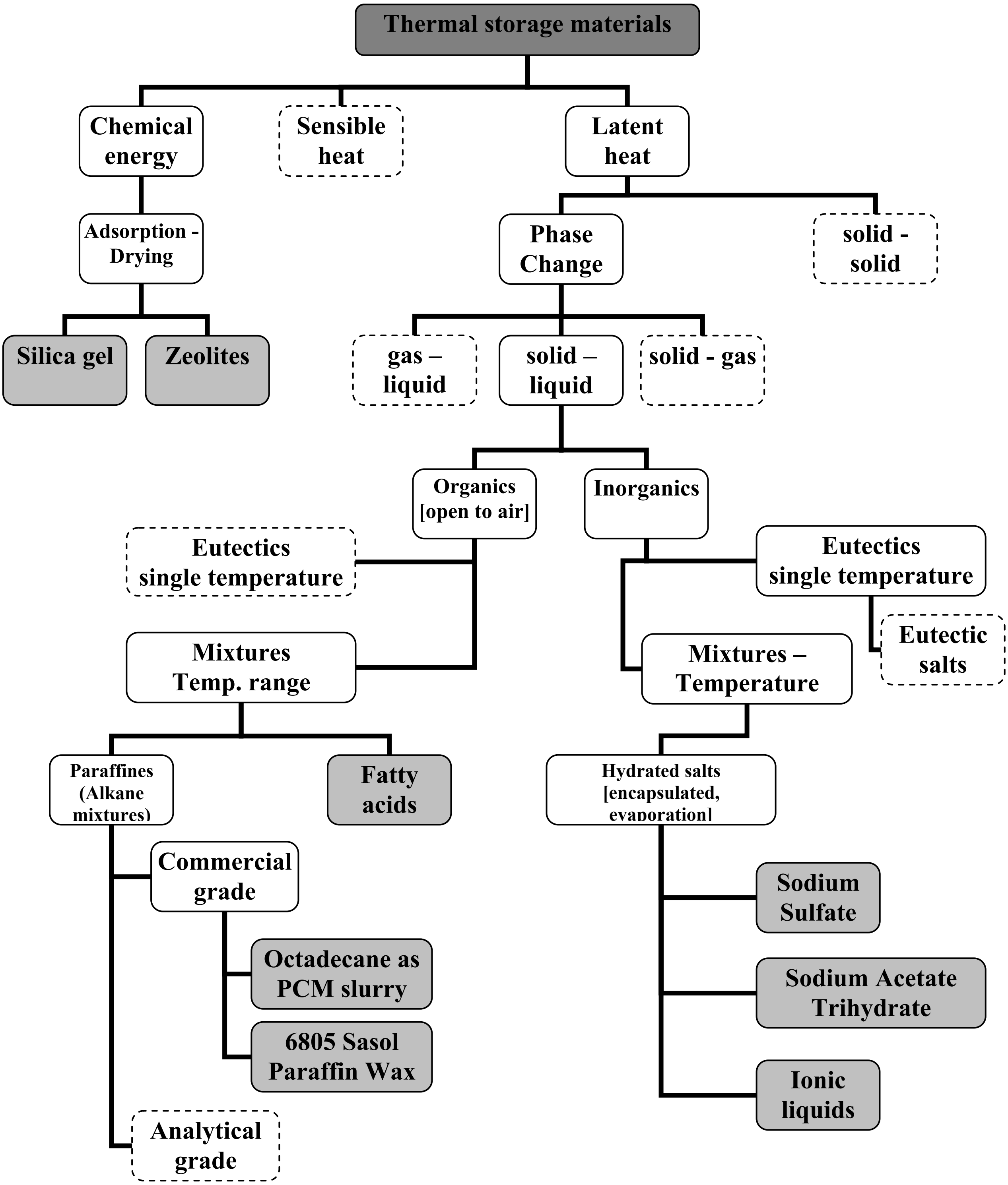


Figure 2.9 thermal storage materials with potential in automotive application (source: based on Heinz, 2007)

The big branch in Figure 2.9 indicted with ‚Phase change' refers to Phase Change Materials (PCM). In a catalytic converter developed by the National Renewable Energy Laboratory (NREL), Golden, CO, USA, PCMs are used to store heat *(Benson et al, 1996)* and hence avoid disfunction due to cool off caused by several engine start-stops of a hybrid vehicle.

2.5 Electrostatic storages

In this group all types of capacitors as conventional ‘electrostatic’ or ‘electrolytic’ capacitors *(Miller, Smith, n.d.)* (e.g. common aluminum electrolytic capacitors) are included as well as supercapacitors. However, the conventional types used in electronics and microelectronics are not discussed in this work whereas supercapacitors (also referred to as ultracapacitors) used in power applications are.

Figure 2.10 shows a classification of supercapacitors distinguishing between *(Burke, 2000)* common carbon Electrochemical Double Layer Capacitors (EDLC), pseudocapacitors and hybrid capacitors. Hybrid capacitors are a combination of battery- and capacitor technology and therefore they do not base on just electrostatic principles *(Burke, 2000)*. However, they are discussed in this group.

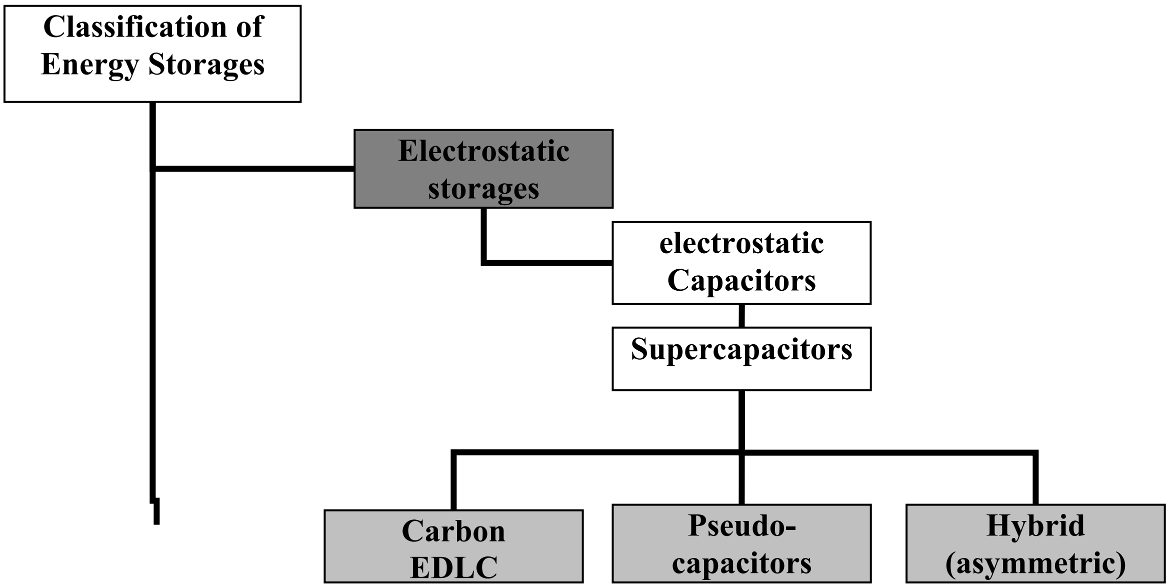


Figure 2.10 Classification of Electrostatic Storages

Supercapacitors differ from conventional capacitors in many aspects: In first line, the energy to power ratio is higher by the factor of 1000 or more (*compare Miller, Smith, n.d., figure 2)*. Specific energy is 10 times higher than that of electrolytic ones and 5 times than that of electrostatic ones *(compare Miller, Smith, n.d., pp. 2-4)*.

In comparison to high pulse batteries (e.g. SAFT VL - series) energy to power ratio is approximately 8 times lower *(compare Miller, Smith, n.d., figure 2)*. For more detailed comparison see chapters 3.3 and 3.4 of this work.

The first patent of supercapacitors is assumed to be from the mid 60s *(Burke, 2000)*. In the beginnings carbon paste in combination with H_2SO_4 in aqueous solution as electrolyte was used. Since today materials changed using high porous carbons, mixed metal oxides or conducting polymers and organic electrolytes *(Burke, 2000), (Miller et al, 2004).*

2.5.1 Carbon Double-layer capacitors

This type is the more common type of supercapacitors presently (2008) available *(compare Table 3.2)*. As shown in Figure 2.11 a carbon EDLC consists of two electrode plates, each connected with a collector and with electrolyte between the plates and a separator dividing them. *(Maxwell, n.d.)*

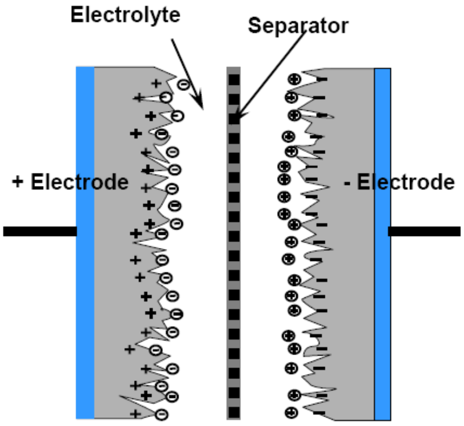
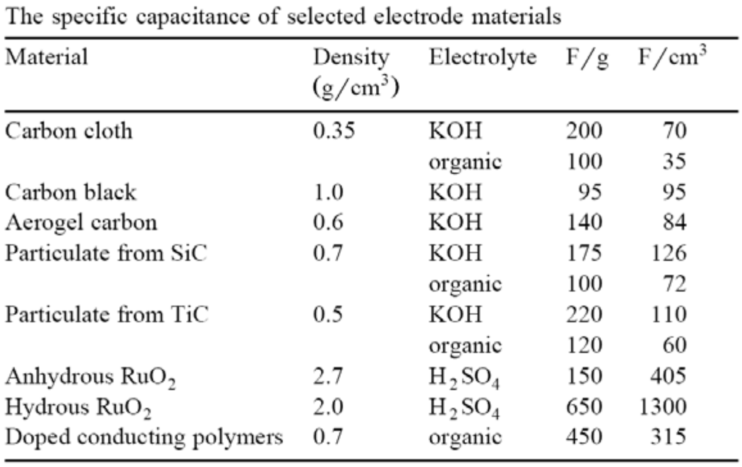


Figure 2.11 schematic sketch of a carbon EDLC (source: Maxwell, n.d.)

Energy is stored electrostatically by polarizing the electrolytic solution when charged. Due to there are no chemical reactions involved in this process it is highly reversible enabling efficient charge and discharge and long life *(Burke, 2000)*. During charge positive ions move to the surface of the negative and negative ions to the surface of the positive electrode. In order to achieve high capacity, the surface area of the activated carbon electrodes should be as high as possible. Resulting from the porous structure, surface areas of about 2000 square meters per gram *(Maxwell, n.d.)* can currently be achieved. The resulting specific capacitance is shown in Table 2.2 in the second-to-last column in [Farad/g] whereas there are differences in using organic or aqueous electrolytes. The last coloumn states values of the volumetric capacitance in [Farad/cm^3].



The specific capacitance of selected electrode materials

Material	Density (g/cm^3)	Electrolyte	F/g	F/cm^3
Carbon cloth	0.35	KOH	200	70
		organic	100	35
Carbon black	1.0	KOH	95	95
Aerogel carbon	0.6	KOH	140	84
Particulate from SiC	0.7	KOH	175	126
		organic	100	72
Particulate from TiC	0.5	KOH	220	110
		organic	120	60
Anhydrous RuO_2	2.7	H_2SO_4	150	405
Hydrous RuO_2	2.0	H_2SO_4	650	1300
Doped conducting polymers	0.7	organic	450	315

Table 2.2 specific capacitance of selected electrode materials (source: Burke, 2000, table 2)

Structures with smaller pores have bigger surface areas and thus higher capacity. However, the pores must be big enough for the ions of the used electrolyte *(Burke, 2000)*.

As electrolytes potassium (K) or sulfuric acid (H2SO4) in aqueous solution *(Burke, 2000)* but more recently ammonium salts in organic solvents *(compare chapter 3.3)* as acetonitrile (AN), propylene carbonate (PC) or dimethyl-carbonate (DMC) are used. The latter is also used for lithium ion batteries *(compare chapter 2.7.17.2.3)*. Acetonitrile offers higher power by reducing electric series resistance (ESR) at low temperatures (e.g. -20°C) but at the expense of using a toxic and flammable material. *(Burke, 2000)* Improvements can already achieved by using AN just as an additive in combination with PC: With the addition of AN the ESR is found to increase by less than a factor of 2 at –40°C compared to a 12 fold increase in PC. *(Miller, Smith, n.d., p.3)* Presently, in most supercapacitors AN is used *(compare chapter 3.3)*.

Cell voltage results from the electrolyte used: for an aqueous one it is about 1 V and for organic electrolytes between 2,5 and 3,5 *(Burke, 2000)*.

Data of commercial carbon EDLC capacitors was collected from Maxwell Technologies, San Diego, California, USA; Nesscap, Yongin-si, Gyeonggi-do, Korea and Nippon Chemi-Con, Tokyo, Japan *(chapter 3.3 and Appendix B)*.

2.5.2 Pseudo-capacitors

In an ideal EDLC no charge transfer reactions (faradic reactions) between the electrode and the electrolyte occur. In pseudo capacitors it is the case. *(Burke, 2000)*

As electrode materials in pseudo-capacitors mixed metal oxide materials as ruthenium and tantalum oxides or surface treated carbons are used *(Burke, 2000)*. Further efforts were made using manganese oxide-based complex metal oxides in an aqueous electrolyte of potassium and sodium salts.

Another way is, as the Los Alamos National Laboratory (LANL) did, to use conducting polymers as poly[3-(parafluorophenyl)thiophene] (PFPT) as the active material in combination with an organic electrolyte (2 Mol Et_4NBF_4 in acetonitrile). *(Burke, 2000)*

Commercial pseudo-capacitors are available for instance from Nippon Chemi-Con, Tokyo, Japan.

2.5.3 Hybrid capacitors

As a combination of battery and capacitor technology, hybrid capacitors employ a conventional carbon EDLC electrode as anode and a battery cathode (compare products of ESMA, Troitsk, Moscow region, Russia, www.esma.com). This configuration is also referred to as asymmetric due to the different electrodes. During charge, electrochemical reactions occur which influence discharge and charge characteristics. In contrast to flat discharge curves (linear voltage – state of charge (SOC) profiles) of conventional carbon EDLCs, the profile is more battery like *(compare Burke, 2000, p.41)*. Hybrid capacitors fill the gap between conventional capacitors and high pulse batteries: They represent a trade-off of advantages and disadvantages of the particular technology as higher life than batteries but smaller than that of capacitors or higher specific energy than conventional capacitors but smaller than that of batteries (see chapter 3.4).

Hybrid capacitors are of recent interest in research and development: Similar to lithium-ion technology efforts are made to employ Ionic Liquids (IL) as electrolyte. *(Arbizzani et al, 2007)* Ionic liquids are more environmentally friendly and have excellent characteristics concerning conductivity. They only consist of ions and no solvent is necessary. *(Mastragostino, Soavi, 2008)* Early forms of ILs were molten salts at high temperatures whereas recent developments are molten at temperatures under 100°C or less.

Commercial hybrid capacitors are available from the Russian company ESMA, Troitsk, Moscow region. Corresponding to the lack of time, these products are not subject of the comparative analysis done later in this work. Much work is underway on this technology *(compare Abbrizzani 2007; Mastragostino, Soavi, 2008; Lazzari et al, 2008)* which also intersects with lithium-ion battery electrolytes. *(compare 2.7.17.2.6)*.

2.6 Chemical storages

Outlining the group of electrochemical storages as an own group, this category mainly includes chemicals oxidized with oxygen in a combustion or in a controlled reaction in fuel cells. Examples are gasoline, Diesel, Raps methyl ether (RME), dimethylether (DME), straight vegetable oil (SVO), methanol, ethanol, liquefied natural gas (LNG), compressed natural gas (CNG) or hydrogen[1]. Considering fuels as not rechargeable storage with exception of hydrogen they will not be investigated further.

For the purpose of comparison with other storages' specific energy, Table 2.3 provides an overview of calorific values of various fuels.

Fuel	Gasoline	Diesel	pure Alcohol (E100)	Fuel oil	Natural gas	Hydrogen	Carbon Monoxid
Calorific value [MJ/kg]	44-48	42,8	25-27	41-44	39 - 82	12	12

Table 2.3 Calorific value of various fuels (sources: MS Encarta Enzyklopädie 2004, 1993-2003; Meyers Lexikonverlag, 2007d)

When considering hydrogen as a rechargeable system for automotive applications, it implicates the combination of a bidirectional energy converter – e.g. a 'reversible or also called combination fuel cell'[2]- and a storage like a tank[3] or hydrogen-absorbing material. A reversible hydrogen fuel cell is able to convert energy saved in form of hydrogen to electricity and backwards.

Recent fuel cells (FCs) differ regarding the operation on various hydrogen rich compounds. As for instance directly methanol processing FCs are called 'direct fuel cells' (direct methanol fuel cell, DMFC) whereas FCs, which operate on hydrogen rich compounds, which have to be

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[1] Hydrogen Center in Graz, Austria: http://www.hycenta.tugraz.at, consulted 2008-02-27

[2] Combination cell, Inventors: Clifford; John E. (Columbus, OH) Assignee: Battelle Memorial Institute (Columbus, OH), United States Patent 4,048,383, Clifford September 13, 1977, Appl. No.: 05/656,659; http://patft.uspto.gov/netacgi/nph-Parser?Sect2=PTO1&Sect2=HITOFF&p=1&u=%2Fnetahtml%2FPTO%2Fsearch-bool.html&r=1&f=G&l=50&d=PALL&RefSrch=yes&Query=PN%2F4048383, consulted 2008-02-28

[3] Hydrogen tank developed by Magna Steyr, Graz, Austria as part of the BMW Clean Energy program, Munich, Germany: http://www.magnasteyr.at/cps/rde/xchg//magna_steyr_internet/hs.xsl/5049_783.php?rdeLocaleAttr=de, consulted 2008-02-28

‘reformed’ to hydrogen before further processing as for instance natural gas are called ‘reformer fuel cells’ or indirect fuel cells. *(see Fuel Cell Europe, 2008)*

However, in this work we focus on rechargeable systems whereas conventional FCs just work in one direction. The nickel-hydrogen battery (chapter 2.7.11) and the metal-hydride fuel cell (chapter 2.7.12) are capable to work in both directions: to generate electricity from chemical energy and the way back to store electrical energy in chemical energy. But these systems differ from other fuel cells because they store hydrogen in the cell itself and thus are discussed as batteries in the next chapter.

Companies supplying reversible FCs could not be evaluated during research of this work.

Hence, it can be concluded that there are no applications for hydrogen fuel tanks[3] which support a rechargeable hydrogen system and thus this type of storage will not be investigated further in this work.

2.7 Electrochemical storages

This chapter primarily bases on information given in *Linden D., Reddy T.B., 2002*.

2.7.1 Categorization

Originally a subgroup of chemical storages, this group represents the broad field of batteries and metal-fuel cells. Electrochemical storages can be distinguished between primary systems (not rechargeable, including reserve systems) and secondary systems.

Reserve batteries, a subgroup of primary batteries, use “*highly active component materials to obtain the required high energy, high power, and/or low-temperature performance, are often designed in a reserve construction to withstand deterioration in storage and to eliminate self-discharge prior to use. These batteries are used primarily to deliver high power for relatively short periods of time after activation in such applications as radiosondes, fuzes, missiles, torpedoes, and other weapon systems. The reserve design is also used for batteries required to meet extremely long or environmentally severe storage requirements.*” *(Linden D., Reddy T.B., 2002, ch. 16)*

A standardization and classification of batteries was done by the International Electrotechnical Commission (IEC). *(Linden D., Reddy T.B., 2002, chapter 22)* In this work only secondary batteries are considered and in particular those as highlited in Figure 2.12.

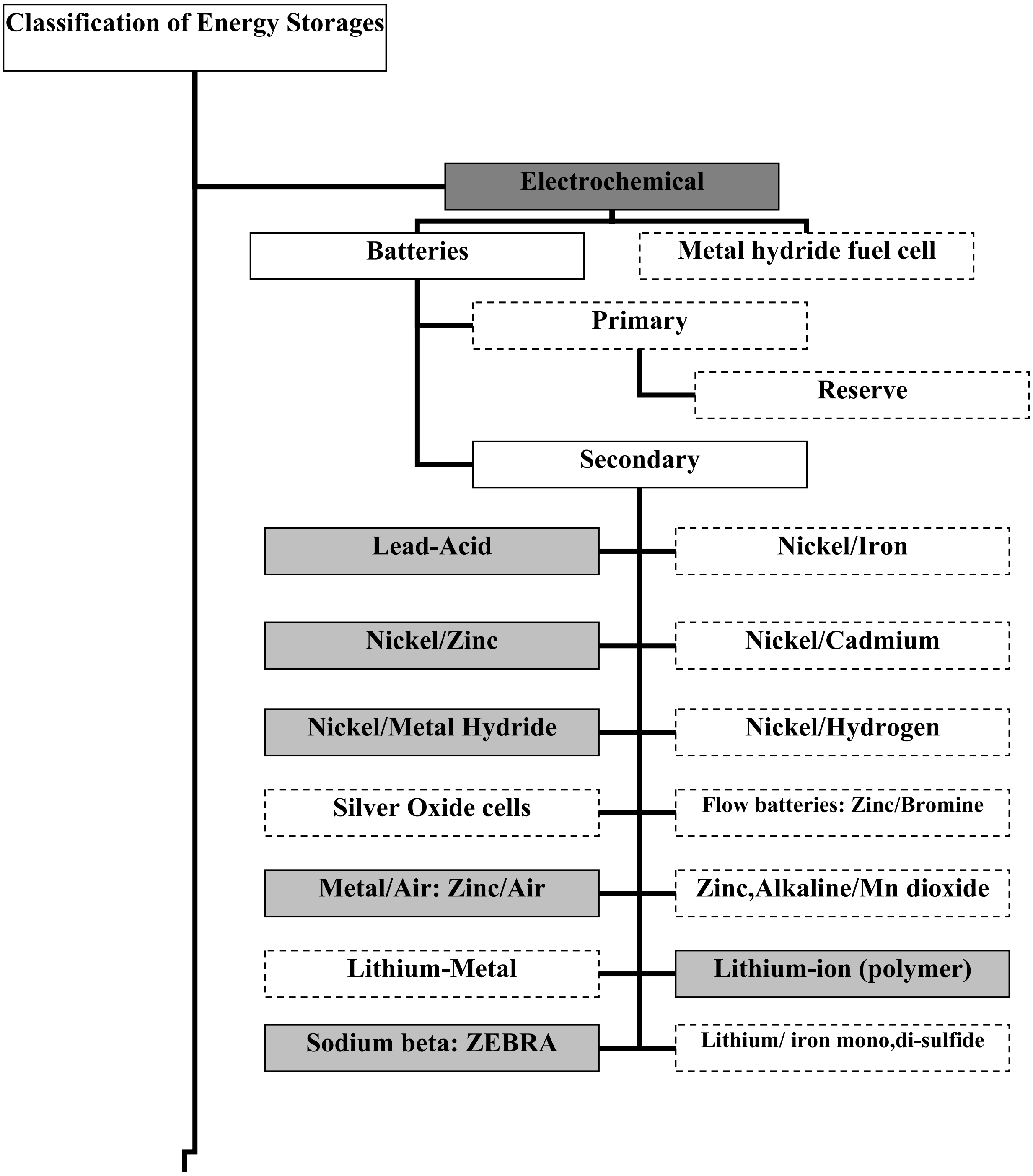

Figure 2.12 Classification of electrochemical storages (compare Linden, Reddy, chapter 22, 2002)

Secondary or rechargeable batteries are widely used in many different applications and thus design and characteristics vary to meet requirements. They can be divided into the group of starting, lighting, ignition (SLI) automotive applications; industrial truck materials-handling equipment and emergency & standby power as uninterruptible power sources (UPS). Small, secondary batteries are also used in increasing numbers to power portable devices such as tools, toys, lighting, and photographic, radio, and more significantly, consumer electronic devices (computers, camcorders, cellular phones). Electric and hybrid electric vehicles form a new field of application. Major development programs have been initiated toward improving the performance of existing battery systems and developing new systems to meet the stringent specifications. *(Linden, Reddy , 2002)*

2.7.2 Standards

Standards for secondary batteries *(Ciliberti, Wicelinski, 2002)* were developed by the Society for Automotive Engineers (SAE), the Battery Council International (BCI) and the Storage Battery Association of Japan as well as by IEC and the American National Standards Institute (ANSI). The recent version of IEC and ANSI is shown in Table 2.4 and Table 2.5. It has to be mentioned that it doesn't cover the entire state of the art of secondary battery technologies.

ANSI System letter	IEC system letter	Negative electrode	Electrolyte	Positive Electrode	Nominal cell Voltage [V]
H	H	Hydrogen absorbing alloy	Alkali metal hydroxide	Nickel oxide	1,2
K	K	Cadmium	Alkali metal hydroxide	Nickel oxide	1,2
P	PB	Lead	Sulfuric acid	Lead oxide	2
I	IC	Carbon	Organic	Lithium cobalt oxide	3,6
I	IN	Carbon	Organic	Lithium nickel oxide	3,6
I	IM		Organic	Lithium manganese oxide	3,6

Table 2.4 ANSI and IEC battery standardization (2002) (source: Ciliberti, Wicelinski, 2002)

Nomenclature	System letter	Shape	Diameter, mm	Height, mm	Terminals
KR 15/51	K*	R**	14,5***	50,5***	CF****
Example: A unit round** battery of the K system* having dimensions shown***, with no connecting tabs****					

Table 2.5 IEC Nomenclature System for Rechargeable Nickel-Cadmium Cells and Batteries (2002) (source: Ciliberti, Wicelinski, 2002)

2.7.3 Principles and structure of secondary batteries

"*A battery is a device that converts the chemical energy contained in its active materials directly into electric energy by means of an electrochemical oxidation-reduction (redox) reaction. In the case of a rechargeable system, the battery is recharged by a reversal of the process. This type of reaction involves the transfer of electrons from one material to another* *through an electric circuit. In a nonelectrochemical redox reaction, such as rusting or burning, the transfer of electrons occurs directly and lonely heat is involved. As the battery electrochemically converts chemical energy into electric energy, it is not subject, as are combustion or heat engine, the limitations of the Carnot cycle dictated by the second law of thermodynamics. Batteries, therefore, are capable of having higher energy conversion efficiencies.*" *(Broadhead, Kuo, 2002)*

While the term 'battery' is often used, the cell is the basic electrochemical unit providing a source of electrical energy by direct conversion of chemical energy. The cell's voltage is restricted by the used electrochemistry. *(Broadhead, Kuo, 2002).*

A battery consists of one or more cells, connected in an appropriate series/ parallel configuration to provide the required operating voltage and current. They include case terminals and markings and may include monitors, controls and other ancillary components. Bigger batteries as for applications in electric or hybrid electric vehicles often include a cooling system *(compare ch. 3.3, Supplier data).* Therefore, several cells are stacked together to 'modules' which are connected with a central cooling system. The modules itself don't have a separately working cooling system. *(see modules of Cobasys, SAFT, ch. 3.3).* They only provide the infrastructure as cooling coils. Several modules form the battery, which then is referred to as a package or battery pack.

The cell consists of an assembly of electrodes, separators, electrolyte, container and terminals. The three major components are defined as the following *(Broadhead, Kuo, 2002)*:

1. The **anode** or negative electrode – "*the reducing or fuel electrode - which gives up electrons to the external circuit and is oxidized during the electrochemical reaction.*"
2. The **cathode** or positive electrode – "*the oxidizing electrode-which accepts electrons from the external circuit and is reduced during the electrochemical reaction.*"
3. The **electrolyte** – "*the ionic conductor- which provides the medium for transfer of charge, as ions, inside the cell between the anode and cathode. The electrolyte is typically a liquid, such as water or other solvents, with dissolved salts, acids or alkalis to impart ionic conductivity. Some batteries use solid electrolytes, which are ionic conductors at the operating temperature of the cell.*"

2.7.3.1 Anode

The anode material *(Broadhead, Kuo, 2002)* should fulfill the following criteria:

- efficiency as a reducing agent
- high Coulombic output (Ah/g)
- good conductivity
- stability
- ease of fabrication
- low cost

An attractive material would be hydrogen, but obviously, it must be contained by some means (as by AB2 and AB5 compounds for Ni-MH batteries) which effectively reduces its electrochemical equivalence.

The lightest metal, lithium, having a high value of electrochemical equivalence, has become a widely used anode material. It is used in combination with carbon in various forms as suitable and compatible electrolytes have been developed to control its activity. Anodes consisting of pure lithium were also available (e.g. Avestor, ceased) but soon were replaced by the carbon-lithium compounds. Pure lithium anodes, referred to as ‘Lithium Metal’ or ‘Lithium Metal Polymer’ tend to be unsafe because of the highly active anode.

2.7.3.2 Cathode

Criteria for cathodes are:

- efficient oxidizing agent
- stable (thermally, in contact with the electrolyte)
- having a useful working voltage

Oxygen can be used directly from ambient air, as for instance in the zinc/air battery. Most of the common cathode materials are metallic oxides, others include halogens and oxyhalides, sulfur and its oxides *(Broadhead, Kuo, 2002).*

2.7.3.3 Electrolyte

Criteria *(Broadhead, Kuo, 2002)* are:

- good ionic conductivity
- not be electronically conductive (this would cause internal short-circuiting)
- nonreactivity with the electrode materials

- little change in properties with change in temperature
- safety in handling
- low cost

Most electrolytes are aqueous solutions, but there are exceptions as, for instance, in thermal and in recently developed lithium-ion batteries, where molten salts (see 2.7.18.1) as ionic liquids and other non aqueous electrolytes are used.

2.7.3.4 Separator

In batteries a separator material is used to separate the anode and cathode electrodes mechanically and isolates the electrodes to prevent internal short-circuiting. However, this material is permeable to the electrolyte and transport of ions. In some cases when the electrolyte is immobilized in a non spill design by e.g. a gel, the gel operates also as seperator. *(Broadhead, Kuo, 2002)*

2.7.4 Design

The cell itself can be built in many different shapes and configurations depending on the particular electrochemistry. Variations of different designs are:

- Button
- Cylindrical
- Flat
- Prismatic

whereas suppliers for conventional automotive SLI favor the prismatic design as well as some suppliers offering systems for HEVs *(see suppliers ch. 3.3: Altair Nanotechnologies, Cobasys, Valence Technology, confidential supplier S9)* in order to increase power and energy density. However, some others *(see SAFT, A123, ch. 3.3)* still favor the cylindric design due to minimize manufacturing cost.

Cells are sealed *(Fehling, 2002)* in a variety of ways to prevent leakage and dry-out. Some cells as lead acid systems are provided with venting devices or other means to allow accumulated gases to escape.

Suitable cases or containers, means for terminal connection and labeling are added to complete the fabrication of the cell and battery.

2.7.5 Electrochemistry

As already mentioned (2.7.3) the principle of a battery is basing on an electrochemical oxidation-reduction reaction (redox reaction) of the active materials of the battery's anode and cathode. The theoretical cell voltage results from the difference of the redox potentials of the anode and cathode active materials *(see Tatsumi, 2007)*. Figure 2.13 shows an overview of the standard potentials of some selected chemical compounds used in battery technology with hydrogen's standard potential set to zero.

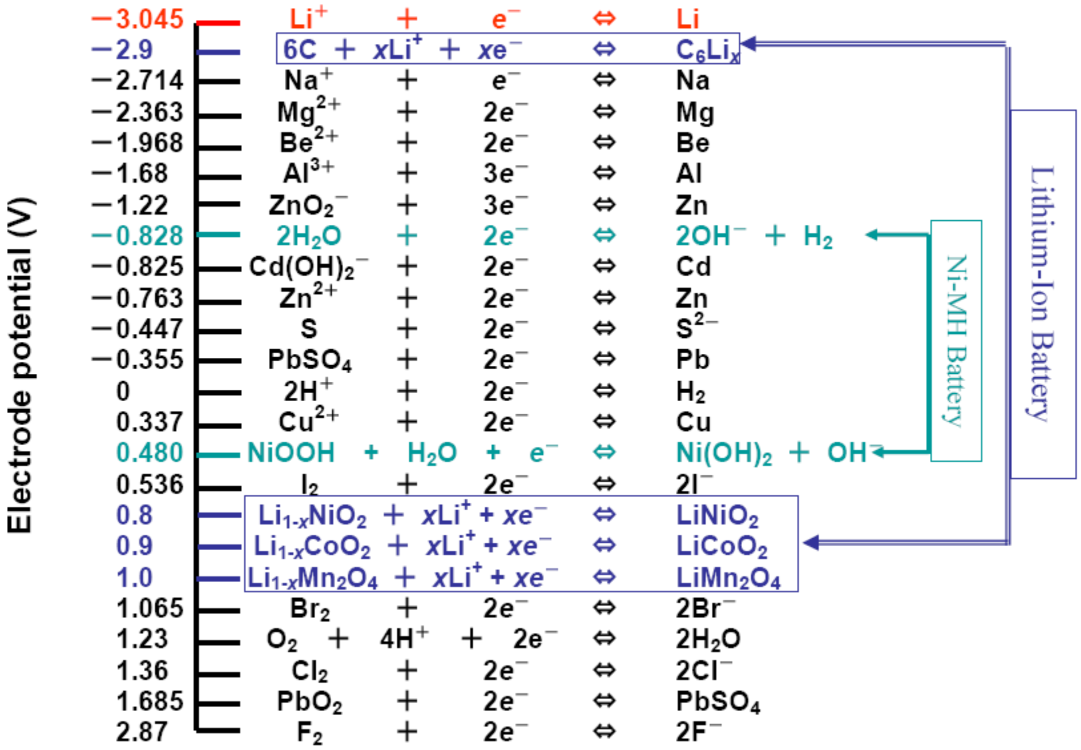

Figure 2.13 Standard potentials of some selected chemical compounds (source: Tatsumi, 2007)

As can be seen the Nickel-Metal hydride (Ni-MH) battery technology for instance is restricted to 1,38 Volt theoretical Voltage. Because design can't meet theory (see ch.2.7.3.1: containment of hydrogen in metal alloys reduces electrochemical equivalence) Ni-MH cells usually achieve nominal voltages of 1,2 Volt.

According to the subsection 2.7.3, different battery technologies are the result of combining different active materials. A list of recently (2008) feasible battery technologies is presented in table Table 2.6 and Table 2.7. The last four battery types represent high temperature batteries.

Battery System	Negative Electrode	Positive Electrode	Electrolyte	Nominal Voltage (V)	Theoretical Specific Energy (Wh/kg)	Practical Specific Energy (Wh/kg)	Practical Energy Density (Wh/L)	Major Issues
Lead-Acid	Pb	PbO_2	H_2SO_4	2,0	252	35 (35)	70 (70)	Low cost, Heavy, Low Cycle Life, Toxic Materials
Nickel Iron (Edison)	Fe	NiOOH	KOH	1,2	314 (313)	30 (45)	55 (60)	Heavy, High Maintenance, low performance, high abuse tolerance
Nickel Zink	Zn	NiOOH	KOH	1,6	372	60 (60)	120 (120)	Low cycle life
Nickel Cadmium	Cd	NiOOH	KOH	1,2	244	35 (50)	100 (75)	Toxic materials, maintenance
Nickel Metal Hydride	(AB2)H or (AB5)H	NiOOH	KOH	1,2	240 (278 – 800) (depends on MH)	75 (70)	240 (170)	Performance dependent on temperature
Nickel Hydrogen	H_2	NiOOH	KOH	1,2	434	55 (55)	60 (60)	Cost, High Pressure Hydrogen, designed for space
Silver Zinc	Zn	AgO	KOH	1,5 (1,9)	524 (524)	105 (100)	180 (180)	Very expensive
Silver Cadmium	Cd	AgO	KOH	1,1	318	70	120	Very expensive
Zinc Bromine	Zn	B2 (B-Complex)	$ZnBr_2$	1,6	572 (450)	70	60	Low Power, hazardous components, bulky
Zinc/ Air, (metal fuel cell)	Zn	O_2	KOH	1,1	1320	110	80	moderate Power, limited cycle life, bulky
Lithium/ manganese (or Zinc or Alkaline) dioxide	Li	MnO_2		3	1001	120	265	Hybrid of primary+secondary

Table 2.6 Overview of recent battery technology (1/2) (based on sources: Linden, Reddy, 2002, p.1.12; terms in gaps: Kopera, 2004)

Battery System	Negative Electrode	Positive Electrode	Electrolyte	Nominal Voltage (V)	Theoretical Specific Energy (Wh/kg)	Practical Specific Energy (Wh/kg)	Practical Energy Density (Wh/L)	Major Issues
Lithium/ CoO2	Li	LixCoO2	PC or DMC w/ LiPF6	4,1 (4,0)	410 (766)	150 (120)	400 (*) (200)	High power+energy, Safety Issues, Calendar Life, Cost
Lithium/ CoO2 (Metal-) Polymer	(Li)/Li-C	LixCoO2	e.g. LiPF6 based					High power+energy, Safety Issues, Calendar Life, Cost
LMO- (Metal-) Polymer	(Li)/Li-C	LiMn2O4	e.g. LiPF6 based					High power+energy, moderate safety, Calendar Life, cost
Lithium/ 'nickel oxide'	C	LiNiO2	e.g. LiPF6 based					High power+energy, moderate safety, Calendar Life, cost
Lithium/ nickel cobalt oxide	C	Li(NiCo)O2	e.g. LiPF6 based					High power+energy, moderate safety, Calendar Life, cost
Lithium/ 'nickel oxide based'	C	LiNiCoAlO 2	e.g. LiPF6 based					High power+energy, moderate safety, Calendar Life, cost
Lithium/ iron phosphate	C	LiFePO4	e.g. LiPF6 based					Moderate power+energy, high safety, Calendar Life, cost
Sodium/ Sulfur	Na	S	Beta Alumina	2.0	792 (792)	170 (**) (100)	345 (**) (>150)	High Temperature Battery, Safety, Low Power densities
Sodium/ Nickel Chloride	Na	NiCl2	Beta Alumina	2,58 (2,5)	787	115 (**) (90)	119 (**) (>150)	High Temperature Battery, Low Power densities
Lithium/ iron disulfide	Li(Al)	FeS2		1,7	493	180 (**)	350 (**)	high temperature battery
Lithium/ iron monosulfide	Li(Al)	FeS		1,3	459	130 (**)	220 (**)	high temperature battery

Table 2.7 Overview of recent battery technology (2/2) (based on sources: Linden, Reddy, 2002, p.1.12; terms in gaps: Kopera, 2004)

2.7.6 Lead-Acid

2.7.6.1 State of the art

The lead acid battery is the most common battery system due to its low price and broad operating temperature range. It dominates the starting-lightning-ignition market (SLI) as well as the market of stationary batteries for UPS applications. Moreover, they are applied as traction or portable batteries. These four types differ in design as well as characteristics. Traction batteries used for fork lifts for instance are commonly larger than SLI batteries and of higher quality. For application as energy storage in HEVs, modified batteries similar to SLI or traction batteries are imaginable. *(Hammel, Salkind, 2002)*

Lead acid technology was developed in the late 19th century whereas the main principle remained the same. Lead (anode) and lead-oxide (cathode) plates are used in combination with sulfuric acid as electrolyte. To raise rigidity and to reduce corrosion, the lead plates are alloyed with antimony. However antimony leads to water decomposition and to oxygen formation why calcium or calcium and tin is used instead of antimony to reduce decomposition to a certain degree. Evolved hydrogen gas increases the pressure in the cell and in turn has to leave it, when pressure is high. In sealed systems this leads to a loss of electrolyte and thus, gradually damages the cell. In flooded systems, water has to be refilled. *(Heinemann, 2007)*

Cell reactions can be written as:

anode reaction: $Pb + HSO4- \leftrightarrow PbSO4 + H+ + 2\cdot e-$
cathode reaction: $PbO2 + HSO4- + 3\cdot H+ + 2\cdot e- \leftrightarrow PbSO4 + 2\cdot H2O$
net reaction: $Pb + PbO2 + 2H2SO4 \leftrightarrow 2\ PbSO4 + 2H2O$
← Charge, → Discharge
2V cell voltage

Lead acid batteries can be categorized as following *(Hammel, Salkind, 2002)*:

- Flooded/wet lead acid batteries (not discussed)
- Valve Regulated Lead Acid batteries (VRLA):
  - AGM (Absorbed Glass Mat batteries) -type
  - gel - type
  - (carbon foam lead-acid, in development)

VRLA-batteries are also referred to as maintenance free and sealed lead acid (SLA) batteries in contrast to flooded systems. They can be constructed in spiral wounded cells (maintain higher internal pressure *(Hammel, Salkind, 2002)*) as well as in prismatic design. Usually they are bigger sized but also small size fabrication is possible with e.g. thin metal film (TMF) technology[4].

The containment of lead acid batteries is plastic.

Both types of VRLA batteries use a limited amount of electrolyte whereas in the batteries of the Absorbed Glass Mat (AGM) type, the electrolyte is absorbed completely in the separator of the battery, which is made of a highly porous and absorbent mat fabricated from micro glass fibers. Therefore, the mat acts as both, as the separator and as an electrolyte reservoir. *(Hammel, Salkind, 2002)*

In contrast to AGM, in gel-type batteries the electrolyte is immobilized in a gel. Fumed silica is added to the electrolyte, resulting in hardening of the electrolyte into a gel. On the first charges, water is lost and the gel dries until cracks occur, opening the hardened gel to provide oxygen recombination reaction. Thus this can be seen as a positive effect on aging *(Heinemann, 2007)*.

AGM technology was developed later than gel-technology but both are still common. The advantage of both types is to be able to operate in different orientations (except when charged) because spillage of the electrolyte is avoided by a high extend. *(Hammel, Salkind, 2002)*

Other advantages are relatively higher safety regarding electric abuse. As nickel-metal hydride batteries, cells do not have to be balanced as in contrast to lithium-ion to avoid thermal runaway when overcharged. A battery management unit of lead-acid batteries monitoring voltage, current and temperature of the battery is also simpler than that of a Ni-MH battery system. *(Heinemann, 2007)*

2.7.6.2 Research and further development

Firefly Energy Inc., Peoria, Illinois, USA – a spin off from Caterpillar, Peoria, Illinois, USA – developed new electrodes for use in theoretically every lead acid battery type. *(Firefly Energy, 2006)* The company offers a battery which is an AGM-VRLA battery. Instead of conventional lead and lead-oxide electrodes much of the electrode material could be replaced by a high surface area non corrodible and light weight carbon foam material, which in turn is impregnated with slurry of lead oxides. In earlier realizations *(Firefly Energy, 2006)*, the

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[4] developed by Bolder Technologies, subsidiary of Gold Peak Batteries, Hong Kong, China
http://www.boldertmf.com/

company already delivered battery systems using a graphite foam electrode as anode to the U.S. military. Compared to conventional systems weight and volume, respectively could be reduced to 20 to 40%, low temperature performance at -20°C of 65% of power at room temperature and specific energy of 38 Wh/kg. The US department of defense (DOD) sponsored further development. Currently, in new series (available summer 2008) both electrodes are modified and consist of the carbon foam material. According to the company characteristics of the new series are comparable to those of Ni-MH and Li-ion systems, but at a tremendous lower price. *(Firefly Energy, 2006)*

Other efforts are made to combine lead acid batteries and ultracapacitors. Hence, it can be benefited from the battery's energy content and from the supercapacitor's peak power performance and cycle life:

Furukawa Battery CO. LTD., Yokohama City, Japan produced the prototype 'Ultrabattery' as a subcontractor of the Australian Commonwealth Scientific and Research Organization (CSIRO). *(Furukawa et al, 2007)* It consists of an asymmetric capacitor and a lead-acid battery in one unit cell. It was tested in a 144V system of a Honda Insight HEV showing four times longer cycle life than conventional VRLA batteries and equivalent performance to Ni-MH packs.

2.7.7 Nickel/ Iron

Nickel iron *(Bayles et al, 2002)* is presently the most common representative for iron electrode batteries. Nickel iron cells have been used since the turn of the 19th to the 20th century and in many applications general design remained the same. Efforts have been made in the advanced nickel iron technology. However, Nickel Iron is not subject of further discussions in this work concerning application in hybrid vehicles because performance characteristics are too low. A short illustration of characteristics is given in Table 2.8 and advantages and disadvantages are mentioned.

Specific power (30sec average at 50% (SOC))	100 W/kg
Specific energy	55 Wh/kg
Specific power (30sec average at 50% (SOC))	110 Wh/l
Cycle life	> 900 cycles
Westinghouse nickel iron battery 1991, 210 Ah nominal capacity	

Table 2.8 Characteristics of Nickel/Iron batteries
(source: Bayles et al, p.25.14, table 25.4, 2002)

Advantages of this technology are the rugged physical structure which is nearly indestructible and the ability to withstand electric abuse. High cycle life at deep discharges is possible. Manufacturing costs are low and high volume production by sintering fiber-metal-plaques (steel wool) is possible. *(Bayles et al, 2002)*

Disadvantages are a low power and energy content regarding mass und volume as well as poor low temperature performance, high self discharge, hydrogen evolution on charge and discharge and even lower cell voltage as Ni-MH batteries. Moreover batteries are damaged by high temperatures. Average price is higher compared to lead acid batteries. *(Bayles et al, 2002)*

2.7.8 Nickel Zinc

Nickel Zinc batteries are a low cost option for a long cycle life alkaline rechargeable system *(Coates, Charkley, 2002)*. The technology emerged at the beginning of the 20th century. A battery consists of the nickel/ nickel oxide – cathode also used in nickel-cadmium cells and the zinc/ zinc oxide anode which is known for its high specific energy. General advantages are a fast recharge capability in comparison to lead acid batteries, good cycle life, low environmental impact and abundant raw materials. Although cost per Wh is relatively low, price is higher than lead acid systems on average. *(Coates, Charkley, 2002)*

Problems using Nickel-Zinc batteries in the past were dendrite formation and shape change of the zinc electrode during cycling *(PowerGenix, 2008)*. A dendrite is a spiny outgrowth of the zinc surface that may lead to premature cell failure by creating an electronic short circuit between the positive and negative electrodes. Dendrites are formed as zinc metal re-deposited during the recharge of the zinc electrode *(PowerGenix, 2008)*. Using both a patented electrolyte and a patented electrode composition, the company PowerGenix, San Diego, California (www.powergenix.com) has eliminated these issues. Furthermore in the new cells high discharge rate capabilities with power pulses to 0,9 kWh were achieved *(PowerGenix, 2008)*.

"*Dendrite formation and shape change of the zinc electrode have been the primary hindrances to a commercially viable rechargeable Ni-Zn battery*" states PowerGenix (2008) on their website.

Nowadays Nickel-Zink systems are competitive to other Nickel systems as Nickel-Metal hydride and Nickel Cadmium. Especially the higher nominal voltage of 1,6 in contrast to 1,2 Volt of Ni-MH and Ni-Cd makes them more attractive. *(Coates, Charkley, 2002)* Regarding most specifications they are better than lead acid systems except of low temperature performance *(compare 3.3 and Appendix B).*

Examples of applications of Ni-Zn systems are the predominantly Asian market of electric bicycles and electric scooters as well as electric wheelchairs, golf carts, electric lawnmowers, electric and hybrid vehicles or other deep cycle applications *(Coates, Charkley, 2002).*

Most electric bicycles and scooters equipped with Ni-Zn batteries have system voltages of 24 or 48 Volt with capacities of 10 to 40Ah resulting in a range of 15 km at minimum up to 30km/hour for electric bicycles and 80 km for scooters at a maximum speed up to 80 km/h. *(Coates, Charkley, 2002)*

Although nickel zinc is not traded on a mass market *(Coates, Charkley, 2002)* during research in this work it turned out that it has potential for future motive applications and thus is subject for further considerations. Products of three different companies were studied in the later part of this work (see 3.3 and Appendix B).

2.7.9 Nickel Cadmium

According to the 'Directive 2006/66/EC' of the European parliament and of the 'Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators' and repealing directive '91/157/EEC Nickel cadmium batteries' the "*placing on the market of cadmium batteries is prohibited with exceptions*" *(Directive 2006/66/EC)*:

"*In order to achieve its environmental aims, this Directive prohibits the placing on the market of certain batteries and accumulators containing mercury or cadmium. It also promotes a high level of collection and recycling of waste batteries and accumulators and improved environmental performance of all operators involved in the life cycle of batteries and accumulators, e.g. producers, distributors and end-users and, in particular, those operators directly involved in the treatment and recycling of waste batteries and accumulators.*" … *(Directive 2006/66/EC, Paragraph (5))*

"Automotive and industrial batteries and accumulators used in vehicles should meet the requirements of Directive 2000/53/EC, in particular Article 4 thereof. Therefore the use of cadmium in industrial batteries and accumulators for electrical vehicles should be prohibited, unless they can benefit from an exemption on the basis of Annex II to that Directive." (Directive 2006/66/EC, Paragraph (30))

In the United States when purchasing nickel-cadmium batteries a fee is included to the price for a proper disposal. *(42 U.S.C 14301-14336 Act)*

Regarding these restrictions Nickel cadmium battery technology is not discussed further in this work.

2.7.10 Nickel Metal Hydride

The nickel metal hydride battery is presently one of the most common battery technologies (compare Table 3.3) used in several different applications as consumer products, portable devices, aircraft and military auxiliary power systems (APU) but also in hybrid vehicles (Toyota, GM, etc.) or Electric Vehicles (EV). Nevertheless the biggest market is the conventional SLI (Start, Light, and Ignition) sector which is still ruled by lead-acid systems. *(Fetchenko, 2002)*

Advantages are to be environmentally acceptable in contrast to nickel cadmium technology, to be recyclable and maintenance free, safe regarding abusive overcharge or discharge under a specified cut off voltage *(Fetchenko, 2002)*. Therefore they do not need a complex battery management unit for cell balancing as Li-ion batteries *(Heinemann, 2007)*. Disadvantages include significant performance dependency on temperature (see Table 2.9) and thus the need of a cooling system *(compare e.g. products of Cobasys, Appendix B)* and moderate memory effect *(Fetchenko, 2002)*.

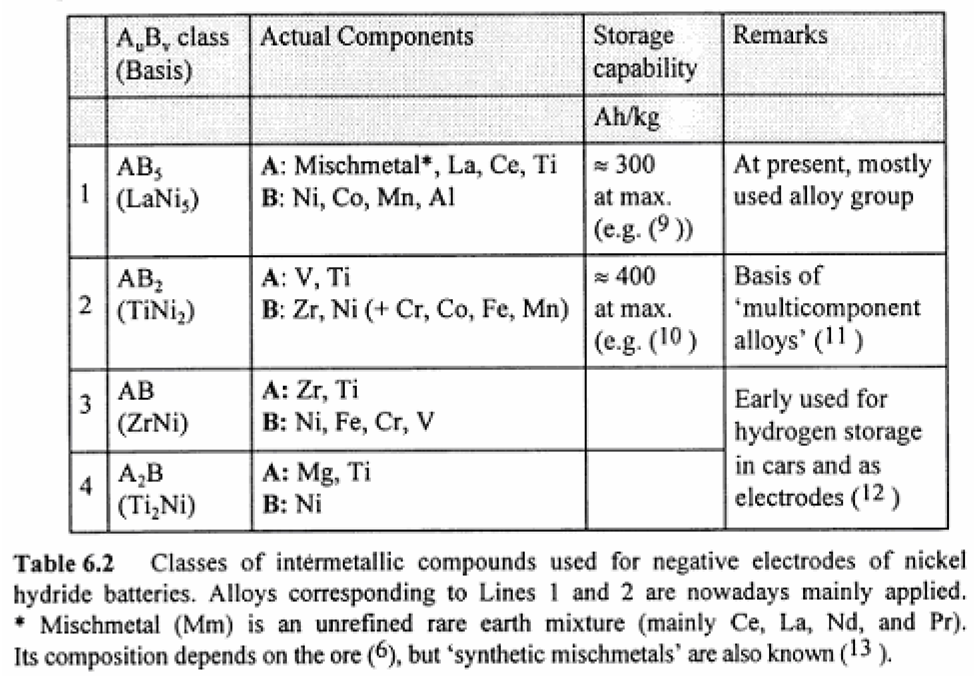
A cell employs a nickel hydroxide cathode as used in other nickel systems as in the nickel cadmium cell and as anode a hydrogen storing intermetallic compound. Hence, the electric materials are nickel hydroxide NiOOH and hydrogen H. The electrolyte consists of an aqueous solution of potassium with an additive of lithium hydroxide (LiOH). The separator is a highly porous „*permanently wettable polypropylene*". (Fetchenko, 2002)

The equations of chemical reactions *(Heinemann, 2007)* can be stated as follows:

Anode reaction: MH + OH- ↔ M + H2O+ e-
Cathode reaction: NiOOH + H2O + 2·e- ↔ Ni(OH)2 + OH-
Net reaction: MH + NiOOH · H2O ↔ M + Ni(OH)2 + H2O
← Charge, → Discharge
1.2 V cell voltage

2.7.10.1 Anode

The anode material has the function to store hydrogen, which is possible by the use of microstructured intermetallic alloys termed as AB_x. “A” represents alloys as for instance LaCePrNd (called “*Mischmetal*”, natural deposit), *(Berndt, 2003, pp.223)* whereas an alloy belonging to group B is for instance VNiCrCoMnAlSn *(Fetchenko, 2002)*. The x refers to the stochiometric ratio between A and B (A/B = 1/x). Common combinations *(Fetchenko, 2002), (Berndt, 2003, pp.223)* of A and B are AB_5 (e.g: LaCePrNdNiCoMnAl), the “*ovonic alloys*” of AB_2 (e.g. VTiZrNiCrCoMnAlSn), AB and A2B. These combinations used in nickel metal hydride battery technology are listed in Table 2.9.



	A_uB_v class (Basis)	Actual Components	Storage capability	Remarks
			Ah/kg	
1	AB_5 ($LaNi_5$)	**A**: Mischmetal*, La, Ce, Ti **B**: Ni, Co, Mn, Al	≈ 300 at max. (e.g. (9))	At present, mostly used alloy group
2	AB_2 ($TiNi_2$)	**A**: V, Ti **B**: Zr, Ni (+ Cr, Co, Fe, Mn)	≈ 400 at max. (e.g. (10)	Basis of ‘multicomponent alloys’ (11)
3	AB (ZrNi)	**A:** Zr, Ti **B:** Ni, Fe, Cr, V		Early used for hydrogen storage in cars and as electrodes (12)
4	A_2B (Ti_2Ni)	**A:** Mg, Ti **B:** Ni		

Table 6.2 Classes of intermetallic compounds used for negative electrodes of nickel hydride batteries. Alloys corresponding to Lines 1 and 2 are nowadays mainly applied. * Mischmetal (Mm) is an unrefined rare earth mixture (mainly Ce, La, Nd, and Pr). Its composition depends on the ore (6), but ‘synthetic mischmetals’ are also known (13).

Table 2.9 Classes of intermetallic compounds used for anodes in Ni-MH systems (source: Berndt, 2003, p.223)

As can be seen also very rare elements as Neodymium (Nd) and Lanthanum (La) are used. Stochiometric examples for used AB_5 alloys are *(Fetchenko, 2002)*:

La5,7Ce8,0Pr0,8nd2,3Ni59,2Co12,2Mn6,8Al5,2 or

La10,5Ce4,3Pr0,5Nd1,3Ni60,1Co12,7Mn5,9Al4,7 and for AB_2 *(Fetchenko., 2002)*:

V18Ti15Zr18Ni29Cr5Co7Mn8

V5Ti9Zr26,7Ni38Cr5Mn16Sn0,3

V5Ti9Zr26,2Ni38Cr3,5Co1,5Mn15,6Al0,4Sn0,8

AB_5 currently is the most used alloy followed by AB_2 despite AB_5 has significantly lower hydrogen storage capacity: AB_2 with 385-450 mAh/g versus AB_5 with 290-320 mAh/g *(Fetchenko., 2002)*. Reasons are lower raw material cost, easier electrode manufacturing and higher discharge rate performance *(Fetchenko., 2002)*, which is essential regarding HEV application.

Regarding electrode manufacturing nickel plated steel but more recently a copper substrate is used instead of pure nickel because of lower cost and higher conductivity. *(Fetchenko., 2002)*

2.7.10.2 Cathode

Presently, there exist two manufacturing processes of nickel hydroxide: Sintered and pasted technology. They differ in the characteristics of the product as well as in the manufacturing process *(Fetchenko., 2002)*.

Sintered cathodes show best power capability corresponding to high rate performance but with lower capacity per weight and volume and thus lower energy content of the cell *(Fetchenko., 2002)*. In turn, manufacturing of sintered cathodes is more complex and needs a significant capital investment for facilities and know-how resulting in higher cost. Thus, pasted technique became more common. As a consequence, research of pasted technology was also more intensive, so that both technologies are approximately at same technological standard *(Fetchenko., 2002)*. Pasted technology uses the advantage to place expertise on the suppliers.

The main differences between the two processes are the fabrication of a nickel skeleton and the addition of nickel hydroxide: chemical/electrochemical impregnation vs. pasting on a polyurethane substrate *(Fetchenko., 2002)*.

Presently a high density spherical type of nickel hydroxide (Ni94Co3Zn3, % ref. to weight) is most common basing on the pasted technique *(Fetchenko., 2002)*.

2.7.10.3 Electrolyte

Usually a concentration of potassium (K) in water of 30% is used. About 17 g of lithium hydroxide is added to one liter water to improve charging efficiency at the nickel hydroxide electrode by suppressing oxygen evolution. The operating temperature range of the system depends on the concentration of potassium in the electrolyte. *(Kopera, 2004)*

2.7.10.4 Separator

Unless nickel-cadmium or nickel-hydrogen systems, which use standard materials, the nickel-metal hydride system uses modified materials. The separator is a highly porous, "*permanently wettable polypropylene*" – a polypropylene/polyethylene composite. *(Fetchenko., 2002)*

2.7.10.5 Construction

Ni-MH cells are completely sealed. Cylindrical cells are contained in metal cans, because the can is used as negative terminal *(Fetchenko., 2002)*. The containment of prismatic batteries can be made of metal as well as of plastic (compare Panasonic EV, chapter 3.3). However, when using plastic, the thickness has to be considered because of gas permeation. Moreover plastic has the advantage to isolate the battery. *(Fetchenko., 2002)*

Due to its high tolerance to overcharge and abusive discharge below a specified cut-off voltage, which prevents too high increase of internal resistance, Ni-MH batteries are well suited to be manufactured in monoblock design. This design is very attractive to reduce cost. *(Fetchenko., 2002)*

2.7.10.6 Characteristics

Generally, specifications of battery systems are discussed later in this work. At this site, only temperature dependency of capacity and power of Ni-MH systems is underlined. Usually at ambient temperatures over 50°C power decreases rapidly as shown in Figure 2.14 on an Cobasys series 1000 module with 8,8 Ah nominal capacity and 12V Voltage *(Cobasys, 2007a)*. Thus thermal management is necessary.

Heading from 50°C to lower temperature, power decreases linear due to a indirect proportional increase of internal resistance. This leads to totally no power at -30°C *(Cobasys,* *2007a)*. This may be a reason why present vehicles equipped with Ni-MH systems need an additional system as for instance a lead acid battery.

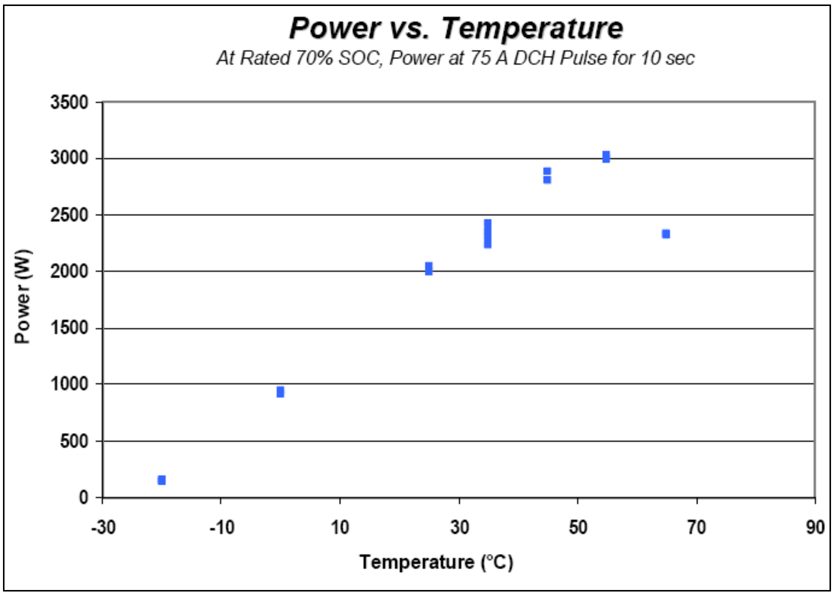


Figure 2.14 Temperature dependency of a Cobasys Series 1000 Ni-MH system (Cobasys, 2007a)

To overcome problems, which emerge over 50°C, current efforts are made using nanomaterials. *(Fetchenko., 2002)*

The list of nickel metal hydride battery producers and suppliers is long *(compare ch. 3.3)*. Regarding HEV application, Panasonic EV Energy Co. Ltd (abbreviated as PEVE), Tokyo, Japan; Cobasys LLC, Orion, Michigan, USA; Johnson Controls (VARTA), Milwaukee, Wisconsin, USA and SAFT, Bagnolet, France are to mention for instance. Later in this work products of these companies are discussed.

2.7.11 Nickel - Hydrogen

The sealed nickel hydrogen (Ni-H2) secondary battery (shown in Figure 2.15) is a hybrid of fuel cell and battery technology. The hydrogen anode comes from the hydrogen-oxygen fuel cell whereas the nickel/ nickel oxide – cathode comes from nickel batteries, e.g. the nickel-cadmium battery. *(Brill et al, 2002)*

Figure 2.15 Mars Global Surveyor nickel-hydrogen battery with 16 Ah (source: NASA Glenn Research Center, 2008)

Almost all its applications are directed toward aerospace (satellites, sondes) but recent fields of research also involve programs in search of terrestrial applications as photovoltaic. *(Brill et al, 2002)*

Programs were initiated by manufacturers like Eagle-Picher Technologies LLC and US Sandia National Laboratories, which sponsored a cost sharing program with COMSAT Laboratories and Johnson Controls, Inc. *(Brill et al, 2002)*

The Advantages of nickel - hydrogen systems are high pulse power, long cycle life (40000 cycles for low-earth-orbit (LEO) applications at 40% DOD) respectively long lifetime (15 years for geosynchronous earth orbit (GEO) applications) and tolerance to overcharge and reversal. *(Brill et al, 2002)*

Disadvantages are high initial cost, self discharge proportional to H_2 pressure and low energy density. *(Brill et al, 2002)*

The nickel-hydrogen battery/fuel cell is interesting in respect of emerging hydrogen technology and fuel cell development *(compare 2.7.12)*. State of the art products are definitely not appropriate for use in commercial hybrid vehicles and thus are not discussed further.

2.7.12 Internally fuel storing fuel cells: Metal hydride fuel cell

The principle of fuel cells and batteries is very similar and sometimes it’s difficult to draw a border in order to distinguish between them. Both operate by electrochemical redox reactions. But in contrast to a battery, a fuel cell’s active material is stored externally (e.g. in a tank) whereas the battery employs active materials which are stored internally in anode and cathode (with exception of flow batteries). *(compare Fuel Cell Europe – World Fuel Cell Council e. V., 2008)* Another main difference is that the system fuel cell+tank can be mechanically recharged just by re-filling fuel.

The metal hydride fuel cells (MHFC) utilize the advantages of both systems: they operate as a rechargeable battery similar to the Ni-MH battery using hydrogen as active anode material but can be as well refilled externally by pure hydrogen like a fuel-cell+tank system. The refilled hydrogen is stored directly in the electrodes. *(ECD ovonics, 2007)* (The direct borohydride fuel cell works similar but is currently not rechargeable and thus is not discussed).

Considering similarities to Ni-MH and Ni-hydrogen batteries it can be concluded that they all follow a common technological trajectory. Thus, efforts made in 'old' Ni-MH technology may contribute to the development of the new and emerging metal hydride fuel cell technology. Therefore it doesn't astonish that experienced Ni-MH battery developers as ECD-Ovonics, Rochester Hills, Michigan, USA (founding member of Cobasys LLC) do detailed research on metal hydride fuel cells. *(see ECD Ovonics, 2007, Ovonic Hydrogen Systems, 2008)*

Presently on the company's website there is no commercial system available yet (2008-02). Besides ECD Ovonics, Japan's National Institute of Advanced Industrial Science and Technology (AIST) is also researching on this cell *(Chen et al, 2002)*.

Concerning hydrogen technology, which is currently often discussed, the MHFC overcomes a major problem - the storage of hydrogen which is a major difficulty and not satisfactorily solved by conventional solutions as by a pressure tank: Corresponding to high volatility of hydrogen, conventional gaskets of pressure storages are not capable to do their job in a motive application and therefore special manufactured storages as for instance the cryo tank of the 'BMW 7 hydrogen' manufactured by Magna Steyr, Graz, Austria are used.[5] Detailed data about hydrogen losses of these storages were not available.

MHFC/ Ni-MH technology utilize hydrogen storing intermetallic foams *(Chen et al, 2002)*, *(chapter 2.7.10)*, which may once can be utilized to overcome these problems. Thus the common technological trajectory of these systems intersects with that of hydrogen technology.

Regarding the use in present HEV the MHFC is not observed further because no commercial available system was found.

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[5] Hydrogen tank developed by Magna Steyr, Graz, Austria as part of the BMW Clean Energy program, Munich, Germany: http://www.magnasteyr.at/cps/rde/xchg//magna_steyr_internet/hs.xsl/5049_783.php?rdeLocaleAttr=de, consulted 2008-02-28

2.7.13 Silver Oxide cells: Silver Zinc, Silver Cadmium, Silver Iron

The first person experimented with secondary silver oxide batteries was Jungner in 1880 in order to propel an electric car *(Megahed et al, 2002)*. However, considering advantages and disadvantages of silver-oxide cells listed in Table 2.10, they all have in common one incremental disadvantage which is the reason why this technology cannot be appropriate for commercial use in hybrid vehicles: high cost.

Advantages	**Silver-Zinc**	**Silver-Cadmium**	**Silver-iron**
High specific energy and high energy density	×	× (60% of silver zinc)	×
High discharge rate capability	×		
moderate charge rate capability	×		
good charge retention	×	×	
stable voltage-profile when discharged	×	×	
low maintenance	×	×	×
low self discharge,	×		
safe	×	×	
Nonmagnetic construction		×	
Overcharge capability			×
Disadvantages			
high cost	×	×	×
relatively low cycle life	×		
decreased performance at low temperatures	×	×	
sensitivity to overcharge	×		
Water and gas management required			×
Not yet proven in field use			×

Table 2.10 advantages and disadvantages of silver oxide cells (source: Megahed et al, 2002)

Considering characteristics as stated above, applications of silver-oxide batteries are lightweight medical and electronic equipment, torpedoes and space applications. They are not investigated further regarding use in hybrid vehicles.

2.7.14 Flow Batteries: Zinc/ Bromine

The zinc/ bromine battery is different from common battery principle. It is referred to as a flow battery because the electrolyte circulates through the cell. *(Butler et al, 2002)*

Other representatives of flow batteries, which aren’t discussed further are the Polysulfide/ bromine (Regenesys), redox batteries as vanadium redox or iron/chrom redox. *(Butler et al, 2002)*

The principle of zinc/bromine is sketched in Figure 2.16: Between a zinc anode and a bromine cathode an aqueous zinc-bromine solution is circulated by pumps. This solution is divided into two regions by a micro porous separator – a cathode near and an anode near region. Therefore the electrolyte can be differed in anolyte and catholyte stored in separate tanks. When charged solved zinc-bromine is decomposed and zinc is electroplated at the positive and bromine is deposited at the negative electrode. The anolyte and catholyte are divided by the separator which impedes diffusion of bromine to the zinc deposit and direct chemical reaction. Thus dendrite formation as observed in other zinc systems is no longer a problem. *(Butler et al, 2002)*

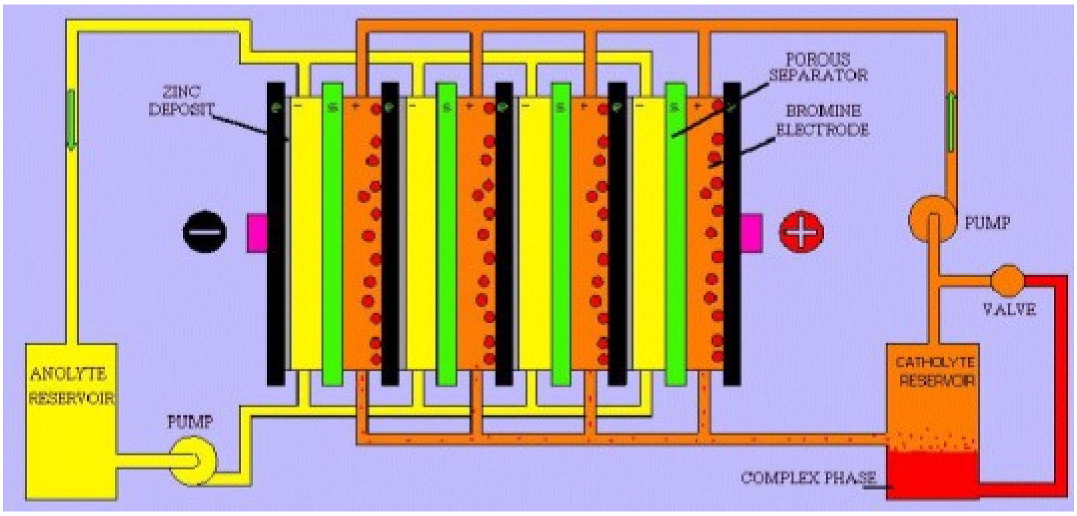

Figure 2.16 Zinc/bromine battery (source: ZBB Energy Corp, 2008)

Zinc/bromine systems were considered for EV. *(Butler et al, 2002)* As for all battery systems, a tradeoff between specific power and specific energy has to be made. Applications possessing high specific power have small sized anolyte and catholyte tanks *(Butler et al, 2002)*.

During research only two suppliers - Powercell GmbH (formerly Studiengesellschaft für Energiespeicher und Antriebssysteme, SEA), Mürzzuschlag, Austria and ZBB Energy Corporation, Menomonee Falls, Wisconsin, USA (www.zbbenergy.com) were detected. The first mentioned company declared bankruptcy[6] whereas the second focuses on UPS systems. Therefore these batteries are not observed further but a brief overview of specifications is given in Table 2.11 to illustrate the actually attractive technology.

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[6] http://members.chello.at/niessler.energie/soli0206.doc

Nominal cell voltage	1,5 V
Specific power	90-110 W/kg
Specific energy	65-75 Wh/kg
Energy density	60-70 Wh/l
Operating temperature	ambient

Table 2.11 Zinc/bromine characteristics (source: Butler et al, 2002)

2.7.15 Metal/Air: Zinc/Air

Metal-air batteries are also referred to as fuel cells because one active material, the air, is not stored in the cell directly but absorbed from the environment when needed. In ‘mechanically rechargeable’ systems also the metal is considered as fuel because it is supposed to be exchanged when the battery is discharged and metal oxidized completely. Then it is substituted by new ‘metal-fuel’ in form of pure metal. *(Atwater, Hamlar, 2002)*

A company producing such mechanically rechargeable systems is Powerzinc Electric, Inc. in Shanghai, China (www.powerzinc.com) using zinc as metal. As applications, electric bicycles, motorcycles, electric taxis and even buses are mentioned *(Powerzinc, 2008)*. Usually, mechanical rechargeable systems were applied to military fields of application *(Atwater, Hamlar, 2002)*. The company also considers a refuel service system retailing zinc similar to gasoline at a petrol station. The total recharge process is shown in Figure 2.17.

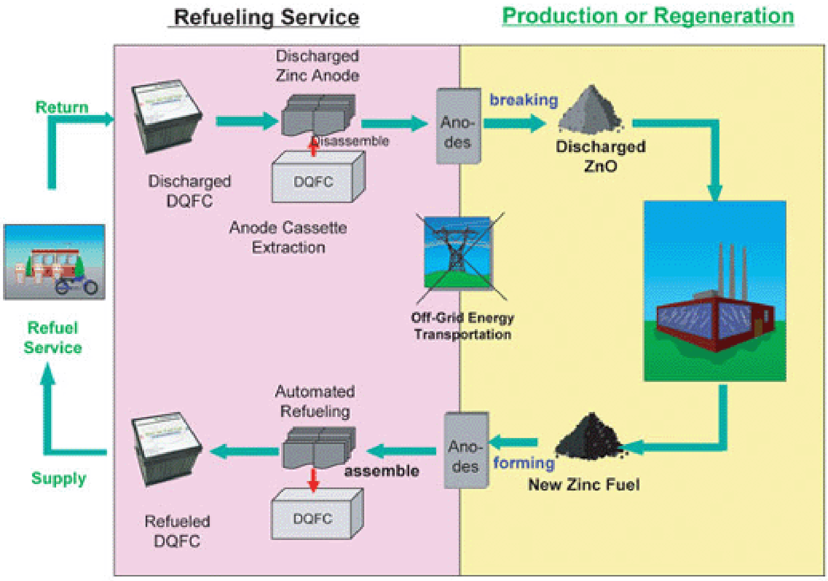


Figure 2.17 Recharge process of a mechanically rechargeable Zinc/air system (source: Powerzinc, 2008)

In this work we will not investigate the mechanical rechargeable concept further.

Regarding rechargeable metal/air systems different metals can be used whereas zinc is assessed as a good choice. It's relatively stable in both aqueous and alkaline electrolytes without significant corrosion despite it's relatively high electropositive. *(Atwater, Hamlar, 2002)*

Generally zinc/air systems have high energy density, cost is low and voltage curve when discharged is flat. However zinc/air systems tend to dry out, power is moderate, operating temperature is limited and hydrogen is generated when charged. *(Atwater, Hamlar, 2002)*

Other systems as Lithium/-, calcium/- magnesium /- or aluminum/air have attractive energy densities but the first three were facing high cost and problems in practical handling what didn't lead to commercial success *(Atwater, Hamlar, 2002)*.

The last mentioned system – aluminum/air was discussed often because aluminum is the third most abundant element on earth which cost is low. However, during charging, considerable amounts of hydrogen is generated and when discharged water is consumed what makes it interesting for marine applications but not for use in land vehicles. Iron air theoretically is also feasible but voltage and specific energy is low. *(Atwater, Hamlar, 2002)*

Problems of dendrite formation of zinc, as mentioned in the nickel-zinc battery and unsatisfactory air electrode performance have slowed progress toward the development of a commercial rechargeable zinc/air battery *(Atwater, Hamlar, 2002)*. During research of this work, no producer of rechargeable zinc/air batteries appropriate to automotive systems was found and thus this technology is not discussed further in this work.

2.7.16 Zinc or Alkaline/ manganese dioxide

These systems are an outgrowth of primary and secondary batteries, sized between AAA and D-size in most cases and are available at low cost. Applications are portable consumer electronics requiring low cycle life. *(Hunter, 2002)*

They are not considered further.

2.7.17 Lithium-Metal, Lithium Ion, Lithium Polymer:

The palette of lithium batteries is broad and it happens easily to mix up different types. The first commercial Lithium system was introduced by Sony in 1990 *(Hossain, Reddy, 2002)*. These batteries were referred to as 'Lithium-Metal' or 'Lithium-Metal Ion' batteries.

In search of more safe systems, lithium-ion (Li-ion) batteries containing no metallic lithium as anode material *(Ehrlich, 2002)* followed. Using a polymer as an electrolyte *(Hossain, Reddy,* *2002)* or an electrolyte absorbing polymer gel, respectively, (Ehrlich, 2002) 'Lithium Polymer'-batteries emerged. Chronologically 'Lithium Polymer technology' represents the end in modifying lithium systems.

Nowadays the expression 'lithium-polymer' refers primary to batteries utilizing an electrolyte absorbing gel *(compare Appendix B)* whereas the original lithium polymer battery is that using a polymer as electrolyte *(Hossain, Reddy, 2002)*. To make a difference the first ones are also referred to lithium-ion-polymer batteries *(see the supplier's designation of products listed in Appendix B)*.

In the next stages, lithium batteries are classified by lithium-metal, lithium-ion and lithium-ion-polymer whereas the latter both are discussed together. Lithium polymer batteries utilizing a polymer as electrolyte are discussed only briefly.

Moreover, the differences regarding active materials, used in cathode and anode, are outlined in order to assess safety of the particular technology.

2.7.17.1 Lithium Metal

'Lithium-Metal-batteries' consist of a lithium metallic anode, which is attractive regarding high energy density and specific energy, enabling high nominal voltage, good charge retention and low self-discharge rate. *(Hossain, Reddy, 2002)* However, lithium metal as anode causes potential safety problems *(Hossain, Reddy, 2002)* and therefore these batteries were displaced widely by 'Lithium ion batteries' using lithiated carbon or transition metal compounds as anode material *(compare Appendix B)*. Moreover, a disadvantage, in comparison to developed 'Lithium ion'-technology, is low cycle life:

"*The difficulties associated with the use of metallic lithium stem from its reactivity with the electrolyte and the changes that occur after repetitive charge-discharge cycling. When lithium is electroplated, during recharge, onto a metallic lithium electrode, it forms a mossy and in some cases a dendritic deposit with a larger surface area than the original metal. While the thermal stability of lithium metal foil in many organic electrolytes is good, with minimal exothermic reaction occurring up to temperatures near the melting point of lithium (181°C), after cycling the surface area of the lithium increases significantly with a corresponding increase in the reactivity. This lowers the thermal stability of the system, with the result that cells become increasingly sensitive to abuse as they are cycled.*" *(Hossain, Reddy, 2002)*

Considering safety issues and the fact, that developed ‘Lithium-Ion’-systems almost substitute Li-metal technology, this work doesn’t focus on ‘Lithium-metal’ (Li-metal) -systems further.

To be able to distinguish between these two close technologies, Li-metal and Li-ion, Figure 2.18 gives an overview of several different Li-metal configurations to outline what is not observed further in this work. Cells of Figure 2.19, with exception of those marked with a rectangle are also not subject of this work. Marked cells represent Li-ion-(polymer)-cells, discussed later.

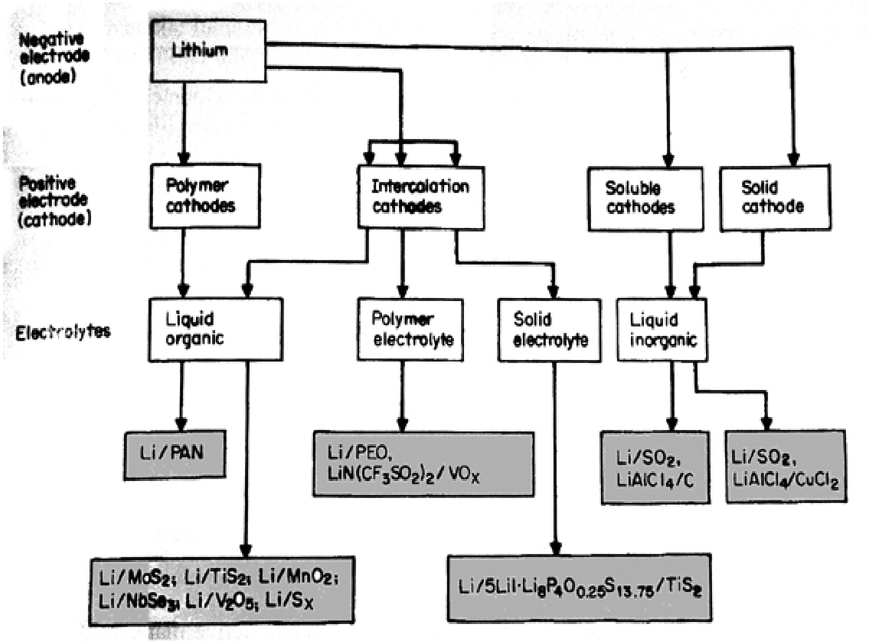


Figure 2.18 various Lithium-Metal cells 1/2 (source: Hossain, Reddy, 2002, Fig. 34-1a)

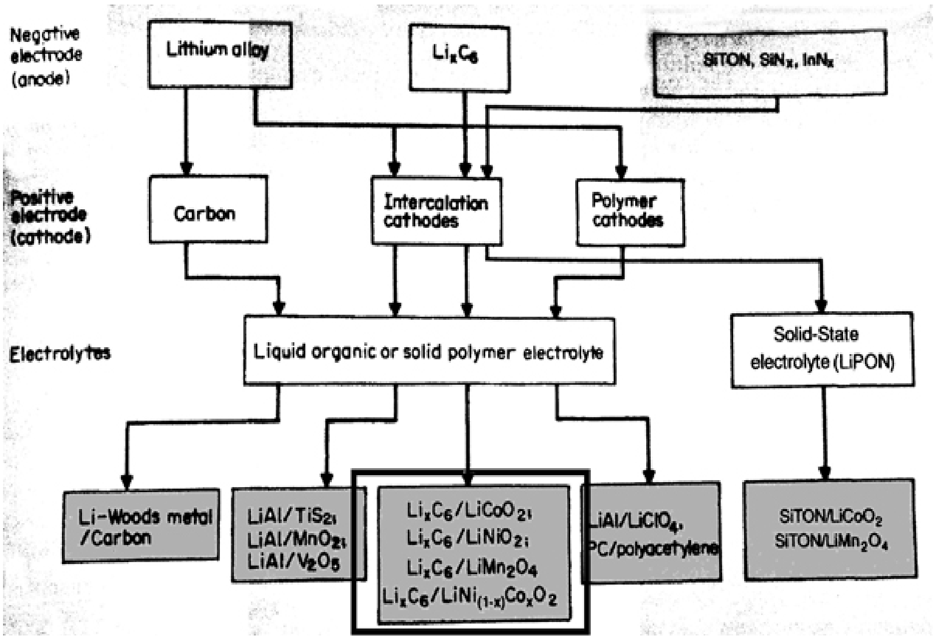


Figure 2.19 various Lithium-Metal cells 2/2 (source: Hossain, Reddy, 2002, Fig. 34-1b)

2.7.17.2 Lithium-ion and Lithium-ion-polymer

Advantages of this group in contrast to other lithium systems are high energy content, high pulse power (specific/density) and rapid charge capability. Moreover they are maintenance-free, work under a broader temperature range than nickel systems and no memory effect occurs during charging as known from Ni-MH (or Ni/Cd) systems. *(Ehrlich, 2002)*

Despite higher saftety than Li-metal systems *(Hossain, Reddy, 2002)*, thermal runaway may also occur for some types of Li-ion-(polymer) batteries (see 2.7.17.2.2) when for instance overcharged or crushed. Thus, regarding overcharging, there is a need for a protective cell balancing *(Ehrlich, 2002)*. Moreover, currently high cost, degradation when discharged below approximately 2V and permanent capacity loss at high temperatures are disadvantages *(Ehrlich, 2002)*.

As lithium-metal cells, this technology operates by lithium ions shuttling back and forth between the electrodes during the discharge-charge cycle. But in contrast to Li-metal no metallic lithium is plated during the charge and no metallic lithium is present in the cell. Instead, intercalation compounds are able to hold and donate Lithium-ions without changing their structure significantly. This can be achieved by employing so called ‘intercalation compounds’ as cathode and anode *(Ehrlich, 2002)*. Lithium-metal systems also employ intercalation compounds, but only as cathodes. The anode is, as already mentioned, highly reactive metallic lithium. *(compare Appendix B)*

2.7.17.2.1 Anode

Presently, there exist two major groups of intercalation compounds used in anodes *(Ehrlich, 2002)*:

- different types of carbon:
    - petroleum coke
    - graphite
    - mesocarbon microbeads (MCMB)
    - hard carbon
- Transition Metal Compounds

Carbon-anodes:

In 1990, when Sony introduced the Li-ion battery, petroleum coke was used as anode material because of its good capacity (180mAh/g) and stability in presence of propylene carbonate-based electrolytes *(Ehrlich, 2002)*.

Soon it became possible to employ graphite with its higher specific capacity, improved cycle life and rate capability. Another advantage was that graphite materials have a flatter discharge line than coke. *(Ehrlich, 2002)* This means, that Voltage remains approximately constant during discharge, what is desirable for most applications.

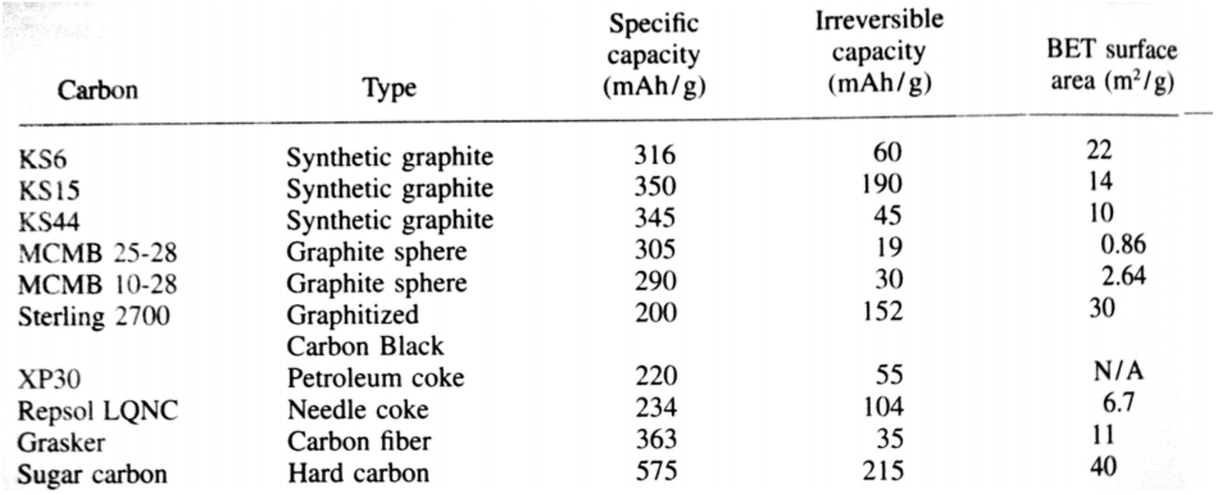
Also mesocarbon microbeads (MCMB), which are also graphitized, were employed. On the one hand they have higher specific capacity (300 mAh/g) and lower irreversible capacity than graphite, but on the other presently cost is higher. *(Ehrlich, 2002)*

To explain the term 'irreversible capacity' the first electrochemical intercalation of lithium into the carbon has to be considered. At this moment, some lithium is irreversibly consumed forming a solid electrolyte interface (SEI) and cannot be recovered in the following discharge, resulting in a loss of capacity. This irreversible capacity, which depends on the electrolyte solution and the type of carbon material, is explained on the basis of the reduction of the electrolyte solution and the formation of a SEI layer on the LixC interface. When the film is sufficiently thick to prevent electron tunneling, the electrolyte reduction is suppressed and the electrode can then be cycled reversibly. The first step is, therefore, critical in order to obtain a uniform passivating film. *(Ehrlich, 2002)* (see 2.7.17.2.3)

The fourth group of carbons employed is hard carbons (HC). In contrast to them, materials that can be graphitized by treatment at high temperature (2000 to 3000°C) are determined soft carbons *(Ehrlich, 2002)*. Hard carbons offer higher capacities than graphitic materials (Table 2.12).

A more complete list of various forms of carbon used as anode material is given in Table 2.12. It also states specific capacity and specific irreversible capacity which both determine specific energy of the battery.

In the last column, surface area is stated: By utilizing low surface area carbons, electrodes with acceptable self-heating rates may be fabricated but with lower capacity. As we can see hard carbon, which is proposed for new emerging Li-ion technologies *(see Enerdel, ch. 3.3)* has a large surface area.



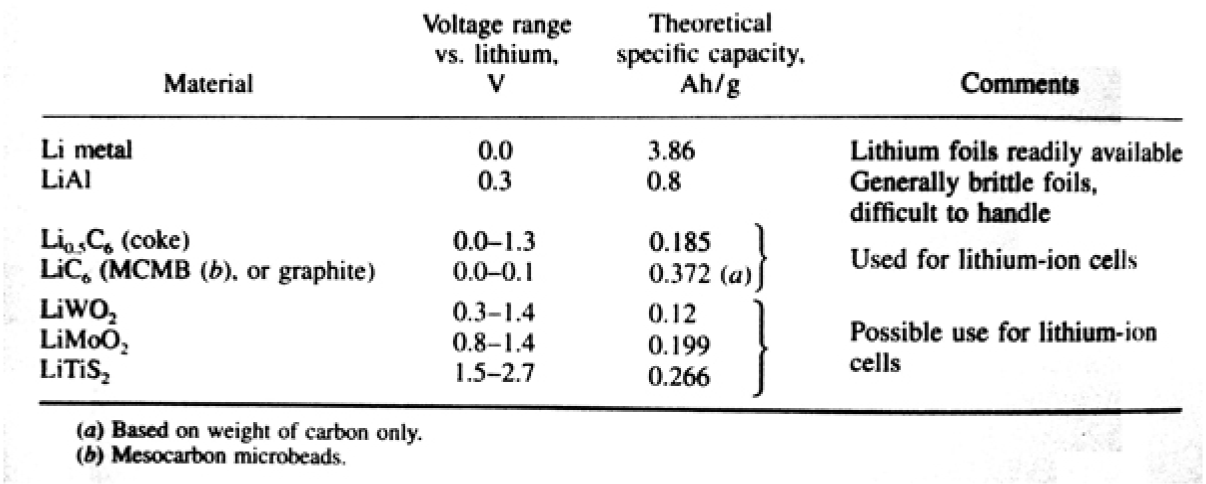
Carbon	Type	Specific capacity (mAh/g)	Irreversible capacity (mAh/g)	BET surface area (m^2/g)
KS6	Synthetic graphite	316	60	22
KS15	Synthetic graphite	350	190	14
KS44	Synthetic graphite	345	45	10
MCMB 25-28	Graphite sphere	305	19	0.86
MCMB 10-28	Graphite sphere	290	30	2.64
Sterling 2700	Graphitized Carbon Black	200	152	30
XP30	Petroleum coke	220	55	N/A
Repsol LQNC	Needle coke	234	104	6.7
Grasker	Carbon fiber	363	35	11
Sugar carbon	Hard carbon	575	215	40

Table 2.12 Characteristics of various forms of carbon used as anode material in Li-ion-(polymer) batteries (source: Ehrlich, 2007, Table 35.4)

Transition metal compounds

Transition metal compounds have layered structures into which lithium ions can be intercalated and deintercalated during charge and discharge. In most cases their electrochemical potentials are close to those of lithiated carbon materials. Examples used as anode materials are LixWO2, LixMoO2, LixTiS2 *(Ehrlich, 2002)* but more recently L4Ti5O12 (Lithium Titanate Oxide spinel, LTO) *(Appendix B)*. Altair Nanotechnologies is a company, which holds a patent on a production process *(Altair Nanotechnologies, 2007)*. Ener1's subsidiary Enerdel developed LTO in an own process in collaboration with Argonne Nationale Laboratory *(Hiroyuki et al, n. d.)*. In contrast to common transition metal compounds, LTO has higher voltage versus lithium (1,5 V) and lower specific capacity (only 170 mAh/g) in comparison to graphite *(Hiroyuki et al, n. d.)*.

Table Table 2.13 provides an insight of anode materials employed in both lithium-ion and lithium-metal systems. The third and the fourth row represent graphite used in Li-ion cells. In this table graphitic materials are stated in combination with the intercalated lithium as a Li_xC_6 compound.



Material	Voltage range vs. lithium, V	Theoretical specific capacity, Ah/g	Comments
Li metal	0.0	3.86	Lithium foils readily available
LiAl	0.3	0.8	Generally brittle foils, difficult to handle
$Li_{0.5}C_6$ (coke)	0.0–1.3	0.185	Used for lithium-ion cells
LiC_6 (MCMB (*b*), or graphite)	0.0–0.1	0.372 (*a*)	
$LiWO_2$	0.3–1.4	0.12	Possible use for lithium-ion cells
$LiMoO_2$	0.8–1.4	0.199	
$LiTiS_2$	1.5–2.7	0.266	

(*a*) Based on weight of carbon only.
(*b*) Mesocarbon microbeads.

Table 2.13 Intercalation compounds used in Li-ion-(polymer) and Li-metal cells (source: Hossain, Reddy, 2002, Table 34.2)

2.7.17.2.2 Cathode

"*The best cathodes for rechargeable batteries are those, where there is little bonding and structural modification of the active materials during the discharge-charge reaction. The insertion or intercalation compounds are among the most useful cathode materials. In these compounds, a guest species such as lithium can be inserted interstitially into the host lattice (during discharge) and subsequently extracted during recharge with little or no structural modification of the host.*" *(Ehrlich, 2002)*

Intercalation compounds include those used in Li-metal technology as lithium cobalt oxide (LiCoO2) or lithium nickel oxide (LiNiO2) (Hossain, Reddy, 2002) as well as the more recent lithium-nickel-cobalt-oxide (LiNi1-xCoxO2), lithium-manganese-spinel (LiMn2O4) or latest lithium-iron-phosphate (LiFePO4) employed in Li-ion technology. *(see Appendix B)*

Besides common denotation, chemical definition and abbreviation, Table 2.14 shows values of specific capacity of the particular cathode materials and theoretical cell voltage in combination with graphite supposed as anode (assumption: 0,1 Volt vs. Li/Li+).

Moreover an assessment of safety was done *(compare Balducci, 2007b, Budiansky, 2007; Hiroyuki, n.d.; Millikin, 2007b)* which bases on chemical stability of the compounds. Major incidents connected with recalls also play a major role. A famous example is Sony's battery recall in 2006 *(Sony, 2006)* of about 340.000 Notebook-Li-ion batteries *(U.S. Consumer Product Safety Commission, 2006)* equipped with Lithium Cobalt Oxide cathodes and graphitic anodes (C/LiCoO2). It is important to mention, that overall safety of the complete cell depends on all components. Regarding anodes LTO is to mention *(see 2.7.17.2.1)* as relatively safe material.

The last column lists producing Li-ion battery suppliers, detected during research, which adopte or developed the particular technologies.

Name	**Chemical definition**	**Common abbreviation**	**Spec. Capacity (mAh/g)**	**Voltage vs. Graphite theor. cell Volt**	**Safety**	**Adopter/ (Developer) in 2007**
Lithium Cobalt Oxide	$LiCoO_2$	LCO	151 (155)	4,0 (3,78)	low	Sony, Kokam, GS Yuasa, Enersys' Modular Energy.
Lithium Nickel Oxide	$LiNiO_2$	LNO	(200)	(3,45)		
Lithium Nickel Cobalt Oxide	$LiNi_{1-x}Co_xO_2$	(LNCO)	(190-220)	(3,60-3,66)		Lithium Technology Corp. = GAIA
Lithium Manganese spinel	$LiMn_2O_4$	LMO	119 (120)	4,05 (3,9)	moderate-high	LGChem= Compact Power Inc, SK Corp, GS Yuasa, Enerdel, Guangzhou Markyn Battery Co, Electrovaya
Doped Lithium Nickel Cobalt Oxide	$LiNi_{1-x-y}Co_{x-y}M^*O_2$					
Doped with: Al	$LiNi_{1-x-y}Co_{x-y}Al_yO_2$	-	195	3,8	moderate-low	SAFT
Mn	$LiMn_yCo_{x-y}Ni_{1-x-y}O_2$	x,y= 1/3 : NMC	153	3,85	moderate-high	x, y = 1/3 : Enerdel (in development); USABC Generation3 test cell
Mg	$LiNi_{1-x-y}Co_{x-y}Mg_yO_2$	-	In development			
Ti	$LiNi_{1-x-y}Co_{x-y}Ti_yO_2$	-	In development			
Lithium iron phosphate	$LiFePO_4$	LFP	161	3,4	high	A123, Valence Technology

Table 2.14 Various cathode materials used in lithium-ion-(polymer) cells (sources: Pesaran, 2006a; terms in brackets: Ehrlich, 2002, p. 35.8, table 35.3; safety: *Balducci, 2007b, Budiansky, 2007; Hiroyuki, n.d.; Millikin, 2007b*)

Considering Table 2.14 $LiCoO_2$, $LiNiO_2$, $LiNi_{1-x}Co_xO_2$ represent materials with layered structures *(Ehrlich, 2002)* whereas $LiMn_2O_4$ has a tunnel structure and thus is referred to as spinel *(Howell, 2007).*

Other cathode materials as those listed above, but which are also used in Li-ion cells, include chemical compounds as vanadium oxides (VO_x), molybdenum-sulfur (MoS_2), titan-sulfur (TiS_2) or niobium-selenium ($NbSe_3$) *(Hossain, Reddy, 2002).*

Lithium Cobalt Oxide ($LiCoO_2$), quoted in Table 2.14, is the oldest *(Hossain, Reddy, 2002)* and was the most widely used cathode material for a long time *(Ehrlich, 2002)* although it is more expensive than for instance LMO, LCO, 'LNCO') and moreover not very safe in combination with conventional electrolytes and anodes as graphitic carbon *(Ehrlich, 2002).* Presently, LMO is used as often as LCO *(Ehrlich, 2002).*

Lithium Nickel oxide was substituted *(compare Howell, 2006 or 2007)* by Lithium Nickel Cobalt Oxide (higher columbic efficiency) and the latter in turn was upgraded by doped materials as $LiNi_{1-x-y}Co_{x-y}Al_yO_2$ (SAFT) *(Appendix B).*

Doped Nickel Cobalt technology (doping metals as Al, Mn, Mg, Ti) enables reducing energy, evolved during positive material decomposition. Therefore new materials have been developed that offer either less evolved energy or higher onset temperatures. *(Ehrlich, 2002)* A 'LNCO' titan magnesium pimped version shows improved safety through reduced exothermic decomposition, offers lower capacity (165 mAh/g) but with voltage similar to other $LiNiCoO_2$ compounds *(Ehrlich, 2002).*

Manganese spinel (LMO) is around for many years but presently one of the most attractive materials. It has good safety properties, lower capacity than LCO or LNO, a higher rate of capacity fade when cycled or stored in the charged or discharged state and the ability sustain electric abuse. LMO is cheaper than LCO and is synthesized of raw materials as lithium carbonate, lithium hydroxide and metal oxide. *(Ehrlich, 2002)*

Modified spinels are doped with various metals *(Howell, 2007 and 2008)* as nickel *(Hiroyuki et al, n. d.).*

Lithium iron phosphate ($LiFePO_4$) is a commercialized representative of the phosphate group *(Millikin, 2007b)* used as cathode materials. Presently, after LMO, it seems to be the safest cathode material in use *(compare Millikin, 2007b and Hiroyuki et al, n. d.).* It's safe on overcharge but however, a battery management system (BMS) is needed anyway to prevent low voltage *(Millikin, 2007b).*

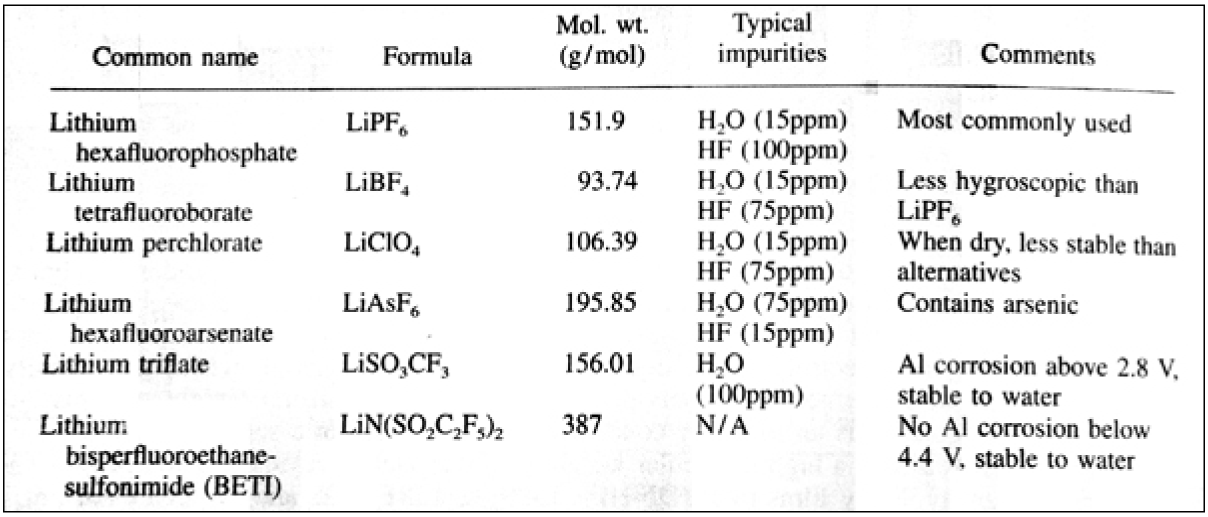
Last but not least the group of polymer and ceramic cathodes is to mention. Polymeric materials include polyacetylene, polypyrole, polyanilene and polythiophene *(Hossain, Reddy, 2002)*. Companies adopting these cathode technologies were not found and thus it's not subject of the comparative data analysis later in this work.

2.7.17.2.3 Electrolytes

In Li-ion batteries, liquid electrolytes are used as well as gel absorbed and polymeric or ceramic ones *(Hossain, Reddy, 2002), (Ehrlich, 2002), (Appendix B)*. Cells containing a polymer or gel-absorbed electrolyte are referred to as 'Lithium polymer' and 'Lithium-ion-polymer', respectively.

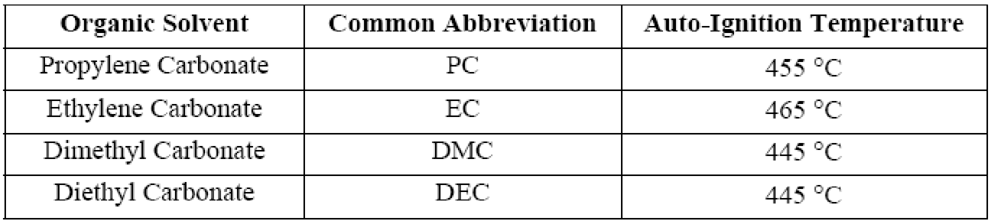
Liquid electrolyte (Li-ion cells)

Liquid Li-ion electrolytes consist of a lithium salt and a solvent, which is in most cases organic as carbonates for instance *(Appendix B)*. Liquid electrolytes have to meet the requirements of good ionic conductivity, stability to the potentials of cathode and anode operating in a wide electrochemical voltage window (0 to 5 V) and compatibility with other cell components. *(Balducci et al, 2007)* Table 2.15 provides an overview of common salts, which are solved in blends of solvents as given in Table 2.16 and Table 2.17. Moreover, in Table 2.17 values regarding boiling point, melting point, density, viscosity and dielectric constant are given. Lithium hexaflurophosphate (LiPF6) is one of the most used *(Appendix B)* electrolytic salts.



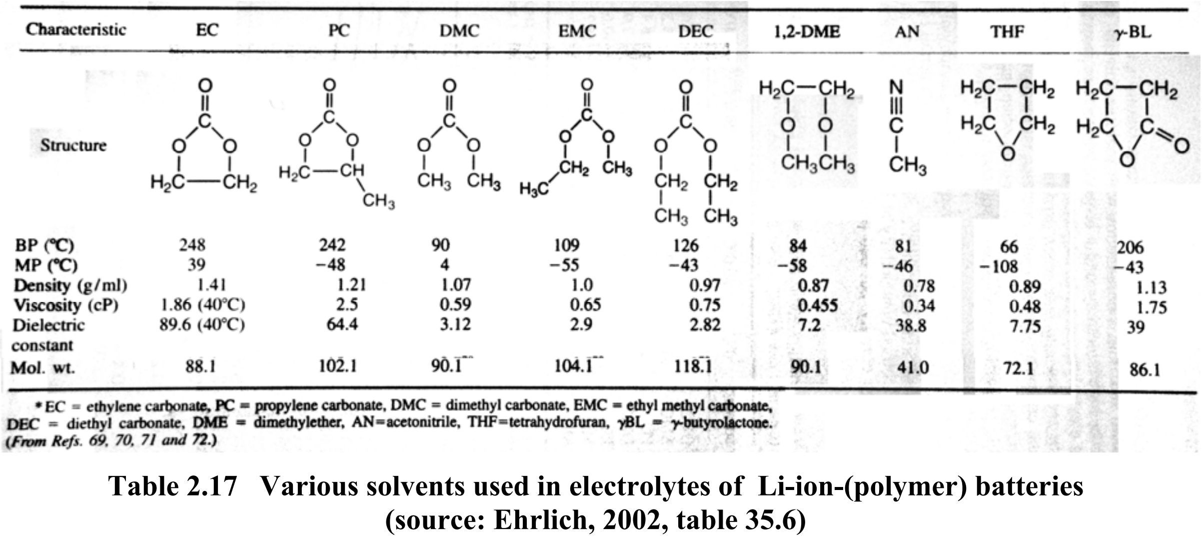
Common name	Formula	Mol. wt. (g/mol)	Typical impurities	Comments
Lithium hexafluorophosphate	$LiPF_6$	151.9	H_2O (15ppm) HF (100ppm)	Most commonly used
Lithium tetrafluoroborate	$LiBF_4$	93.74	H_2O (15ppm) HF (75ppm)	Less hygroscopic than $LiPF_6$
Lithium perchlorate	$LiClO_4$	106.39	H_2O (15ppm) HF (75ppm)	When dry, less stable than alternatives
Lithium hexafluoroarsenate	$LiAsF_6$	195.85	H_2O (75ppm) HF (15ppm)	Contains arsenic
Lithium triflate	$LiSO_3CF_3$	156.01	H_2O (100ppm)	Al corrosion above 2.8 V, stable to water
Lithium bisperfluoroethane-sulfonimide (BETI)	$LiN(SO_2C_2F_5)_2$	387	N/A	No Al corrosion below 4.4 V, stable to water

Table 2.15 Various lithium salts used in electrolytes of Li-ion-(polymer) batteries (source: Ehrlich, 2007, table 35.5)



Organic Solvent	Common Abbreviation	Auto-Ignition Temperature
Propylene Carbonate	PC	455 °C
Ethylene Carbonate	EC	465 °C
Dimethyl Carbonate	DMC	445 °C
Diethyl Carbonate	DEC	445 °C

Table 2.16 Various solvents used in electrolytes of Li-ion-(polymer) batteries (source: Budiansky et al, 2007)



Characteristic	EC	PC	DMC	EMC	DEC	1,2-DME	AN	THF	γ-BL
Structure									
BP (°C)	248	242	90	109	126	84	81	66	206
MP (°C)	39	−48	4	−55	−43	−58	−46	−108	−43
Density (g/ml)	1.41	1.21	1.07	1.0	0.97	0.87	0.78	0.89	1.13
Viscosity (cP)	1.86 (40°C)	2.5	0.59	0.65	0.75	0.455	0.34	0.48	1.75
Dielectric constant	89.6 (40°C)	64.4	3.12	2.9	2.82	7.2	38.8	7.75	39
Mol. wt.	88.1	102.1	90.1	104.1	118.1	90.1	41.0	72.1	86.1

*EC = ethylene carbonate, PC = propylene carbonate, DMC = dimethyl carbonate, EMC = ethyl methyl carbonate, DEC = diethyl carbonate, DME = dimethylether, AN=acetonitrile, THF=tetrahydrofuran, γBL = γ-butyrolactone.
(From Refs. 69, 70, 71 and 72.)

Table 2.17 Various solvents used in electrolytes of Li-ion-(polymer) batteries (source: Ehrlich, 2002, table 35.6)

The liquid electrolye is completely absorbed into the electrode and the separator. There, most solvents as common lithium hexaflurophosphate (LiPF6) aren't thermodynamically stable near 0 V vs. Li (with lithium intercalated graphite, Li_xC_6, as anode for instance), but reaction with the electrode's surface is limited to a formation of a passivation film. *(Ehrlich, 2002)* This film separates the solvent from the electrode but is ionically conductive to the passage of lithium ions and thus is referred to as solid electrolyte interphase (SEI). The SEI enables stability of the cell for years without significant degradation. *(Ehrlich, 2002)*

During the formation of the SEI on a cell’s first cycle, lithium is irreversibly incorporated which leads to a loss of capacity (irreversible capacity). Electrolytes containing alkyl carbonate, in particular ethylene carbonate, have been shown to offer low irreversible capacity corresponding to low capacity fade and high capacity. *(Ehrlich, 2002, p.25.28)*

In first line the cell’s low temperature performance depends on the electrolyte’s conductivity at low temperatures. *(Ehrlich, 2002)* Figure 2.20 indicates conductivity in dependence of temperature for 1 M LiPF6 solved in several different solvents. MF stands for methyl formate, DEC for diethyl carbonate, EMC for ethyl methyl. Carbonate, PC for propylene carbonate, DMC for dimethyl carbonate, EC for ethylene carbonate and MA for methyl acetate.

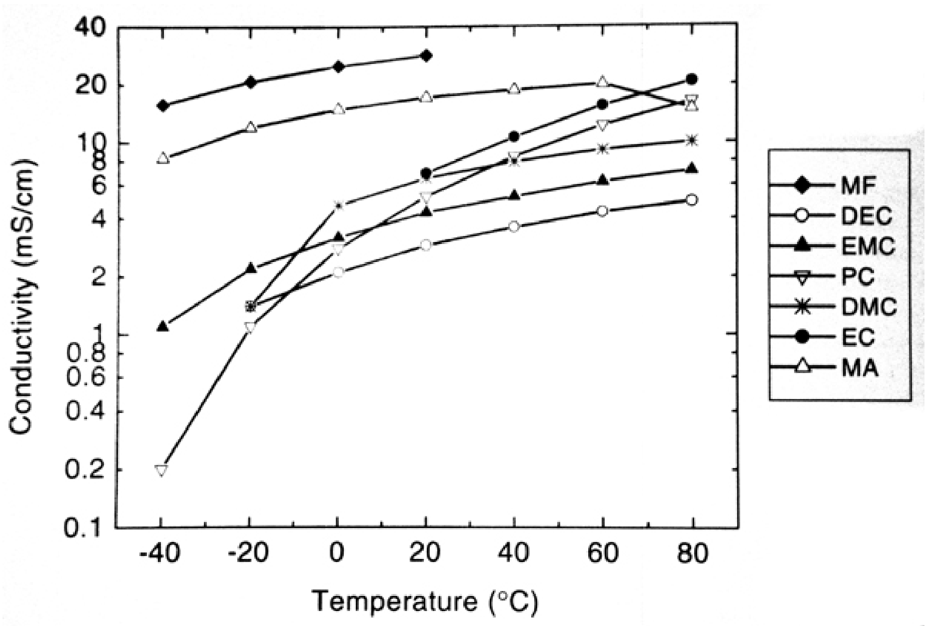


Figure 2.20 Conductivity, in mS/cm, of 1M LiPF6 solutions in various solvents in dependence of temperature (source: Ehrlich, 2002, figure 35.23)

In Li-ion and gelled lithium-polymer cells blends of two or three various solvents as stated in Figure 2.20 or Table 2.17 are used. Thus conductivity also depends on the ratio of mixture. For more details see Appendix A, Table A.1, Figure A.1 and Figure A.2.

Solid Polymer Electrolyte (SPE) – (Lithium Polymer cells)

In this group salt as LiPF6 is incorporated in matrices of a solid high molecular weight polymer (polyethyle oxide (PEO) for instance) *(Hossain, Reddy, 2002)* which is free of any flammable and reactive liquid solvents and thus can be considered as safer than liquid or gel-absorbed electrolytes. An additional separator between polymeric electrolyte and electrode is not necessary. *(Hossain, Reddy, 2002)*

The polymer is fabricated in films, enabling thin cell construction as the gelled technology. Presently SPEs have lower ionic conductivities and lower lithium-ion transport numbers than their liquid and gelled counterparts. Moreover they need elevated temperatures, starting at 65°C to operate with a satisfying performance. *(Nelson, 2000)*

Li-ion cells with gel-absorbed electrolyte

Cells with electrolyte absorbing polymeric gels are sometimes also referred to as lithium polymer cells although the electrolyte is not the polymer but the solved salt is absorbed by the polymer. To distinguish they are also called Lithium-ion-polymer cells *(compare Appendix B)*. Concerning lithium polymer batteries, gel-absorbed electrolytes are presently more common than SPEs. *(compare Appendix B)* The high molecular weight polymer gel as for instance Polyvinylidene-hexafluoropropene (PVDF-HFP) or polyacrylonitrile (PAN) absorbs the solvent and dissolved salt but is ionically conductive for lithium-ions *(Ehrlich, 2002)*. Fumed silica may be added for additional structural integrity *(Ehrlich, 2002)*. As electrolytes salts in combination with blends of various solvents as described under solid electrolytes are used.

The advantage of electrolyte absorption is that there is no free liquid electrolyte which improves safety and electrical abuse of the total system. However, the absorbed electrolyte is still more reactive than a solid polymer in comparison. *(Ehrlich, 2002)*

The main issue considering lithium polymer (LiPo) cells is that it is possible to package them within a barrier film and not as conventional Li-ion cells within an aluminum or steel containment. Moreover the electrodes, the separator and the electrolyte can be fabricated in flat thin plates enabling high form factors and flat designs as in use for cellular phones. *(Ehrlich, 2002)*

Both facts result in a tremendous increase of volumetric and specific performance and ease manufacturing and thus reduce cost. Cells can consist of one or more plates of electrode-separator-electrolyte-electrode sandwiches which are stacked together to batteries or are Zfolded. Another approach is the bicell design following a “cathode - double thickness anode - cathode” sandwich configuration. *(Ehrlich, 2002)*

Examples of LiPo products offering gelled polymer cells or batteries in prismatic format are *(Appendix B)*:

- Kokam Co. Ltd, Kyunggi-do, South Korea (polymer: PVDF-HFP, in combination with LCO cathodes)
- LGchem (Compact Power Inc.), Seoul, South Korea
- SK Corp, Jongru-gu, South Korea
- Valence Technology Inc., Austin Texas, USA (solvent: blend of DMC and EC in 2:1 ratio)

2.7.17.2.4 Additives

To improve electrolyte performance, additives have been developed.

2.7.17.2.5 Separator:

Thin 10 to 30 micrometer, microporous films are used to electrically isolate the positive and negative electrodes of Li-ion cells. The effective pore size mustn’t be bigger than 1 micrometer. For automated winding it has to withstand high tensile stresses. *(Ehrlich, 2002)*

2.7.17.2.6 Research and further development of materials used in Li-ion cells:

According to the Institute for chemical technology of inorganic materials at the technical University Graz[7], Austria several different active materials as shown in Figure 2.21 are possible under following constraints[7]:

- Capacity besides Voltage is one of the two factors, which determines energy content of a battery. It depends on both, the anode and the cathode material. Presently in Li-ion batteries it is restricted primarily by anode materials and thus, in figure Figure 2.21 improvements in capacity are only related to the anode (x-axis).

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[7] ‘Electric & Hybrid Vehicles’-Workshop, 2007-10-24, Arsenal Research, Vienna, Austria

- The cathode makes a major part of total cell cost. Moreover, considering the electrochemical potential of elements (Figure 2.13) new cathode materials enable higher cell voltages. (In contrast the anode of course is bounded to 0 Volt vs. Li/Li+ which is already approximately achieved by commercial graphitic anodes with 0,1V. Thus new anode materials can't contribute increasing cell voltage). Thus in figure Figure 2.21 improvements in cell voltage are only related to the Cathode (y-axis).
- The electrolyte should stay stable in the potentials generated by cathode and anode. Thus one way is to reduce cell voltage but the better is to improve electrolytes to withstand higher potentials. Moreover, conductivity especially at low temperatures is an issue.

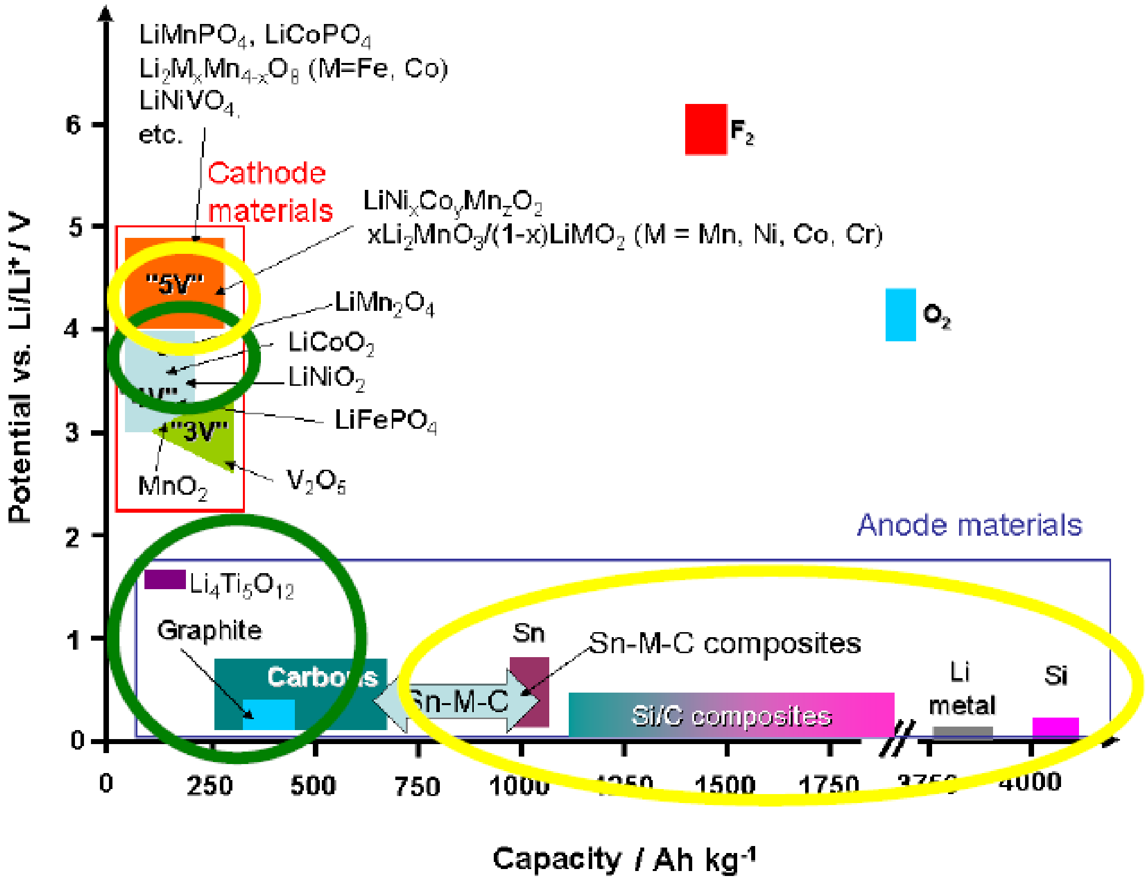

Figure 2.21 prospects of electrode materials (source: Balducci et al, 2007)

Anode:

Presently Lithium Titanat Oxide spinel ($Li_4Ti_5O_{12}$) is gaining gradually more attention. The company Altair Nanotechnologies Inc., Reno, Nevada, USA has a patent on a production process of this material *(US Patent 6,890,510).*

Moreover battery producer Enerdel, Indianapolis, Indiana, USA, subsidiary of Ener1 developed LTO in cooperation with Argonne US National Laboratory. It is used as anode material in combination with LMO or Lithium-Manganese-Nickel-Cobalt-Oxide as cathode material, whereas the latter is still in development. The latter is also identical with the cathode material used in the 'USABC generation 3' test cell. We refer later to USABC in chapter 3.2.

LTO, a Transition metal compound, offers several advantages in comparison to graphitic anodes. It generates no heat below 200°C *(Howell, 2007, p.40)* is more stable in presence of the electrolyte (compare Figure 2.25 and thus safer than common graphitic anodes. Moreover it experiences only a 0,2 % volume change during a cycle in contrast to graphite with 9%.

Because voltage vs. Li/Li+ is higher (1,5 V) as that of graphite (0,1 V), nominal voltage of a cell equipped with LTO as anode is lower than that of conventional Li-ion cells (compare Figure 2.25). However, therefore it is safer because LTO operates in the stable window of conventional electrolytes (compare Figure 2.25). Moreover high rate capabilities of discharge and charge even at low temperatures are possible *(Howell, 2007)* and thus compensating power performance. A severer disadvantage is low specific energy capacity (170 mAh/g) *(Hiroyuki et al, n. d.)* which is approximately equal to only the half of Graphite *(compare Table 2.12)*.

Accredited institutions and researches as Japans National Institute of Advanced Industrial Science and Technology (AIST) or Professor Martin Winter, formerly head of the 'Institute for chemical technology of inorganic materials' at the technical University of Graz, Austria and now professor at the 'Foundation for applied material sciences for energy storage and energy conversion', Institute of Physical Chemistry, Westfälische Wilhelms Universität Münster in Germany asses silicon-compounds as prospective materials with higher specific energy and energy density, respectively. [7]*,(Tatsumi, 2007)*

According to AIST *(Tatsumi, 2007)* there are candidates possessing specific capacity of more than 2000 mAh/g, which equals specific capacity of seven times that of graphite. However, AIST *(Tatsumi, 2007)* and TU-Graz[7] go ahead, that such materials generally show large volume change during a charge-discharge cycle. Capacity fading and thus cycle life are major issues. Figure 2.22 illustrates specific and volumetric capacity of a lithium-silicon compound in comparison to other candidates as aluminum and tin compounds.

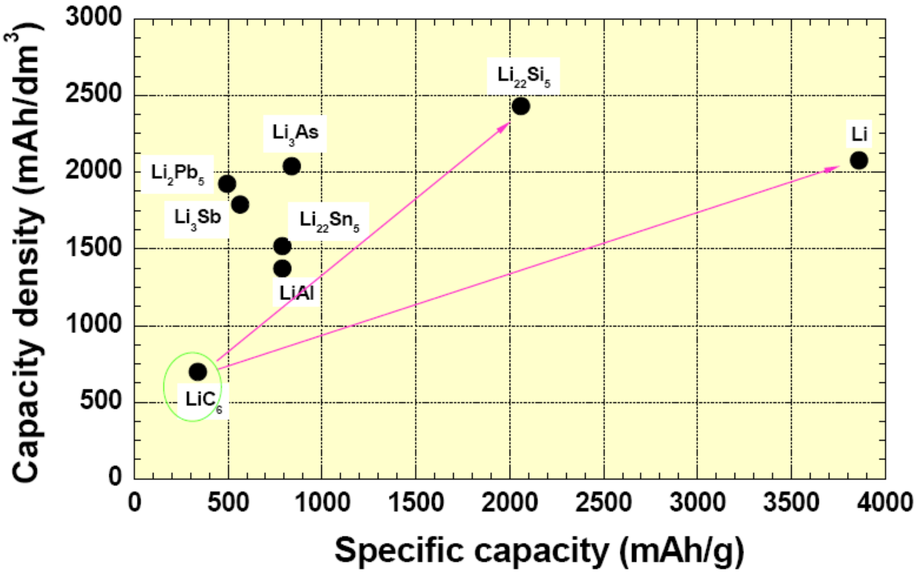

Figure 2.22 specific and volumetric capacity of various prospective anode materials (source: Tatsumi, 2007)

One innovative development basing on silicon may be silicon nanowires. As the scientific journal '*Nature Nanotechnology'* reports, a nanowire inventor, Yi Cui, and a battery expert, Robert Huggins, at 'Stanford's Materials Science and Engineering Department' found ways to utilize these nanowires as anode material to overcome the effect of capacity fading but to benefit of the huge specific capacity of silicon: about 4200mAh/g theoretically were reported. *(Chan et al, 2007)*

There have been many different approaches taken for developing a silicon-based anode material. A few others include amorphous silicon thin films deposited on copper, multi-walled carbon nanotube (MWNT)/silicon composites (with up to 1,770 mAh/g) and silicon quantum dots (n-Si), coated with an amorphous carbon layer. (First charge capacity: 1,257 mAh/g). *(Millikin, 2007c)*

Researchers from the Lawrence Berkeley National Laboratory, Berkeley, CA, USA are analyzing Li - Mg alloy anodes which are assessed to offer very high capacities and also inhibit dendrite formation. Rate capability, initially low (~ 0.5 mA/cm2 in 2006) is assumed to be improved. *(Howell, 2007, p.94 and Howell, 2008, p.112)*

Cathode:

Currently two developments are observable: the further development of commercial nickel cobalt manganese systems and the introduction of phosphate based systems. *(Howell, 2007 and Howell, 2008)*

Figure 2.21, Figure 2.23 & Figure 2.24 are demonstrating Voltage vs. Lithium, volumetric and specific capacity and specific energy of these compounds.

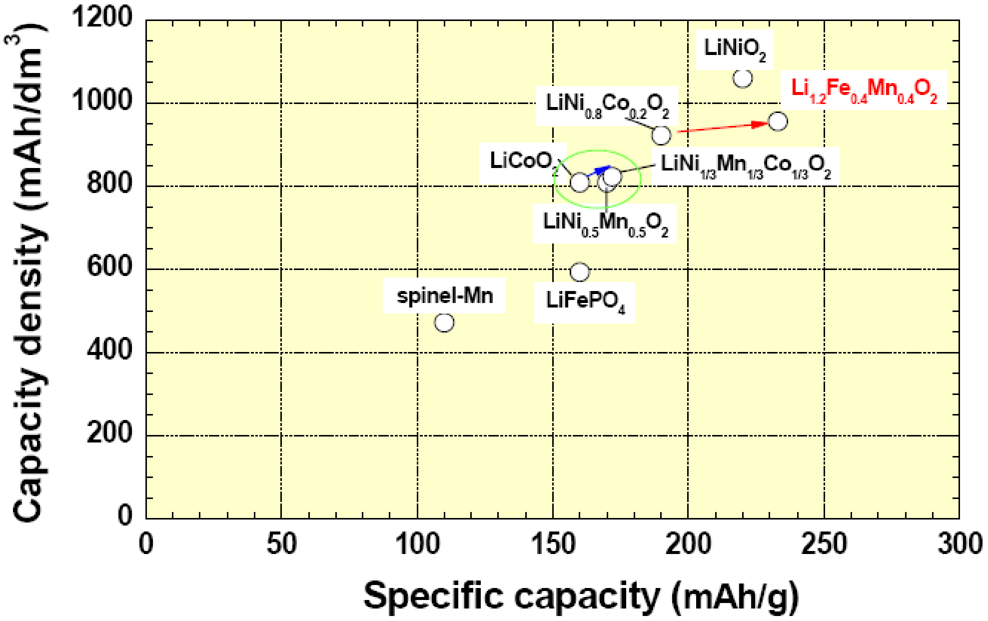

Figure 2.23 Specific and volumetric capacity of various prospective cathode materials (source: Tatsumi, 2007)

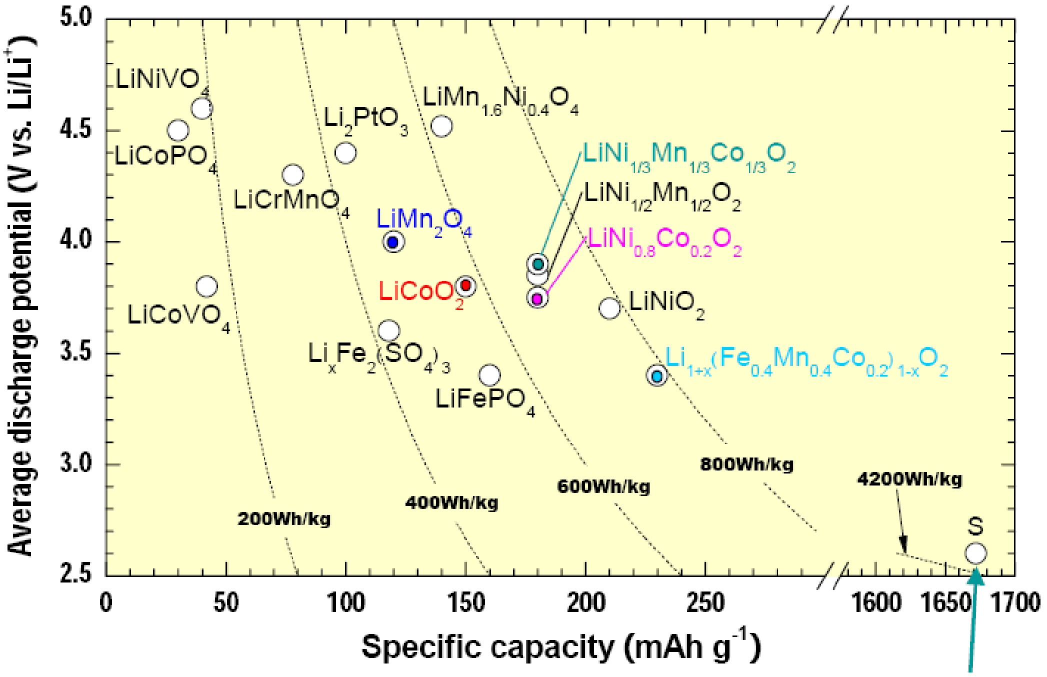

Figure 2.24 Average discharge potential over specific capacity of various prospective cathode materials (source: Tatsumi, 2007)

Commercially available systems basing on nickel cobalt or manganese systems include Manganese spinel ($LiMn_2O_4$), which shows short life at high temperature *(Millikin, 2007b)* and aluminum doped nickel-cobalt-oxide ($LiNiCoAlO_2$), which is thermally unstable at high states of charge *(Millikin, 2007b)*. Regarding the latter compound, alternative doping metals as magnesium, titan or manganese are used. $LiNiCoMnO_2$ for instance is gaining momentum, although there is not much durability data yet *(Millikin, 2007b)*.

Regarding the group of phosphates, Lithium Iron Phosphate ($LiFePO_4$), originally developed by Dr. Goodenough at the University of Texas *(Howell, 2007 or Millikin, 2007b)* is already commercialized. It is the most thermally stable compound in comparison to the mentioned nickel manganese cobalt cathode materials *(Howell, 2007, Appendix-C; Millikin, 2007b)*, but with lower voltage (3,4 Volt vs. Li/Li+) and thus lower energy.

Modified iron phosphate cathodes are the choice of Valence Technologies Inc., Austin, Texas, USA and A123Systems, a spin-off of the Massachusetts Institute of Technology (MIT), Boston, Massachusetts, USA *(compare Appendix B)*.

In April 2007, SAFT, Bagnolet, France, one of the well-established Li-ion battery manufacturers, announced also to adopt iron phosphate technology as cathode material in batteries of its space and defense division *(SAFT, 2007a)*.

Instead of iron, elements as manganese, cobalt, or nickel are also considered in phosphatic compounds with higher voltages vs. lithium (see Figure 2.21). According to *Millikin, 2007b* the 'Laboratoire de photonique et interfaces', Ecole Polytechnique Federale de Lausanne (EPFL), Switzerland assesses nanostructured lithium manganese phosphate as a solution "*offering durability, safe performance and cost effectiveness*", which is a "*voltage compromise*" between the other three phosphatic solutions mentioned above.

The element Vanadium is also considered in compounds as $LiNiVO_4$, shown in Figure 2.21 which also enables higher voltages vs. lithium.

Corresponding to Figure 2.24 sulfur is a very attractive material, but cycle life is too short *(Tasumi, 2007)*.

Electrolyte:

According to researchers of the 'Institute for chemical technology of inorganic materials' at the Technical University of Graz, Austria[7], first criterion considering the selection of liquid electrolytes is that electrolytic decomposition products, resulting from the electrodes' potentials, should form a thin passivation film, the solid electrolyte interphase (SEI). This film covers the anode and thus protects the electrolyte against further decomposition and guaranties safety of the cell. Nevertheless, the film should be ionically conductive to the passage of lithium ions and enable high rate performance.

As further criteria conductivity, viscosity and wettability were mentioned.

Figure 2.25 illustrates the context of electrodes and electrolyte to guaranty a stable system. As can be seen no common anode material with exception of LTO operates in the stability window of conventional liquid electrolytes. Efforts are made to widen this window.

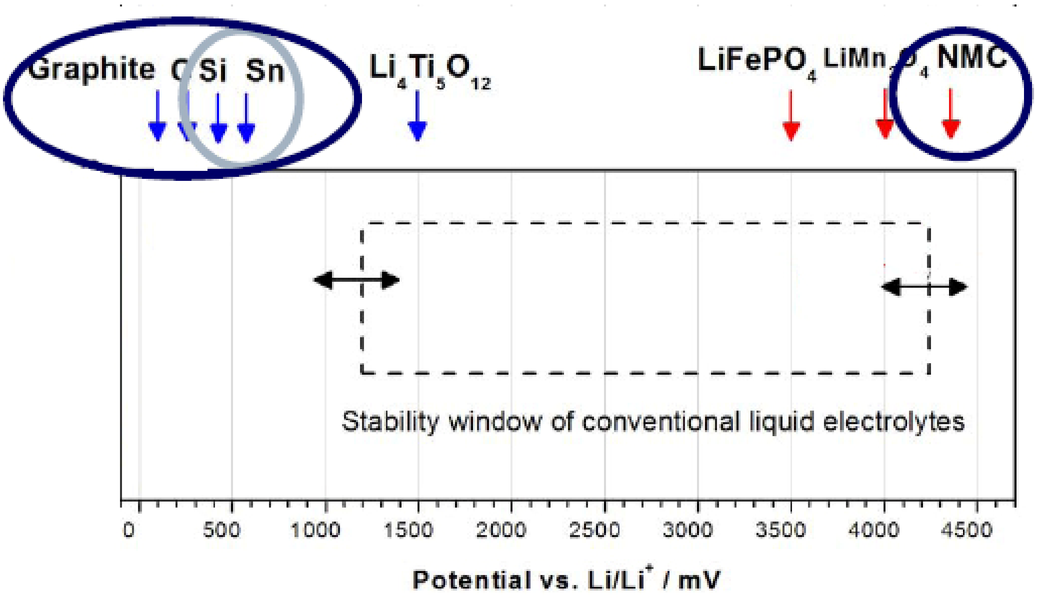

Figure 2.25 stability window of common electrolytes in presence of various electrodes (source: based on Balducci et al, 2007)

A new group of electrolytic chemistry is ionic liquids. Ionic liquids are molten salts at ambient temperature and represent green chemistry. Compared to conventional chemistry they are superior regarding ionic conductivity electrochemical and thermodynamic stability, toxicity and cycling rates. Battery development on this basis in combination with lithium polymer technology is the goal of the European Union’s project ILLIBAT (Ionic Liquid-based Lithium batteries) which is lead by the Technical University of Graz, Austria *(Winter, 2007).*

For additional detailed information on research and development of future electrode materials and production processes, separators and electrolytes see the ‘Annual Progress’-reports of the ‘Energy storage research and development program’, US-DOE of the recent years 2006 and 2007. (2006: LiPO4: p.71, spinel: p.81, nickelate: 88; 2007: LiPO4: p.81, spinel: p.89, nickelate: 95). (http://www1.eere.energy.gov/vehiclesandfuels/resources/fcvt_reports.html).

2.7.18 High temperature batteries

2.7.18.1 Sodium beta: Sodium/sulfur and Sodium/ nickel-chloride (ZEBRA)

Both, sodium/sulfur and sodium/nickel-chloride are called sodium beta batteries corresponding to sodium employed as anode material and beta referring to the ceramic β’’-alumina (β’’-Al_2O_3) electrolyte. As high temperature batteries they operate at elevated temperatures between 270 and 350 °C. *(Aueer, Braithwaite, 2002)*

Because the principle of both systems is nearly the same but the ten years later developed sodium/nickel-chloride system is superior regarding most characteristics *(Aueer, Braithwaite, 2002)*, we will focus only on sodium/nickel-chloride systems in the further stages of this work.

In contrast to conventional batteries the sodium/nickel-chloride battery, also called ZEBRA (Zeolite Battery Research Africa Project) by its inventors, employs a liquid anode, a solid primary and a liquid secondary electrolyte and a solid cathode *(Heinemann, 2007).* As active anode material molten sodium is used whereas the cathode consists of nickel-chloride *(Heinemann, 2007).* Moreover, the two electrolytes -solid β’’-alumina and a molten NaAlC14 - act together in series *(Aueer, Braithwaite, 2002).* To ensure that all sodium and NaAlC14 is molten, the cell is operated over the respective melting points at approximately 300°C *(MES-DEA, 2003).*

The principle of the charging process is shown in Figure 2.26: Hence, when discharged sodium from the negative electrode passes the semi permeable ceramic electrolyte and sodium chloride is generated at the positive electrode (net reaction: NiC12 +2Na → Ni + 2NaCl). Nominal cell Voltage is 2,58 Volt. *(Heinemann, 2007)*

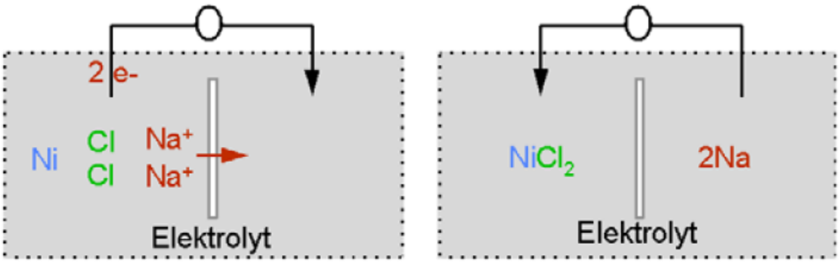

Figure 2.26 principle of a ZEBRA cell (source: Heinemann, 2007)

Advantages of the system are that it can safely be overcharged by more than 50%, has 100% columbic efficiency and deep cycle is possible *(Aueer, Braithwaite, 2002).*

ZEBRA systems were considered for use in large scale UPS systems or Power Improvement, for space application and for use in the electric vehicles or electrical buses *(Aueer, Braithwaite, 2002)*.

Battery suppliers offering such systems are MES-DEA S.A., Stabio, Switzerland and Rolls-Royce, Derby, UK (http://www.rolls-royce.com/marine/products/submarine/zebra_batteries.jsp).

In the comparison of product specifications in chapter 3, a MES-DEA battery, type Z33-93-ML3P-152, was included. Cycle life was reported to exceed 1300 cycles using an ECN European vehicle test. *(Aueer, Braithwaite, 2002, p. 40.26)*. Another source[8] reported from over 3000 test cycles. Details about test conditions of cycling (depth of discharge, etc.) were not found and thus Zebra's cycle life is not compared to other system's life.

A major issue regarding ZEBRA batteries is their ability to operate in a broad ambient temperature range (-40 to 50°C). Batteries are well isolated to avoid heat transfer to surrounding. However internal operating temperature of 300°C is achieved by heating up the battery by the internal resistance of the system using stored energy. This aspect has to be considered when comparing energy content of ZEBRA to other systems *(Aueer, Braithwaite, 2002)*.

2.7.18.2 Lithium/ iron monosulfide and Lithium/ iron disulfide

Lithium/ metal-sulfide batteries as Li-Al/iron-sulfide or Li-Al/iron-disulfide are representatives for another group of high temperature batteries using molten salt technology *(Henrikson, Jansen, 2002)*.

Development started in the early 1960s and almost ended in the middle of the 1990s. R&D of the rechargeable lithium/iron sulfide battery is still continued but instead of molten salt as electrolyte and magnesium as separator a composite polymer electrolyte that operates at temperatures of 90 to 135°C is used *(Henrikson, Jansen, 2002)*. This technological trajectory is similar to lithium-metal polymer technology using a solid-state polymer (SPE) as discussed earlier in chapter 2.7.17.2.3. In the US, the United States Advanced Battery Consortium (USABC) stopped long term development in 1995 in favor of the emerging Li-ion technology which operates at significantly lower temperatures *(Henrikson, Jansen, 2002)*. Reasons were

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[8] 'Zebra Batterie', Wikipedia - the free encyclopedia, http://de.wikipedia.org, consulted 05-01-08

that the latter allows the use of lower material cost as well as easier manufacturing *(Henrikson, Jansen, 2002)* what in turn resulted in higher commercial success.

Thus, in this work, high-temperature lithium/metal-sulfide batteries are not investigated further.

2.8 Magnetic, Eletroinductive, Electromagnetic storages

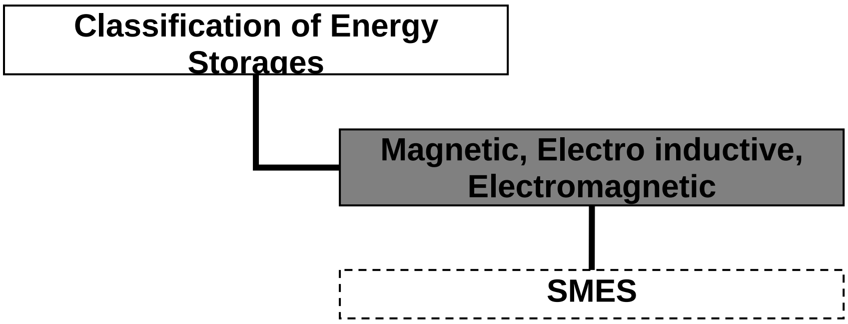

Figure 2.27 Classification of magnetic, electro inductive storages

This group contains super-conductive magnetic energy storages (SMES). SMES store energy in a magnetic field created by a direct current in a cryogenically cooled superconducting coil. At the breakdown of the electromagnetic field energy is released in form of electricity over the coil *(MagnetMotor GmbH, 2008).* SMES in comparison to other storages have round trip efficiencies greater in the range of 92 to 97% *(Tam, Kumar, 1990)* neglecting power used for the cryogenic refrigeration.

SMES are commercially available but only few products were found. For motive application the complex cooling system and environmental and health issues regarding the strong electromagnetic fields may be a problem.

State of the art SMES are used as uninterruptible power supply (UPS) *(see below)* in combination with the grid. There are no commercial automotive applications and thus are not discussed further. For more information on products, it is referred to the following three companies offering SMES on their websites as UPS systems:

- Accel GmbH, Germany
  http://www.accel.de/pages/2_mj_superconducting_magnetic_energy_storage_smes.html
- American Superconductor,Inc., Massachusetts, USA
  http://www.amsc.com/products/transmissiongrid/104273034641.html

- Magnetmotor GmbH, Germany
  www.magnetmotor.de

2.9 Nuclear storages

This group is not considered for any commercial application in HEV.

2.10 Energy Conversion Devices

Energy converters are not discussed in this work. In respect to energy storages, two converters play a major role: the fuel cell and a thermoelectric converter. Recent fuel cells are not capable to operate in both directions of conversion *(see 2.6)* and thus can not be a part of a rechargeable system used for recuperation as regenerative braking. Therefore, they have to be combined with rechargeable storages with electric interface as for instance batteries.

Currently, efforts are made regarding thermoelectric converts used for waste heat recovery *(for instance: Hendricks, Lustbader, 2002a, 2002b, 2003; Crane, Jackson, 2002; Martin, Olsen, 2003)*. Such converters transform heat to electricity which can be stored in energy storages with electric interphase, what again underlines their importance.

3 Characteristics and requirements of energy storages

3.1 Sample of energy storages

Potential candidates of energy storages were already evaluated in chapter 2 of this work. Some of them are investigated further by collecting and analyzing technical data and some not. The respective reasons not to further observe a storage were also stated in chapter 2. In most cases, the reason that data of a particular type of storage was not collected was simply that no supplier and thus no data were available.

During research of this work, which took place in the months from October 2007 to January 2008, websites of approximately 280 secondary battery suppliers, 40 supercapacitor suppliers and 10 kinetic energy storage suppliers were found and consulted. In comparison to these three types of storage, product data on other types was rare or couldn't be found.

Confidential data provided by AVL List GmbH was also used whereas particular suppliers of the observed products are referenced anonymous as S1 to S9.

The complete data collection can be found in Appendix B, which was very time consuming to create (about half of the time invested in this work): In the first stage characteristics and definitions had to be adopted, which are explained in chapter 3.2. In the next stage values for these characteristics (as shown in Appendix B) were calculated. The calculation methods are explained in chapter in 3.3.

In the next stage, this data could be analysed (chapter 3.4).

Table 3.1 indicates the companies from which technical product data was collected. The complete data collection can be found in Appendix B.

It was focused on mechanical storages as flywheels, electrostatic storages as supercapacitors and electrochemical storages as batteries. All observed storages have an electrical output interphase and thus can be integrated in hybrid electric vehicles (HEV).

Group	Subgroup	Company	Abbrev.	Holding
Flywheel	Electric output	Compact Dynamics	CD	Compact Dynamics GmbH
		S6	S6	S6
Super-capacitors	EDLC	Maxwell Technologies	MAX	Maxwell Technologies Corp
		Nesscap	NES	NESSCAP Co., Ltd
		Nippon Chemi-Con	NIP	Nippon Chemi-Con Corporation
		S1	S1	S1
		S2	S2	S2
		S3	S3	S3
		S4	S4	S4
		S5	S5	S5
	Pseudo-Cap	Nesscap	NES	NESSCAP Co., Ltd
	Hybrid	S1	S1	S1
Lithium	Li-Ion	A123systems	A123	MIT Spin-off
		Altair Nanotechnologies, Inc.		Altair Nanotechnologies, Inc.
		EnerDel	ENE	Ener1
		GAIA Akkumulatorenwerke, GmbH	GAI	Lithium Technology Corporation
		GS Yuasa	GSY	GS Yuasa
		Lithium Technology Corporation	LTC	Lithium Technology Corporation
		LGChem/ CompactPowerInc	LG	
		Magna Steyr	Magna	Magna International
		Modular Energy Devices, Inc	MED	EnerSys
		SAFT	SAF	Johnson Controls–SAFT Advanced Power Solutions - Joint Venture
		S8	S8	S8
		S9	S9	S9
	Li-ion-polymer	Kokam Co. Ltd	KOK	Kokam Co. Ltd, Joint Venture with EaglePicher
		LGChem/ CompactPowerInc	LG	
		Valence Technologies Inc.	VAL	U-Charge® Power System / XP System

Nickel	Ni-MH	Cobasys	COB	Chevron Technology Ventures LCC (Chevron) +ECD Ovonics Joint Venture, Cobasys was Texaco Ovonic Battery Systems
		Electro Energy Inc.	EEI	Electro Energy Inc (EEI),
		Panasonic EV Energy Co.	PEV	Toyota (majority) - Matsushita Electric Industrial Co. Joint Venture
		SAFT	SAF	Johnson Controls–SAFT Advanced Power Solutions - Joint Venture
	Nickel/Zinc	PowerGenix	NiZn1	PowerGenix
		Xellerion	NiZn2	Evionyx
		Evercel	NiZn3	ceased
High Temperature	ZEBRA	MES-DEA	NaNiCl2	MES-DEA
Lead-Acid	VRLA	representative data	VRLA	representative data

Table 3.1 Suppliers of products discussed in chapter 3

Products from companies as indicated in Table 3.1 represent a sample of current commercial state-of-the-art realisations. They were chosen from a list of potential candidates because they produced interest when studying news or because detailed data was available on the web or just randomly.

Regarding lead acid technology ‘representative data’ indicates that data stems from various sources: specific and volumetric power and energy stems from *Pesaran, 2006* operating temperature and calendar life from *Linden, Reddy, 2002, p.22.12*, self discharge from *Linden, Reddy, 2002, p.23.12* and cycle life from *Keyser et al, 2000*. Recharge rate as well as the battery’s total volume and weight were calculated from the ‘Elite’ series of Yuasa 12V (www.yuasabatteries.com).

Table 3.2 and Table 3.3 list more suppliers of supercapacitors and secondary batteries, which may be potential candidates for use in hybrid vehicles but which were not investigated in this work.

Company/ Brand	Website	Notes
Batscap	www.batscap.com	carbon EDLC
Bombardier	www.bombardier.com/de/1_0/pdf/Mitrac_ES_de.pdf	carbon EDLC
Elit-Cap	www.elit-cap.com	bipolar design
Elna Capacitor / Asahi Glass	www.elna.co.jp/en/capacitor/ double_layer/catalog/index.html	carbon EDLC
Esma	www.esma-cap.com	hybrid supercapacitor
LS Cable / LS Group	www.lscable.com/product/ product_info02.asp?cate_code=328&idx=0	carbon EDLC
Nichicon	www.nichicon.co.jp/english/products/evercap/list_f.htm	carbon EDLC
Shizuki	www.shizuki.co.jp/english/f_pr.html	carbon EDLC
SPSCAP	www.spscap.com	carbon EDLC

Table 3.2 Evaluated suppliers of supercapacitors - not observed in this work but may be prospective for application in HEV

Company/ Brand	Website	Notes
Advanced Battery Factory	http://www.splendidbattery.com/	
ALCAD Nickel Cadmium Batteries	http://www.alcad.com/	
Amperex Technology Limited	http://www.atlbattery.com/eng/productseries.asp	Li-Polymer
APL	http://www.aplbattery.com/	
B & K Technology	http://www.bkbattery.com/	Li-Polymer 4,5Ah, Li-Ion Power Battery 100Ah
BAT Scap	http://www.batscap.com/	UC, Li-Polymer
Bellcore		acquired by Telecordia
BMZ Batterien-Montage-Zentrum GmbH	http://www.bmz-gmbh.de/	battery packs
Bolder Technologies Pte Ltd	http://www.boldertmf.com/Product%20Spec-Single%20Cell.pdf http://www.boldertmf.com/Product%20Brochure-single%20cell.pdf	Thin Metal Film
Bullith Batteries	http://www.bullith.de/	Li, Ni-MH (small)
BYD	http://www.byd.nl/	Li, Ni-MH
Chung Pak Group	http://www.chungpak.com/pdf/ rechargeable/H700D.pdf	Ni-MH D-size
Coslight Group	http://www.coslightnewgen.com/index1.htm	VRLA, Li-Ion (small)
Daily Power Batteries	http://www.dpbatteries.com.hk/	supercaps/Ni-MH/lithium
Danionics	http://www.dpbatteries.com.hk/ products_details.php?cid=23&pid=149	Li-Polymer, JV with GP Batteries

Decktron	http://www.decktron.com/lit_rc_01.asp	Li-Polymer
Eagle Picher	http://www.epcorp.com	Lithium/Nickel
Edan Technology Corp.	http://www.edan.com.tw/	Prismatic Li-Ion, Li-Ion cylindrical
EEMB	http://www.eemb.com	Li-Polymer, LiMnO2, Li-Ion, Li-SO2, Ni-MH, NiCd, supercaps
Electro Energy Inc.	http://www.electroenergyinc.com/products.html	Ni-MH bipolar, Ni-MH pulse power, NiCd, Li-Ion
Electrochem	http://www.electrochempower.com/	
Electrovaya	http://www.electrovaya.com/	Li-ion-polymer
ENAX	http://www.enax.jp/battery/lsb/index.html	Li-polymer
E-One Moly Energy Corp.	http://www.e-one.com.tw/product/products13.html	Li-ion
ERUN GmbH	http://www.erun.ch/	Li-ion-pack
Fenghua Lithium Battery Co.	http://www.fenghua-lib.com/en/productlist.asp?id=5#	Li-Polymer
Firefly Energy	http://www.fireflyenergy.com	Pb, new AGM type
FOB China	not found	
Guangzhou Markyn Battery Co	http://www.gmbattery.com	Lithium Polymer (LiMn2O4)
HYB Battery	http://www.hyb-battery.com/Productshow.asp?CountryGroup=4	Li-ion
Hymotion	http://www.hymotion.com/pdf/Specs_PHEV_L5.pdf	Li-Polymer
Hyper Battery	http://www.hyperbattery.com/Documents/HYLPM_List.xls	Li-polymer packs
Impact	http://www.imotive.pl/products/battery_packs.htm	Li-ion
JAPAN STORAGE BATTERY CO	see GS Yuasa Corporation, Table 3.1	see GS Yuasa Corp.
Johnson Controls	http://www.jci.com/bg/	see subsidiaries and joint ventures
LifeBatt	http://www.lifebatt.com/index.html	Li-ion (LiFePO4)
Lishen	http://www.lishen.com.cn/lishenen/cpsz/cpzse.aspx	Li-ion, Li-Polymer
McNair Technology Co Ltd	http://www.mcnair-tech.com/	Li-ion/ Li-polymer (small)
Nanoexa	http://www.nanoexa.com/lithium.html	Li-ion/ Li-Polymer
NEC Lamilion Energy	http://www.lamilion.com/en/technology/index.html	Lithium
Nerada	http://www.naradalicom.com/english/product/index_5.htm	Li-Polymer
NGK	http://www.ngk.co.jp/english/products/power/nas/index.html	sodium/sulfur batteries (NAS)

Nissan	https://www.nissan-global.com/EN/TECHNOLOGY/INTRODUCTION/DETAILS/CLB/index.html	Compact Lithium-ion Battery
Phylion Batteries	http://www.xingheng.com.cn/en/products.html	Li-ion
Pionics	http://www.pionics.co.jp/index.html	
Powerstream	http://www.powerstream.com/Ni-MHP.htm	
Samsung	http://www.samsungsdi.com/contents/en/product/battery/battery.html	Li-ion, LiPo (only small found on web)
Sanyo	http://us.sanyo.com/batteries/specs.cfm	Ni/Cd, Li-ion, Ni-MH, LiPo, primary Lithium (only small found on web)
SEQUENCE TECHNOLOGY CO	http://www.seq2000.com/	Ni-MH, Li-ion, packs
SHIN-KOBE ELECTRIC MACHINERY CO., LTD	http://www.shinkobe-denki.co.jp	Li-ion
SK Mobile Energy	http://www.skme.co.kr/	Li-ion-polymer
Sony	http://products.sel.sony.com/semi/energy/productinfo.html	Ni-MH, Li-ion, LiPo (only small found on web)
Thunder Sky	http://www.thunder-sky.com/	ultra large Li-ion cells (10, 50, 100, 500 Ah), packs
Toshiba	http://www.toshiba.co.jp/about/press/2005_03/pr2901.htm	Li-Polymer (no data available on web)
Ultralife (Li batteries)	http://www.ulbi.com/	Li-ion-pack, Li-Polymer 3,3Ah
Uniross	http://www.uniross.com/UK/industrial/Lithium-Ion/0104	Li-ion 4,2V, Ni-MH D-size high power
VARTA microbatteries	http://www.varta-microbattery.com/en/oempages/index.htm	Ni-MH, LiCoO2
Worly Energy Cells	http://www.worley.com.au/wecs	batteries from KOKAM
Wuhan Lixing(torch) Power Sources Co. Ltd	http://www.lisun.com/	e.g.: Li-Polymer 8Ah, Li-ion Power 11Ah

Yoku	http://www.yokuenergy.com/en/proindex203.asp	Li-Polymer
Yuntong Power Co	http://www.yuntong-batt.com/	Ni-MH D-cell, NiCd, Li-ion, Li-Polymer, primary batteries
ZBB Energy Corporation (Zinc Bromine battery)	http://www.zbbenergy.com/	zinc/bromine
ZOXY (Zn-air, Germany)	website not found	zinc/air

Table 3.3 Evaluated suppliers of secondary batteries - not observed in this work but may be prospective for application in HEV

3.2 Characteristics and Requirements

Usually for international standardization the International Standardisation Organisation (ISO) is responsible. However for batteries the International Electrotechnical Commission (IEC) is responsible *(see chapter 2.7.2 Standards)*. As can be seen in Table 3.1 in this chapter it is focused on storages with electrical output and primarily on batteries. Thus, these standards may be relevant. Nevertheless, as already mentioned *(chapter 2.7.2)* these standards do not cover all battery types which are currently available. Moreover, detailed characteristics as described later in this chapter are not subject of standardization. Furthermore, the test procedure of hybrid vehicle application is completely different *(Barnes et al, 2003)* from that of conventional use resulting in a need for particular standards. They may be developed from lead users *(Hippel, 2005, p.22)*, accredited institutions or research programs.

An example of such an institution is NEDO, Kawasaki, Japan[9] which directs and organizes national research programs delegated by the ministry of economics, trade and industry (METI).

More often mentioned in literature and widely accepted are characteristics, test procedure and specification goals set by the Advanced Battery Consortium (USABC) of the United States Council for Automotive Research (USCAR) developed in cooperation with the Department of Energy's (DOE) FreedomCar program[10]. USCAR is an Umbrella organization of DaimlerChrysler, Ford and General Motors, formed to conduct cooperative, pre-competitive research[11].

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[9] http://www.nedo.go.jp/english/introducing/what.html

[10] http://www.uscar.org/guest/view_team.php?teams_id=12

[11] http://www.uscar.org/guest/index.php

For further considerations in this work, USABC characteristics are adopted as described in the USABC goals of supercapacitors and 42 Volt battery packs, respectively *(see Table 3.4)*. These characteristics are also used to describe kinetic storages with electric interphase.

However, definitions made for supercapacitors are not consistent and can be interpreted differently. A test manual as the ‘FreedomCAR Ultracapacitor Test Manual’ from 2004 *(Anonymous, 2004)* is available but test procedure is different from that of the goals *(Anonymous, 2004, App. F)*. For batteries, definitions are consistent. Regarding inconsistent definitions, assumptions were made descriped later.

Table 3.4 states characteristics and goals for a system of supercapacitors (ultracapacitor, ‘UC’) *(USABC, 2004)* and a 42 Volt battery system (‘42V’) *(USABC, 2002)*, both set by USABC. Goals refer to complete packages (inclusive cooling if necessary, etc).

For each system, three categories were defined (compare chapter 1), whereas the first two categories of supercapacitors and the first category of the 42 Volt battery system are considered for micro hybrids. The third category of supercapacitors and the second of batteries are considered for mild hybrids. Goals for plug-in hybrids are given in the third 42V battery category. Plug-in hybrids are not considered to use supercapacitors due to their low energy content *(USABC 2002 and 2004).*

As can be seen, characteristics of both systems are similar but they differ regarding parameters and test procedure *(USABC 2002 and 2004)*. Goals differ completely from category to category.

	UC							42V					
Characteristics	12V Start-Stop (TSS)		42V Start-Stop (FSS)		42V Transient Power Assist (TPA)		Characteristics	Start-Stop		M-HEV		P-HEV	
Discharge Pulse	4.2 kW	2s	6 kW	2s	13 kW	2s	Discharge Pulse Power (kW)	6	2s	13	2sec	18	10sec
Regenerative Pulse Power	N/A		N/A		8 kW	2s	Regenerative Pulse Power (kW)	N/A		8	2sec	18	2s
Cold Cranking Pulse @ -30 °C	4.2 kW	7 V Min.	8 kW	21 V Min.	8 kW	21 V Min.	Cold Cranking Power @ 30°C (kW)	8	21 V Min.	8	21 V Min.	8	21 V Min.
Engine-Off Accessory Load (kW)							Engine-Off Accessory Load (kW)	3	5min	3	5min	3	5min
Available Energy (CP @1kW)	15 Wh		30 Wh		60 Wh		Available Energy (Wh @3 kW)	250		300		700	
Recharge Rate (kW)	0.4 kW		2.4 kW		2.6 kW		Recharge Rate (kW)	2.4 kW		2.6 kW		4.5 kW	
Cycle Life / Equiv. Road Miles	750k / 150,000 miles		750k / 150,000 miles		750k / 150,000 miles		Cycle Life, Miles/Profiles (Engine Starts)	150k (450k) ????		150k (450k)		150k (450k)	
Cycle Life and Efficiency Load Profile	UC10		UC10		UC10		Cycle Life and Efficiency Load Profile	Zero Pwr Asst (ZPA)		Partial Pwr Asst (PPA)		Full Pwr Asst (FPA)	
Calendar Life (Yrs)	15		15		15		Calendar Life (Yrs)	15		15		15	
Energy Efficiency on UC10 Load Profile (%)	95		95%		95%		Energy Efficiency on Load Profile (%)	90		90		90	
Self Discharge (72hr from Max. V)	<4%		<4%		<4%		Self Discharge (Wh/day)	<20		<20		<20	
Maximum Operating Voltage (Vdc)	17		48		48		Maximum Open Circuit Voltage (Vdc) after 1 Sec.	48		48		48	
Minimum Operating Voltage (Vdc)	9		27		27		Minimum Operating Voltage (Vdc)	27		27		27	
Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52		Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52	
Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66		Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66	
Heat Rejection Coefficient (W/°C)							Heat Rejection Coefficient (W/°C)	N/A		N/A		>30	
Maximum Cell to Cell Temperature Difference (°C)							Maximum Cell to Cell Temperature Difference (°C)	N/A		N/A		<4	
Maximum System Weight (kg)	5		10		20		Maximum System Weight (kg)	10		25		35	
Maximum System Volume (Liters)	4		8		16		Maximum System Volume (Liters)	9		20		28	
Selling Price ($/system @ 100k/yr)	40		80		130		Selling Price ($/system @ 100k/yr)	150		260		360	

Table 3.4 Battery and supercapacitor goals set by USABC (source: USABC, 2002 and 2004)

In the following the USABC catalogue as shown in Table 3.4 is discussed briefly. Definitions stem from *USABC 2002 and 2004* and *Barnes et al, 2003*:

3.2.1 Discharge Pulse Power, Regenerative Pulse Power, Cold cranking pulse power @ -30°C

- Discharge Pulse Power is the discharge power capability for a 2 seconds pulse (10s for Plug-in HEVs)
- Regenerative Pulse Power is the pulse power generated during 2 seconds of regenerative braking. Simple start stop hybrids do not use regenerative braking and thus respective USABC goals are indicated with N/A.
- Cold cranking pulse power @ -30°C: Ambient temperature is -30°C. The test profile of both supercapacitors and batteries is 3 times discharge for 2 seconds with breaks of 10 seconds between each discharge. Generally voltage drop on the internal resistance increases during pulse discharge. Thus a minimum terminal voltage is given in Table 3.4.

(USABC 2002 and 2004; Barnes et al, 2003)

Generally for supercapacitors voltage and thus power depends on the state of charge. The state of charge (SOC) is defined as

SOC = charged Ah/ nominal Ah, [%].

A definition of the respective power characteristics mentioned above, which refers to a particular SOC was not found in the USABC goal description *(Anonymous, 2004)*. For this purpose in this work, discharge characteristics were defined at a SOC of 79%. For supercapacitors this value is equal to a state of energy (SOE) of 50%.

Explanation:

Corresponding to $V = Q\times (1/C)$ with voltage V in [Volt] and capacity C of capacitors in [Farad], voltage decreases to 0 when fully discharged (charge Q [Coloumb] = 0). In contrast, batteries show a relatively constant discharge curve. Thus total energy stored in a supercapacitor is

$$E_{total}=C\times V_{max}\text{^}2\ /2$$

For supercapacitors it was assumed that energy can be used between a SOC of 50% and 100% whereas for batteries between 0 and 100%. The energy content that can be stored in this window is called available energy with ‘available’ indicating, that it can be used *(Barnes et al, 2003)*.

The state of energy (SOE) is defined as the ratio of charged energy and available energy ([%])*(Barnes et al, 2003)*. For supercapacitors, the ratio of charged total energy

$$E_{charge}=C\times V_{charge}\text{^}2/2$$

and total energy stored E_{total} is defined as SOE_{total} in this work with

$$SOE_{total} = E_{charge}/E_{total} = (V_{charge} /V_{max})\text{^}2$$

Thus for the SOC it holds:

$$SOC=Q_{charge}/Q_{max}=(V_{charge} /V_{max}) = SOE_{total}\text{^}2$$

With

$$SOE_{total}(SOC=50\%) = 25\%$$

And

$$SOE_{total} (SOE=50\%) =$$
$$= 25\% + 50\%\times(\text{available energy window}) =$$
$$= 25\% + (100\%-25\%)/2 = 62{,}5\%$$

it results

$$SOC(SOE_{total}=62{,}5) = 62{,}5\%\text{^}0{,}5 = 79\%.$$

Moreover power depends on efficiency for both, supercapacitors and batteries *(Barnes et al, 2003)*. Efficiency is defined as the ratio of used power and power invested. Further considerations can be explained on a simple electric circuit illustrated in Figure 3.1.

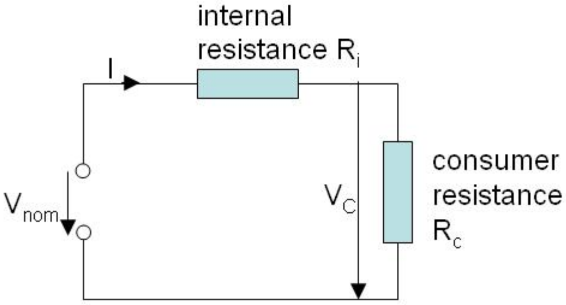

Figure 3.1 electric circuit

Power output P_c is a function of the battery’s nominal Voltage V_{nom}, the internal resistance Ri and the resistance of the electric consumer Rc:

$$P_c=V_c\times I$$

With

$$V_c = (R_c/(R_i+R_c)\times V_{nom})$$

$$I = V_{nom}/(R_i+R_c)$$

it results

$$P_c = (R_c/(R_i+R_c)^\wedge 2\times V_{nom}{}^\wedge 2).$$

For maximum power output it holds:

$$\text{with}\quad d\{ (R_c/(R_i+R_c)^\wedge 2\times V_{nom}{}^\wedge 2)\}/dR_c = 0.$$

$$R_i=R_c$$

Thus for maximal power output, impedance matching with $R_i=R_c$ is needed whereas in this case, efficiency

$$\eta= P_c/(P_c + P_i)$$

is only 50% because power drop on the electric consumer is equal to power loss according to heat generation (P_i) due to the internal resistance of the battery/supercapacitor.

In most cases, suppliers state the maximal power which the battery or supercapacitor is capable to deliver *(see the suppliers' datasheets, weblinks in Appendix B).* In this case, as described above, efficiency is equal to only 50%. Some suppliers also stated a minimum discharge voltage which is equal to a limitation of the ratio R_c/R_i. In these cases efficiency is higher than 50%.

USABC goals presume 90% efficiency for batteries *(USABC, 2002)* and 95% for supercapacitors *(USABC, 2004)* on the load profile which results in

$$\eta_{charge} = \eta_{discharge} = 95\%^\wedge 0{,}5 = 97{,}47\% \text{ for supercapacitors}$$
$$\text{and } \eta_{charge} = \eta_{discharge} = 90\%^\wedge 0{,}5 = 94{,}87\% \text{ for batteries.}$$

For the purpose of comparison of supplier data and goals, the USABC goals of 'discharge pulse power' and 'regenerative pulse power' were recalculated on a basis of 50% efficiency. Thus, characteristics are called '*Discharge Pulse Power @ Maximum (min 50% eff.); 2sec*' and '*Regenerative Pulse Power @ Maximum (min 50% eff.); 2sec*'. Therefore the goals of supercapacitors had to be multiplied with a factor of 10,13 and those of batteries by a factor of 5,14.

Derivation:

$$\eta = P_c/(P_c + P_i) = V_c \times I/(V_{nom} \times I) = V_c/V_{nom} = R_c/(R_i+R_c) = (R_c/R_i)/(1+R_c/R_i)$$

$$\Leftrightarrow$$

$$R_c/R_i = \eta/(1-\eta)$$

$$R_c/R_i(\eta=50\%)=1; \quad R_c/R_i(\eta=97{,}47\%)=38{,}49; \quad R_c/R_i(\eta=94{,}87\%)=18{,}49$$

$$P_c(\eta=50\%) = V_c(50\%) \times I(50\%) = V_{nom}/2 \times V_{nom}/(2\times Ri) = 0{,}25\times V_{nom}\hat{}2/R_i$$

$$P_c(\eta=97{,}47\%) = V_c(97{,}47\%) \times I(97{,}47\%) = 38{,}49/(38{,}49+1)\times V_{nom} \times V_{nom}/(R_i+38{,}49R_i) = $$
$$= 0{,}02467943\times V_{nom}\hat{}2/R_i$$

$$P_c(\eta=94{,}87\%) = V_c(94{,}87\%) \times I(94{,}87\%) = 18{,}49/(18{,}49+1)\times V_{nom} \times V_{nom}/(Ri+18{,}49R_i) = $$
$$= 0{,}048683298\times V_{nom}\hat{}2/R_i$$

$$P_c(\eta=50\%)/ P_c(\eta=95\%)= 10{,}13$$

$$P_c(\eta=50\%)/ P_c(\eta=90\%) = 5{,}14$$

Discharge pulse power and regenerative pulse power requirements as indicated in Table 3.4 are illustrated in Figure 3.2 for a common start stop maneuver. A mild hybrid using a 42Volt battery pack fulfilling USABC criteria is assumed.

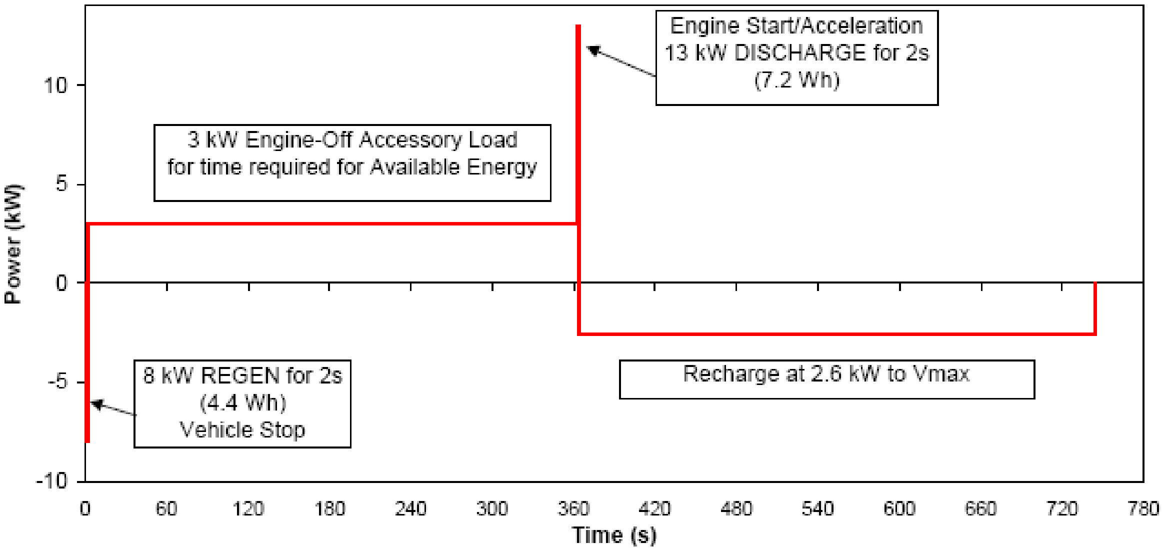

Figure 3.2 discharge and regenerative pulse power requirements of the USABC mild hybrid (M-HEV) (source: Barnes et al, 2003)

3.2.2 Available energy

The USABC test procedure *(Barnes et al, 2003)* defines available energy of batteries as the energy retrieved from a 3kW constant power discharge. In this work, available energy of batteries is calculated from the nominal capacity [Ah] and the nominal voltage as:

$$\text{Eavailable} = C_{nom} \times V_{nom}$$

Capacity and thus available energy stored depends on the charge-rate *(Barnes et al, 2003)*. Hence, further considerations base on the charge rate which is recommended by the supplier and which is equal to that defined in the characteristic discussed below.

For supercapacitors, as already mentioned, energy stored between a SOC window of 50 and 100% is assumed as 'available'. This is equal to 75% of the total energy storage capability. USABC *(USABC, 2004)* requires a 1 kW constant power discharge for measurement.

Subcritical flywheels as observed in this chapter can also use total energy content stored.

3.2.3 Recharge rate

This is the constant rate to fully recharge the storage with constant current, constant voltage (CCCV) without any break. It is stated as the product of current and voltage in [kW]. The recharge rate influences capacity and thus energy storage capability. Therefore suppliers state available energy in combination with the recharge rate.

However, in this work we use the so called 'C-rate' which is used by most suppliers and defined *(see for instance KOKAM, 2007)* as:

C-rate [1/h] = Charge current [A]/nominal capacity [Ah].

It indicates the duration to fully recharge a storage from SOC=0 to SOC=100. C5 for instance indicates a charge duration of 12 minutes whereas C/5 means C1/5 what results in a 5 hours charge.

In combination with nominal capacity, suppliers *(Table 3.1)* also use it to indicate (pulse) charge and discharge current. The advantage is, that for several batteries of a supplier, which use the same electrochemistry (voltage, cathode-, anode material), discharge/charge characteristics can be stated independently of the battery's capacity.

3.2.4 Cycle life

Respective goals *(USABC 2002, 2004)* are stated in number of cycles of respective load profiles, whereas one road profile equals one mile. The load profile of supercaps is called UC10 and shown in Figure 3.3. Regarding batteries for each category – start-stop-, mild- and plug-in hybrid - a particular load profile exists. Figure 3.4 illustrates the partial power assist profile. End of life is reached when the USABC goals can't be met *(Barnes et al, 2003)*.

However, most suppliers *(Table 3.1)* state life time in simple charge/discharge cycles with a Depth Of Discharge (DOD) window.

The Depth Of Discharge is the difference of two States Of Charge (SOC) *(Barnes et al, 2003)*. It can refer to a window which upper boarder is located at 100% SOC or below. The interpretation depends on the context.

Both, the location and the width of this window, influence life time of batteries essentially: Therefore, in current Mild Hybrids using batteries usually this window is only about 5% large and situated at an optimal SOC of about 55% whereas Plug-In Hybrids already utilize a broader window of about 25% located at about 70% SOC (Figure 3.5). *(EnerDel, 2007)*

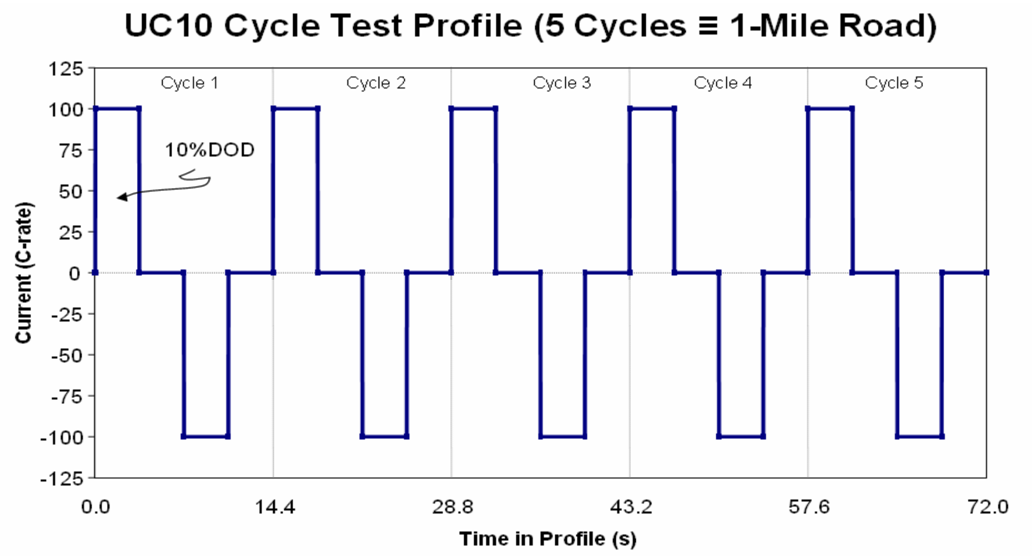

Figure 3.3 FreedomCar UC-10 test cycle (source: Anonymous, 2004)

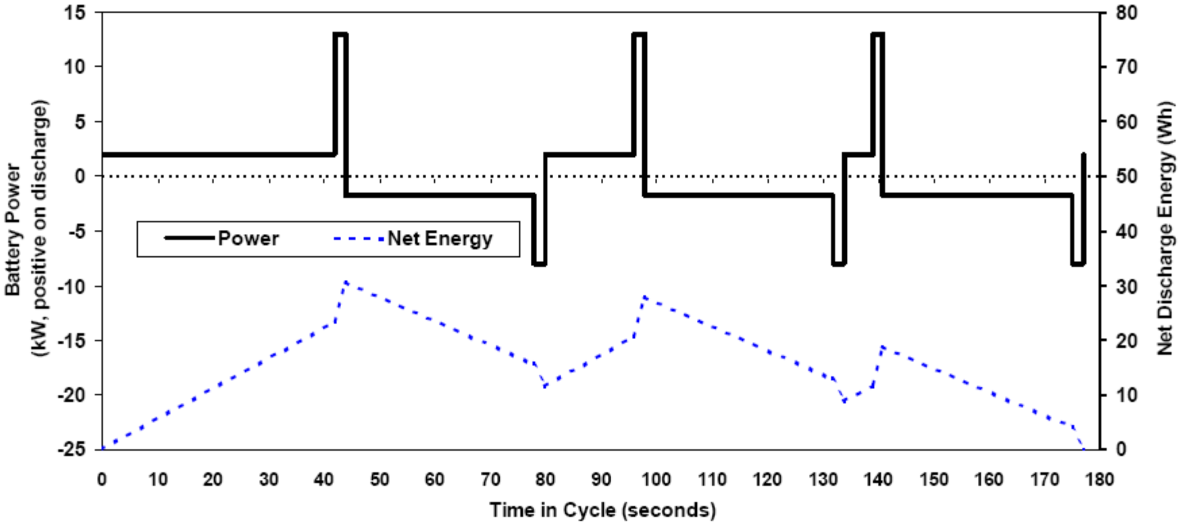

Figure 3.4 FreedomCAR partial power assist (PPA) profile (source: Barnes et al, 2003)

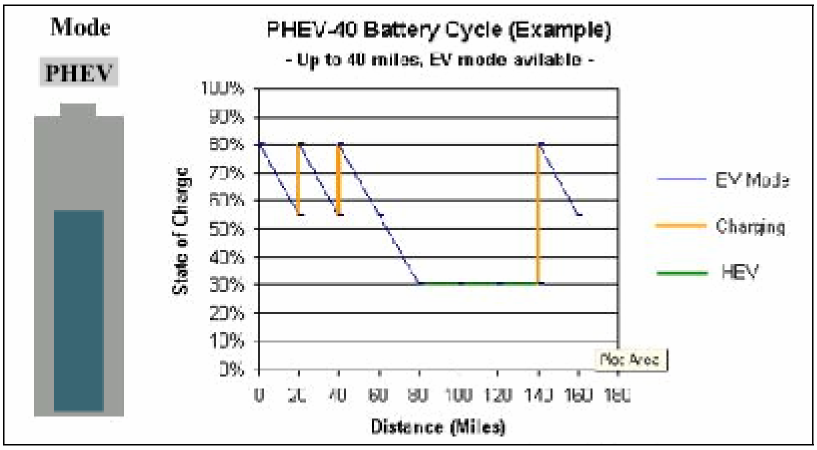

Figure 3.5 utilized DOD window of PlugIn hybrids (source: Enerdel, 2007)

Other major factors are charge/discharge c-rate and temperature *(Barnes et al, 2007)*.

3.2.5 Calendar life

The alendar life test "*evaluates battery degradation as a result of the passage of time with minimal usage. It is not a pure shelf life test, because the devices under test are maintained at or near a target SOE during the test*". *(Barnes et al, 2003)* Accelerated test methods use elevated temperatures to artificially increase rates of performance deterioration.

The corresponding end of life criteria *(Barnes et al, 2003)* for these parameters are:

- available energy < goal energy; and
- a minimum cold-start voltage < goal value

3.2.6 Energy efficiency

It is determined with 95% for supercapacitors *(USABC, 2004)* and 90% for batteries *(USABC 2002)* on the respective load profile,

with $\eta = 95\% = \eta_{charge} \times \eta_{discharge}$ and $\eta = 90\% = \eta_{charge} \times \eta_{discharge}$, respectively

and assuming that $\eta_{charge} = \eta_{discharge}$

it holds for supercapacitors: $\eta_{charge} = \eta_{discharge} = 95\%^{\wedge}0{,}5 = 97{,}47\%$

and for batteries: $\eta_{charge} = \eta_{discharge} = 90\%^{\wedge}0{,}5 = 94{,}87\%$

In most cases as already mentioned the collected data of regenerative pulse power and discharge pulse power is considered with efficiency of 50%. Therefore USABC goals were recalculated on a basis of 50% efficiency in order to be comparable with collected data.

3.2.7 Self discharge:

For batteries a definition was found *(Barnes et al, 2003)* defining self discharge as:

$$\text{Self - Discharge} = \frac{Wh_{3kW\ \text{before test}} - (Wh_{\text{part 1}} + Wh_{\text{part 2}})}{\text{Stand Time in Days}}$$

Before the test, the battery is discharged and then charged constantly with 3 kW. The energy content is measured and indicated with Wh @ 3kW before test. Then the battery is discharged to a defined intermediate energy state. After a stand period of one week, the energy storage is discharged and the remaining energy content is measured. Hence the energy loss due to self discharge is computed at the difference between measured charged and discharged energy. For batteries an average energy loss per day is calculated by dividing this value by 7. In respect to *USABC, 2004* self discharge of supercapacitors is calculated on the basis of 3 days.

3.2.8 Maximum Open circuit/ Operating Voltage and Minimum Operating Voltage

No additional explanation is necessary.

3.2.9 Operating Temperature range

It defines the ambient temperature the battery is capable to operate at. *(compare Barnes et al, 2003)*

3.2.10 Survival Temperature range

A definition was not found. Moreover no supplier gave information on it.

For further considerations the characteristic ‘Storage Temperature range’ was used which determines the temperature range at which the battery should be stored. Such an characteristic was indicated by most suppliers.

3.2.11 Heat Rejection Coefficient

It is only determined for plug-in hybrid vehicles *(USABC, 2002)*. No data was collected in respect to this coefficient.

3.2.12 Maximum Cell to Cell Temperature Difference

It is only determined for plug-in hybrid vehicles *(USABC, 2002)*. No data was collected in respect to this coefficient.

3.2.13 Maximum system weight

It bases on the complete system as it can be integrated in the vehicle. For batteries it includes the battery management unit (BMU) as well as battery cooling if necessary or several plugs. *(compare Barnes et al, 2003)*

3.2.14 Maximum system volume

The volumetric equivalent to maximum system weight.

3.2.15 Selling price

Goals made by USABC base on a production of 100.000 units per year *(USABC, 2002).* Unfortunately, corresponding to limited time, prices of observed energy storages, could not be evaluated.

3.2.16 Calculation of relative goals and characteristics

For further discussions, characteristics of investigated storages were calculated relative to weight and volume. Values divided by weight are called '**specific**' whereas values divided by volume are referred to '**densities**'. This nomenclature is consistent for the whole work. Data about **total mass** and **volume** was also collected as:

- **Maximum System Weight (kg)**
- **Maximum System Volume (Liters)**

Characteristics, as they were used in this work, are shown in Table 3.5:

- Regarding '**Recharge Rate**', data was collected using the c-rate definition instead of the kW definition (see 3.2.3).
- Concerning '**Cycle Life**', data provided by suppliers was only given in numbers of simple charge-recharge cycles performed in a specified DOD window as mentioned before. For further considerations cycle life of suppliers' data as well as USABC goals were calculated to the cumulative energy equivalent, charged or discharged during lifetime. In order to be able to compare data to goals of the partial power assist (PPA) *(USABC, 2002)*, repective values were calculated on the same basis. Therefore energy was cumulated from the respective load profile of a partial power assist (Figure 3.4) and multiplied with the respective cycle number set in *USABC, 2002*.

- Because cycle life in particular depends on the size of the DOD window and the c-rate of charge/discharge these values (see 3.2.4), respective **DOD and c-rate**, were collected, too, as **parameters** of cycle life.
- Regarding **cycle and calendar life** collected data relies on the suppliers' data whereas in some cases it was not stated explicitly. In these cases end of life was assumed at 80% of nominal capacity due to capacity detoriation.
- In order to measure **self discharge** independent from the batteries size, self discharged Watt-hours, as defined in *Barnes et al, 2003* are stated as a ratio to available energy in [%/day]. In order to be able to compare storages on the same basis, self discharge rates of supercapacitors also refer to only one day in this work and not to 3 days as defined by *USABC, 2004*.

  Considering self discharge, it has to be mentioned that for both, batteries and supercapacitors, but in particular for supercapacitors, self discharge rates are higher in the first hours after charge than some days later. *(see* [constant - e^{time}] gradient in *Figure 3.11, later in this work)* Collected data refers to the first 24 hours and thus differs from the average of a total week as presumed in the USABC goal.
- **Storage temperature** was added as characteristic because it was mentioned by most suppliers.

3.2.17 Additional Characteristics

Additionally, data was collected about the product and the company

- supplier name or brand name,
- the supplier's holding,
- the product name or description,
- hyperlink to the data sheet of the respective product,

as well as about the classification of technology

- Technology: flywheel/ supercap/ Lithium/ Nickel/ LeadAcid/ High Temperature,
- technology subgroup: electricoutput/ EDLC, Hybrid, PseudoCap/ LiIon, LiIonPolymer/ Ni-MH, NickelZinc/ VRLA/ ZEBRA,
- the cathode material or rotor material of the flywheel, respectively,
- the constitution of the electrolyte,

- the anode material or the housing of the flywheel, respectively,

and about data describing the total system:

- is it a cell, module or package,
- is an external cooling system necessary,
- nominal system voltage,
- total number of cells in system.

Characteristic	M-HEV[12]
Specific Discharge Pulse Power @ maximum (min 50% eff.); 2sec (kW/kg)	2,670
Discharge Pulse Power density @ maximum (min 50% eff.); 2sec (kW/l)	3,338
Specific Regenerative Pulse Power @ maximum (min 50%eff); 2sec (kW/kg)	6,4
Regenerative Pulse Power density @ maximum (min 50%); 2sec (kW/l)	2,054
Specific Cold Cranking Power @ -30°C maximum (min 50% eff.) 2sec (kW/kg)	0,32
Cold Cranking Power density @ -30°C, maximum (min 50% eff.), 2sec (kW/l)	0,4
Specific Available Energy @ 3 kW (Wh/kg)	12
Available Energy Density @ 3 kW (Wh/l)	15
Recharge rate (C-rate) @ any[13] η (1/h)	2,6
Specific Cycle Life @ 25°C, end of life:80 % of capacity, parameter: c-rate + DOD (kWh / kg)	339,96
Cycle Life Density @ 25°C, end of life:80 % of capacity, parameter: c-rate + DOD (kWh / l)	424,95
Calendar Life (Yrs)	15
Self Discharged Wh of Available Energy after 1 Day @~23°C temperature (%/day)	6,7
Operating Temperature Range (°C)	-30 to 52
Storage Temperature Range (°C)	--
Maximum System Weight (kg)	25
Maximum System Volume (Liters)	20

Table 3.5 Characteristics used in this work and goals derivated from USABC (source: based on USABC 2002 and Barnes, 2003)

3.3 Supplier data

In the following it is described how data was calculated from information given by suppliers. The calculations are illustrated on the examples of three products *([14], [15], [16])*:

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[12] values based on *USABC, 2002* were modified: see chapter 3.2 and in particular the *Derivation* in 3.2.1

[13] no difference was made regarding different recharge efficiency

Category	Product	Supplier	Mass [kg]	Volume [l]
Flywheel – electric output	Hybrid[14]	Compact Dynamics	40	22,81
Supercap – carbon EDLC	BMOD0165 P048 - package[15]	Maxwell	14,2	12,6
Battery – Li-ion – C/LiFePO4	Epoche – EU1[16]	Valence Technologies	7	4,84

Table 3.6 Examples of a flywheel, a supercap and a battery

However, calculations of characteristics may vary from product to product. In these cases different ways of calculation are also described briefly.

3.3.1 Discharge Pulse Power @ Maximum (min 50% eff.); 2sec [kW]

As mentioned in 3.2.1 and 3.2.6, discharge pulse power is considered at its maximum. Thus, regarding batteries efficiency is 50%. Regarding batteries where a a cut-off voltage was stated, efficiency is more than 50%. Hence, the characteristic is stated with the additon '@ Maximum (min 50% eff.)'.

- Flywheel: discharge power is given explicitly as 120 kW resulting in 3 kW/kg and 5,26 kW/L for mass and volume given in table Table 3.6.
- Supercap: the electrical series resistance (ESR) for DC is given with 7,1 mOhm. Thus according to impedance matching in order to achieve maximal power output, power could be calculated from the equation:

  $$P(SOC=100\%) = V_{nom}\hat{}2/(4\times ESR_{DC})$$

  Dividing by a total mass of 14,2 kg specific discharge pulse power was already calculated by Maxwell with 7900 W/kg. However, in the calculations an ESR for 1 kHz with 5,2 mOhm instead of an ESR for DC is asumed. Thus this value was corrected by multiplying with a factor of 0,72 corresponding to the ratio of resistances 5,1/7,1. This results in 5785,92 W/kg and 5,79 kW/kg, respectively.

  Furthermore, P(SOC=100%) indicates that this value represents power capability for a fully charged capacitor. However, in this work performance of supercaps is

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[14] http://www.compact-dynamics.de/anfahrt_adresse.html

[15] http://www.maxwell.com/pdf/uc/datasheets/mc_energy_series_48_1009364_rev5.pdf

[16] http://www.valence.com/assets/pdf/vlnc_epoch_data_sheet.pdf

compared at a SOE of 50%. Therefore this value has to be multiplied by 0,625. This is explained in the following:

As described in the previous part of this chapter, a SOE of 50% is equal to a SOC of 79%. According to V = Q/C (V..voltage, Q..charge, C.. capacity) and the definition of the SOC (3.2.1), voltage is direct proportional to the SOC and with

$$P(SOC) = V(SOC)^\wedge 2/(4\times ESR_{DC})$$

power is proportional to the square of the SOC.

Thus it holds:

$$P(SOE=50\%) = 0{,}79^\wedge 2 \times P(SOC=100\%) = 0{,}625 \times P(SOC=100\%)$$

Hence, concerning our example, specific discharge pulse power results in 3,76 kW/kg. Considering the ratio of mass (14,2 kg) to volume (12,6 L) the respective density is 4,24 kW/L.

- Battery: Regarding battery suppliers, discharge power for a 2 seconds pulse was hardly given explicitly. In some cases ‘10 seconds pulse power’ was given and used as an approximation when no other data was available.

  In our example of a 12,8 Volt package from Valence Technologies Inc., a specified cut off voltage with 10 Volt was given, which indicates a minimum terminal voltage. Terminal voltage decreases at higher discharge rates due to an increase of the internal resistance of the battery. Thus, cut-off voltage can be interpreted as a limitation of the voltage drop due to the internal resistance increase in order to prevent heat increase and damage of the battery’s cells.

  A maximal discharge current corresponding to cut-off voltage was evaluated from a set of discharge curves as illustrated in Figure 3.6. This plot refers to a product called ‘E1’ but characteristics should be the same for the observed product ‘EU1’, which is from the same series.

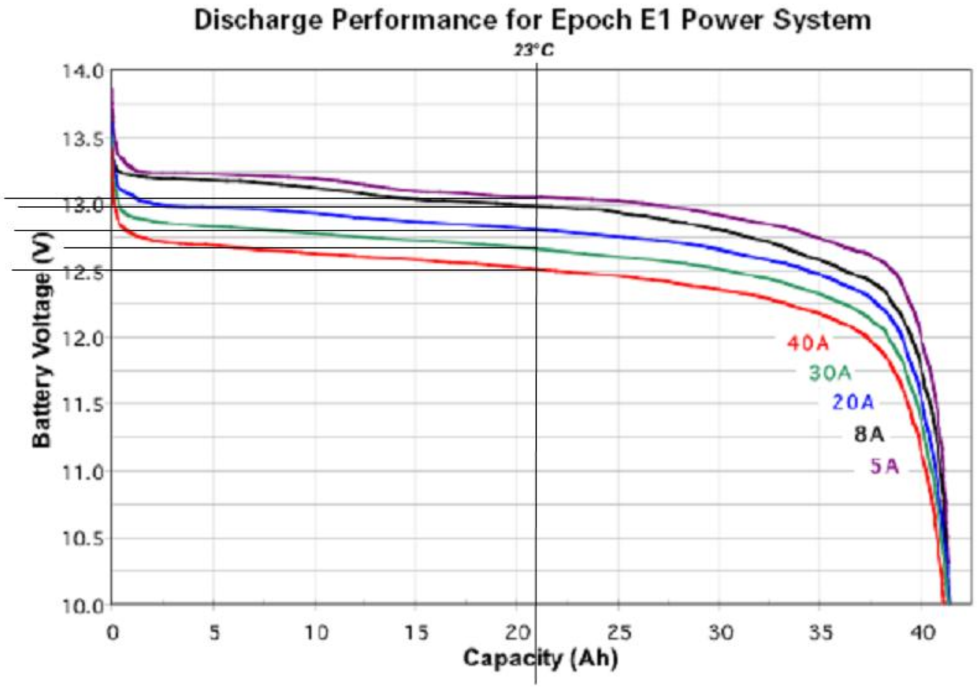

Figure 3.6 Discharge curves at various discharge rates at 23°C ambient temperature (source: Valence Technologies[16])

Other suppliers indicate the C-rate instead of current. However information content is the same when nominal capacity of the cell or battery pack is given additionally. Terminal voltage and discharge current were read off from the discharge curve at 50% of nominal capacity as shown in Table 3.7. According to Ohm's law the ratio of nominal voltage minus terminal voltage and discharge current, is the internal resistance. Assuming that it is constant up to high discharge pulses current in respect to cut-off voltage can be estimated from a regression shown in Figure 3.7.

discharge current [A]	terminal Voltage [V]
5	13,06
8	12,98
20	12,81
30	12,67
40	12,53

Table 3.7 Values of the discharge curve of Figure 3.6 (source: based on Valence Technologies[16])

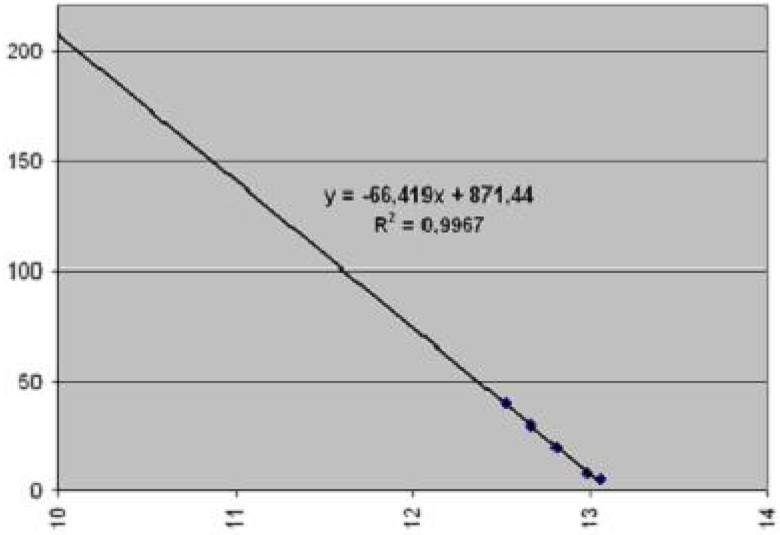

Figure 3.7 Linear regression (R^2=0,997) to predict maximum discharge rate at cut-off voltage (source: based on Valence Technologies[16])

Hence, discharge current could be predicted as 207,25 Amperes for 10 Volt cut off voltage and thus, according to P= V×I power could be calculated as 2,07 kW. With mass of 7 kg and volume of 4,84 liter the specific value is 0,30 W/kg and the density is 0,43 W/L.

Some battery suppliers don’t state a cut-off voltage. In these cases terminal voltage was set to the half of nominal voltage according to impedance matching in order to achieve maximal power. For maximal power the internal resistance has to be equal with the resistance of the electric consumer and hence terminal voltage has to be the half of nominal voltage.

3.3.2 Regenerative Pulse Power @ Maximum (min 50% eff.); 2sec [kW]

- Flywheel: Regenerative pulse power is equal to discharge pulse power.
- Supercap: It holds the same: regenerative pulse power is equal to discharge pulse power.

- Battery: for our example as for any other products, respective data was not available. Regenerative pulse power calculations are discussed on KOKAM's '11043140H Ultra high power'[17] cell:

  According to the datasheet a maximal charge current was limited to 9,6A whereas charge voltage of KOKAM cells is indicated with 4,2V resulting in 0,04 kW for one 11043140H cell. Considering mass with 0,115 kg and volume with 0,065 liter specific regenerative pulse power is 0,35 kW/kg and regenerative pulse power density is 0,62 kW/L.

3.3.3 Cold Cranking Power @ -30°C, Maximum (min 50% eff.); 2sec [kW]

- Flywheel: Cold Cranking Power was estimated as equal to discharge pulse power at 23°C. Due to different characteristics of lubricants at -30°C friction may be higher leading to lower performance. Thus, values of 3 kW/kg and 5,26 kW/l represent an approximation.
- Supercap: As all supercap suppliers, Maxwell gave information on low temperature performance in the form of an increase of the electric serial resistance measured in %. In this example the ESR at -30°C was only 150% of that at 23°C due to the use of acetonitrile as electrolyte additive *(see chapter 2.5)*. Considering the calculations of discharge pulse power, power is indirect proportional to ESR and thus cold cranking pulse power at -30°C was simply divided by 150%. The respective values are 2,51 kW/kg and 2,83 kW/L.
- Battery: Battery suppliers hardly state data concerning cold cranking power at -30°C. Some few suppliers as SAFT and A123 gave explicit information for minus 25°C or in form of discharge plots. This was used as an approximation.

  Others state an operating discharge temperature range starting over -30°C *(e.g. KOKAM, Appendix B)* and thus cold cranking power was set to the Boolean value 'fail'.

  However, in our example from Valence Technologies, discharge plots in dependence of temperature were available as shown in Figure 3.8.

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[17] http://www.kokam.com/product/product_pdf/rc_070226/SLPB11043140H_4800mAh_Grade.pdf

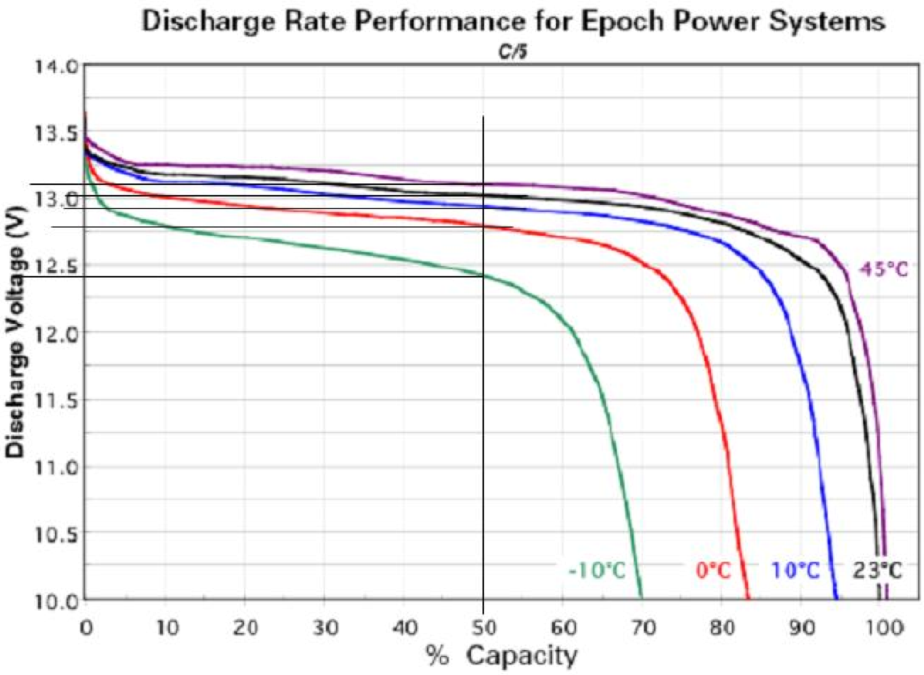

Figure 3.8 Discharge curves at various temperatures at a discharge-rate of C/5 (source: Valence Technologies[16])

Data, as shown in Table 3.8, was read off at 50% of nominal capacity.

Terminal Voltage [V]	Temperature [°C]
13,11	45
13,06	23
12,92	10
12,80	0
12,42	-10

Table 3.8 Data of Figure 3.8 (source: based on Valence Technologies[16])

Figure 3.9 illustrates a regression basing on this data and assuming a parabolic characteristic. Therefore terminal voltage at -30°C could be predicted with 11,74 Volt which is 90% of the value at 23°C.

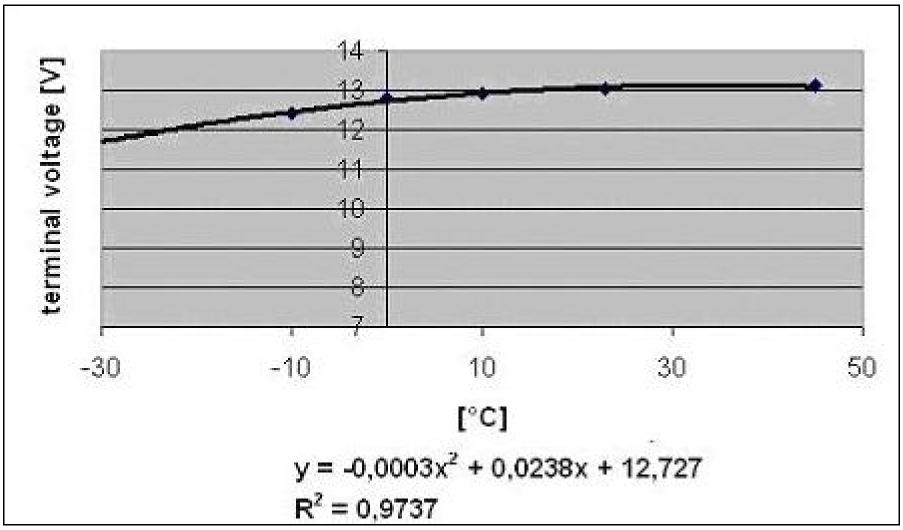

Figure 3.9 Parabolic regression (R^2=0,97) to predict terminal voltage at -30°C (source: based on Valence Technologies[16])

For each measured point, test current was the same. Hence, according to Ohm's law

$$I = V_i / R_i = \text{const.}$$

Thus for terminal voltage drop it holds: $V_{term} = V_{nom} - V_i$

$$\Leftrightarrow$$

$$V_{term} = V_{nom} - R_i \times \text{const}$$

Generally, for a linear function the percentual decrease on the y-axis is equal to the percentual increase on the x-axis (|elasticity|=1). Therefore the voltage decrease of 10% results from an internal resistance increase of 10%.

Considering maximum power as $P = V_{nom}$^2/4/R_i *(see impedance matching, 3.2.1)*, cold cranking pulse power is 100%/110% = 91% that of discharge pulse power at 23°C. Thus, for specific discharge pulse power it results 0,269 kW/kg and for the density 0,390 kW/L.

3.3.4 Available Energy @ 3 kW [Wh]

- Flywheel: Available energy was stated with 2750 kJ resulting in 19,10 Wh/kg and 33,49 Wh/L.
- Supercap: Specific energy was given with 3,81 Wh/kg. Multiplied with 0,75 specific available energy (defined in 3.2.2) was calculated as 2,86 Wh/kg. For the respective density it follows with the ratio of weight to volume (0,127, see Table 3.6) 3,22 Wh/L.

- Battery: Available energy was calculated as a product of the battery‘s nominal voltage and nominal capacity. In our example the 12,8 Volt battery had a nominal capacity of 42 Ampere hours resulting in 76,8 Wh/kg and 111,1 Wh/L.

3.3.5 Recharge rate (C-rate) @ any η [1/h]

- Flywheel: The Recharge rate was not considered as characteristic of flywheels. It can be assumed to be equal to regenerative pulse power.
- Supercap: The Recharge rate was not considered as characteristic of supercaps. It can be assumed to be equal to regenerative pulse power.
- Battery: In most cases a recommended charge current was given but some other suppliers stated it explicitly. In our example charge current is recommended with 40A and capacity is 42Ah what results in a charge rate of C0,95.

3.3.6 Cycle Life @ 25°C (end of life: 80 % of capacity) [kWh], parameter: C-rate + DOD

- Flywheel: The manufacturer stated 5 million full cycles. Multiplied with specific and volumetric available energy of 19,10 Wh/kg and 33,49 Wh/L, respectively this is equal to 95486,11 kWh/kg and 167448,99 kWh/L at a DOD of 100%.
- Supercap: Maxwell stated a life of more than 1 million cycles, cycled between specified a voltage, where SOC is 100% and half rated voltage under constant current at 25 °C. This covers exactly the range of available energy and corresponds to a DOD of 50%. Multiplying 1.000.000 cycles with 2,86 Wh/kg and 3,22 Wh/L, respectively, for cycle life it results 2.857,50 kWh/kg and 3.220,36 kWh/L.
- Battery: As most suppliers Valence technology provided a plot shown in Figure 3.10 indicting capacity fade due to cycling. Most battery suppliers set a remaining capacity of 80% as end of life. Considering Figure 3.10 and continuing the line for 23°C, cycle life may exceed 2500 cycles. However, the manufacturer stated cycle life explicitly with 2000 cycles at 100% DOD and noticed that cycles were performed “*under normal conditions*”[16]. The second parameter, the c-rate, was assumed to as C/2 as indicated on the top of Figure 3.10.

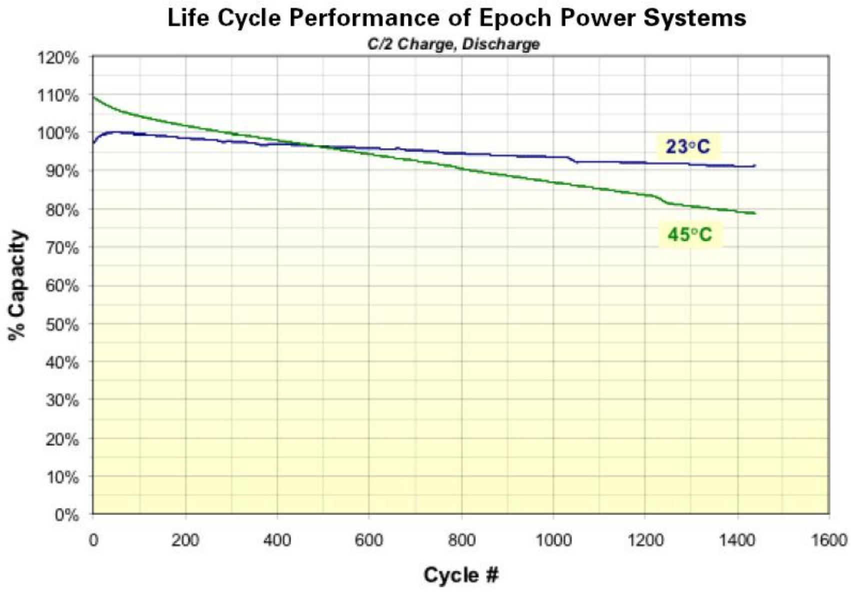

Figure 3.10 Capacity fade (source: Valence Technologies[16])

3.3.7 Calendar Life [Yrs]

- Flywheel: No information was given.
- Supercap: 10 years were indicated.
- Battery: In our example no information was available.

3.3.8 Self Discharged Wh of Available Energy after 1 Day @ ~23°C temperature [%/day]

- Flywheel: No information was given.
- Supercap: Maxwell stated that their supercapacitors loose 1,2% of energy stored per the first day *(Maxwell, 2007)*. Considering, that only 75% of total energy is 'available' this is equal to 1,6% energy loss of available energy.
- Battery: As for most battery products, in our example no data was available on self discharge.

  Regarding Ni-MH packages, SAFT provided a plot as shown in Figure 3.11. Hence, charge retention for SAFT's NHE modules[18] is approximately 4 % per day. Presuming a flat discharge curve, charge retention is equal to energy loss. For Cobasys Batteries, a similar plot was provided with approximately 5% charge retention per day *(Kopera, 2004).*

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[18] http://www.saft.fr/130-Catalogue/PDF/NHE_en.pdf

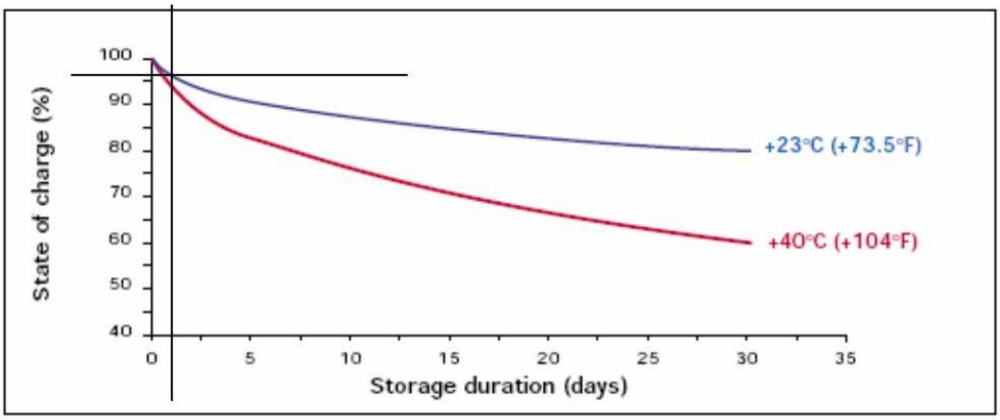


Figure 3.11 Self discharge characteristics of Saft's NHE module (source: SAFT[18])

3.3.9 Operating Temperature Range [°C]

- Flywheel: A broad temperature range starting at -40°C to 150°C was stated.
- Supercap: Maxwell stated that their supercaps can operate between -40 and 65 °C.
- Battery: Valence Technologies stated a range of -10 to 45°C.

3.3.10 Storage Temperature Range [°C]

- Flywheel: No information was given.
- Supercap: Storage temperature was indicated in a range from -40 to 70°C.
- Battery: A range starting from -40 to 70°C was indicated.

3.4 Data analysis

3.4.1 Interpreting Ragone plots

3.4.1.1 Power vs. energy

A so called 'ragone plot', illustrates specific power over specific energy *(suppliers, Table B.1)*. Such a plot is shown in Figure 3.13, whereas it has to be underlined, that values in this plot base on specific 2s pulse power and available energy as defined in 3.2. In Figure 3.13 all - cells, modules and packages - are illustrated in one plot. They can be distinguished by the characters 'c', 'm' and 'p' stated at the beginning of the respective denotation.

Plots showing only the packages are given in Figure 3.15 and Figure 3.16. Enlargements of the left (supercaps) and right rectangle (batteries) highlighted in Figure 3.15 are given in Figure C.1 and Figure C.2. However, these plots are not significant because important technologies, especially new ones as for instance the VL-V series of SAFT, are not included because no packages were supplied at the moment when writing this work.

An analysis of Figure 3.13 is given in Figure 3.14. In this plot, clusters of the respective technologies are highlighted. Ratios of power to energy stated as 'P/E' are drawn in as lines crossing the origin.

It can be seen, that supercapacitors have the highest P/E ratio due to small available energy content but relatively high power capability (*Table B.2*). They are followed by flywheels, then Li-ion, Ni-MH and VRLA batteries and finally by Li-ion-polymer and ZEBRA (NaNiCl2) batteries.

Regarding packages and modules, consisting of several cells of a particular electrochemistry, it can be concluded that, they lie on the particular P/E line:

When implementing cells into a package, weight raises due to additional material used for housing or due to the installation of a cooling system or a battery management unit. At the same stage, energy and power content remains the same and is equivalent to the aggregated content of installed cells. Hence, for the implementation of cells into modules or packages, specific power and specific available energy decrease in the same ratio. This equals to a **shift along the P/E** line to the origin.

Moreover, regarding batteries, **design** and a particular **electrochemistry** determines a P/E ratio:

Assuming maximal 2s pulse power according to impedance matching as

$$P = V^2/4/R_i$$

(compare considerations in chapter 3.2.1)

and energy as $E = C \times V$

(V..voltage, R_i..internal resistance, C..capacity) it holds for the ratio

$$P/E \sim V/(R_i \times C).$$

Moreover, between R_i and C it exists an indirect proportional relation: when the battery's electrodes and thus its capacity is increased its internal resistance decreases. (In this case we have to assume that the battery design e.g. the terminals are scaled up by the same factor.) This can be compared to a parallel connection of several batteries what multiplies the system's total capacity on the one hand and decreases internal resistance of the total system on the other hand. Hence, $R_i \times C$ is a constant and it depends on the design of the cell. This results in

$$P/E=V/const.(design)$$

Regarding a particular battery type, cell voltage is determined by the electrochemistry and thus it is constant as well. Concerning P/E it can be concluded:

$$P/E = P/E(electrochemistry, design)$$

Power and energy capability depends on the design of a cell *(Cuenca, Gaines, 2000)*: High-power cells need a large surface area and thin electrodes, whereas high-energy cells need more material, so larger particle sizes are best for them. However, P/E modification due to desing can be assumed as limited. Hence, all batteries basing on the same electrochemistry from various suppliers should lie close to a common P/E-line. This can be observed for several Ni-MH batteries using the same electrochemistry (AB5-alloy anodes) as highlited in Figure C.2 or in Figure C.3 (ellipse). Other examples are Li-ion batteries using LMO/LTO as highlighted in Figure 3.14 or different designs of KOKAM cells. 45205130P and 75106100 cells of KOKAM are shown in Figure 3.14. These two cells characterize KOKAM's boarders of different P/E ratios due to design modification.

Moreover, the shift to the origin along a P/E-line can be seen on the example of Cobasys' series 1000 modules implemented in a 'Cobasys 42-15' system.

However, some suppliers as SAFT are able to widely modify the P/E ratio for a given electrochemistry. An example is SAFT's VL12V and VL27M cells shown in Figure 3.14, whereas SAFT uses the same technology for both cells *(Table B.1)*. The reason for the considerable differences of SAFT cells may be a variation of the stochiometric ratio of doping materials (Al) in relation to lithium-nickel-cobalt oxide used in the cathode. However, this guess could not be confirmed.

3.4.1.2 Product efficiency in an economic meaning

Considering the term of efficiency in an economic meaning, efficiency is defined as the ratio of outputs to inputs, whereas outputs should be maximized under a minimized consummation of inputs. Hence, power and energy content, cycle life, etc. can be interpreted as outputs and weight or volume as inputs.

For a two-dimensional view, which only considers spec. available energy and spec. power as outputs, products with a specified P/E ratio which lie farther from the origin are more efficient as those which are closer to it. The latter are called x-inefficient products. The set of all efficient products form the efficient envelopment which is characterized as the upper and the right frontier in a Ragone plot. Of course, regarding such considerations only cells should be compared to cells, modules to modules and packages to packages because any cell would be more efficient as any package as discussed in 3.4.1.1.

A plot illustrating efficient envelopments for each technology is given by *SAFT, 2006a* on cell level and shown in Figure 3.12. Crosses indicate the envelopment evaluated in this work (green (light grey)..supercaps, yellow (white)..flywheels, blue(black)..Li-ion and red (dark grey)..Li-ion-polymer), which is indicated in Figure 3.14 as the boarders of the various clusters.

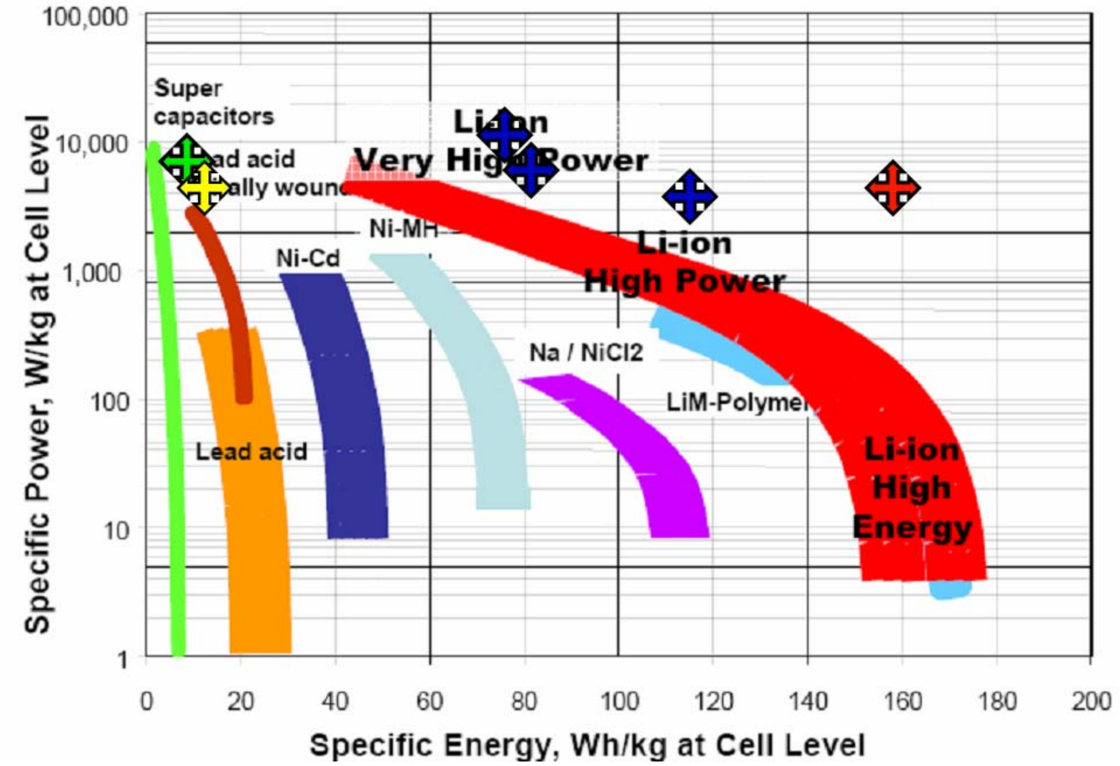


Figure 3.12 efficient envelopment of various technologies (source: SAFT, 2006a)

As can be seen, specific power of various technologies evaluated in this work is higher as that stated in *SAFT, 2006a*. However, primary reason is, that in this work power was evaluated only for a 2 seconds pulse. For higher pulse durations, power decreases. This underlines the importance of exact definition of characteristics when comparing values as it was done by USABC.

However, such a two-dimensional evaluation of product efficiency would be misleading, anyway because other output dimensions as cycle life, low temperature performance and recharge capability would be neglected. In this work, a multi dimensional evaluation using recent mathematical methods as the 'data envelopment analysis, DEA' was considered but in the end it was not feasible due to the incomparability of an important output: cycle life. Data about cycle life was collected in the form of cumulated energy throughput until end of life (in kWh). It depends on two parameters, the Depth Of Discharge (DOD) and the c-rate (see chapter 3.2.4). Failed attempts to transform cycle life data to uniform parameters are discussed in chapter 3.4.2.

3.4.1.3 USABC Goals

In Figure 3.14 and Figure 3.16 modified USABC goals concerning the 42Volt Start-Stop, M-HEV and Plug-In-HEV system as described in chapter 3.2 are drawn in as black boxes with a white cross. The respective P/E lines are also shown and denoted. Two issues are eye-catching:

- As can be seen, USABC calculates a higher P/E ratio for mild hybrids as for plug-in hybrids or even for start-stop systems.
- Moreover, the highest specific values are considered for start-stop systems in comparison to a mild or a plug-in system. This means a regress in specific values from start-stop system to mild hybrids.

Both may seem strange at the first sight but can be explained as follows:

- USABC *(Barnes et al, 2003, Figure 2,3,4)* calculates 13 kW for a mild hybrid regarding a start stop maneuver, which consists of engine cranking plus acceleration assisting. In contrast to mild hybrids, start stop systems are not considered for any acceleration assisting and thus do not have to offer such high power capabilities.
- Moreover, start-stop systems may be considered to be integrated in conventional vehicles. Hence, all additional weight is problematic. Whereas in mild hybrids, a combustion engine is downsized and saved weight can be traded off against additional weight of the electric system consisting of electric machine and storage. Regarding plug-in hybrids, weight can even be saved by downsizing a tank and limitation of fuel because energy can be stored alternatively in the electric storage in order to obtain the same range.

The different goals for the respective forms of hybrids may cause problems. Interpreting the development of start-stop systems, mild hybrids, plug-in hybrids to electric vehicles as a continuous process of the electrification of the car, storage manufacturers have to develop different storages for each successive stage. For instance, the P/E ratio of storages integrated in mild hybrids is higher as that what is optimal for plug-in hybrids. Regarding batteries as mentioned in 3.4.1.1, a manufacturer has limited possibilities to change this ratio which is primarily determined by the electrochemistry of the storage. Thus, manufacturers may face problems.

Moreover, battery types with lower P/E ratio, as for instance the ZEBRA battery or Nickel/Zinc systems are probably not considered for mild hybrids but may become more attractive for plug-in hybrids.

Regarding the strived P/E ratio of start stop systems, a conventional lead-acid battery in combination with supercapacitors may make sense as well as Li-ion batteries. Ni-MH batteries are also imaginable but show poor low-temperature performance, discussed later, and thus are probably not attractive for start-stop systems.

Regarding mild hybrids, currently, Ni-MH in combination with lead acid batteries for cold cranking at low temperature is predominant *(*compare *Panasonic EV Energy, 2007)*. However, the Li-ion battery seems to become the predominant technology in future: In particular new developments as batteries using LMO (2.7.17.2.2) as cathode material and relatively safe LTO (2.7.17.2.1) as anode material show both, P/E ratios close to derived USABC goals (see Figure 3.14, ellipse 'LMO-LTO') and high specific values of about 5kW/kg and 50 Wh/kg on cell level. Assembling such sells to packs would mean a shift to the origin. Then values would meet or still top derived USABC goals highlighted in Figure 3.14.

Recently often discussed Lithium-iron-phosphate shows high specific values but the P/E-ratio is lower as that strived by USABC goals. However, it would fulfill derived USABC criteria.

SAFT's new VL-12V and VL-6A cells are at closest to strived P/E specifications and show excellent specific values up to 12kW/kg and 74 Wh/kg at cell level. However, they use moderately to low-safe cathode materials (*Table 2.14*).

Li-ion-polymer batteries have low P/E ratios and seem to be appropriate only for plug-in hybrids or electric cars.

When considering only ragone plots flywheels may be appropriate for start stop systems and mild hybrids.

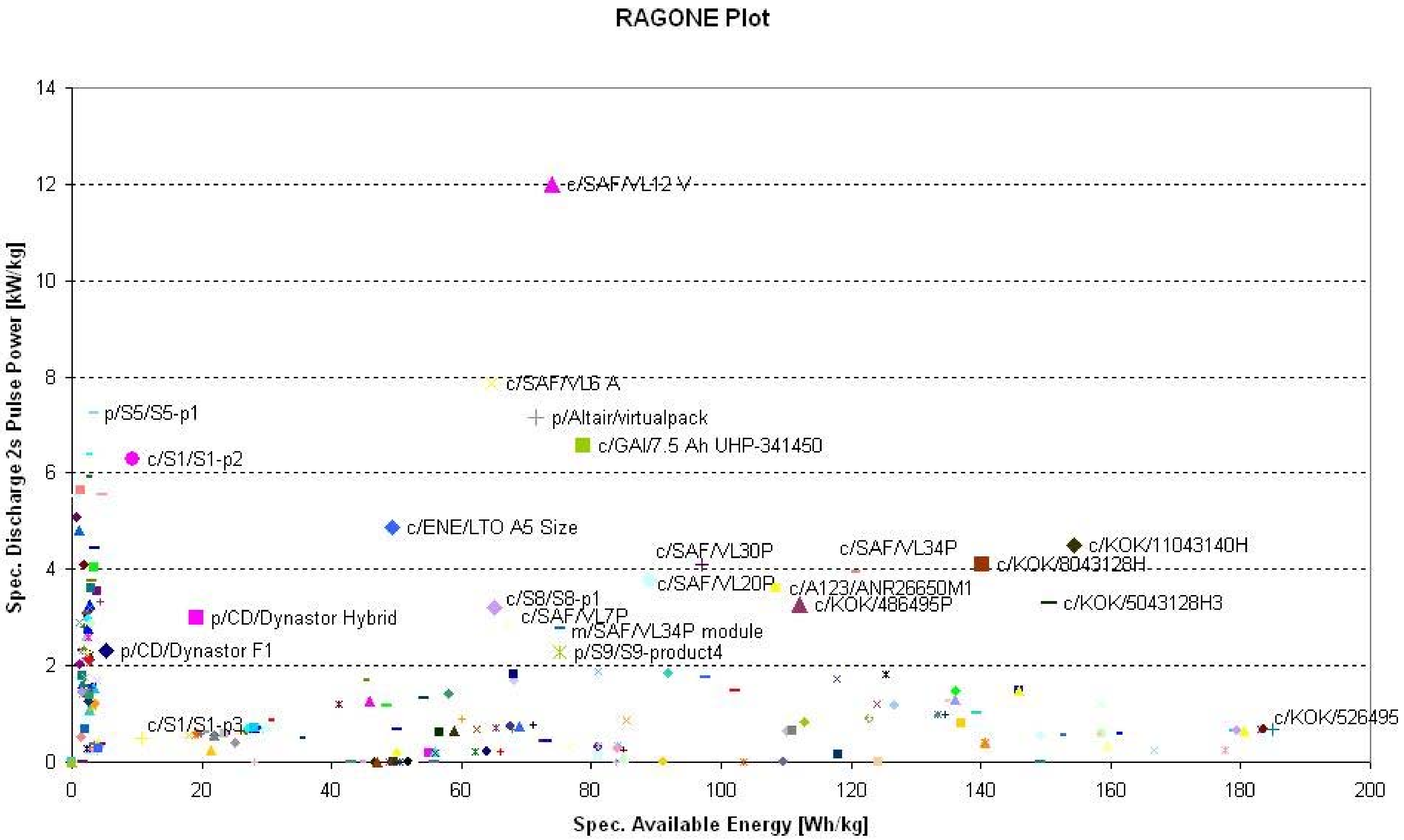


Figure 3.13 Ragone Plot

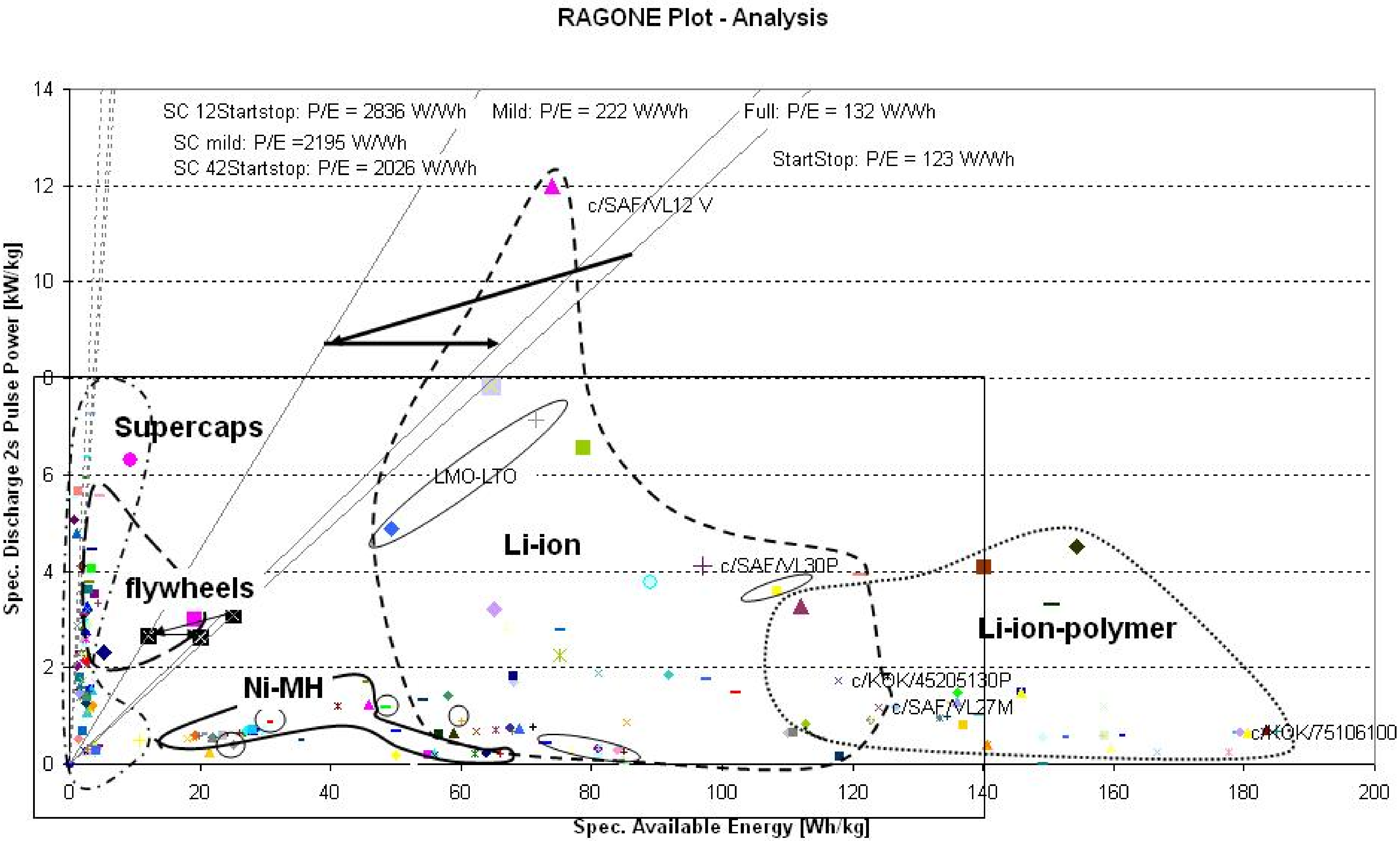


Figure 3.14 Ragone Plot - analysis

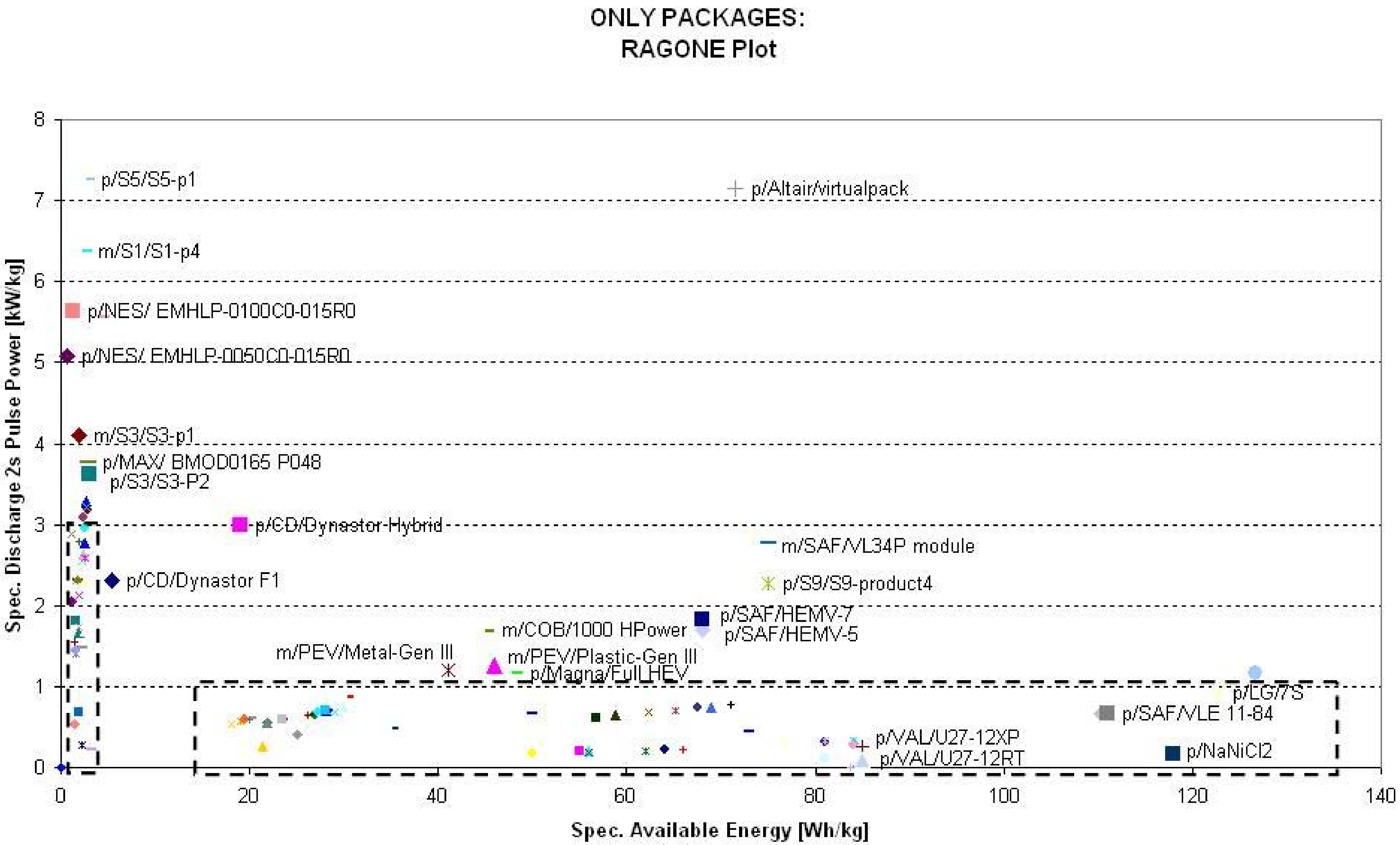


Figure 3.15 Ragone Plot – only packages

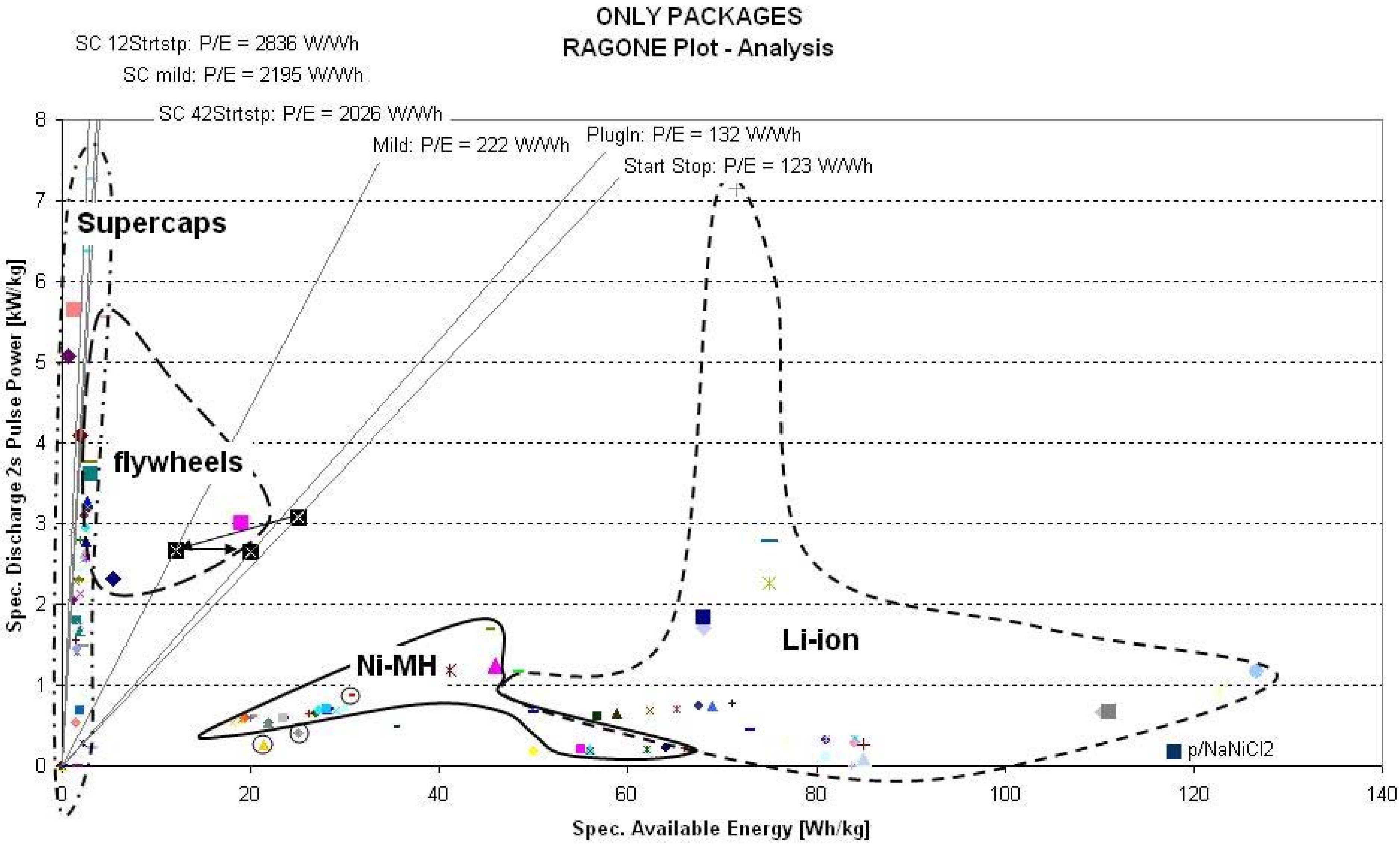


Figure 3.16 Ragone Plot – only packages, analysis

3.4.2 Cycle life and Calendar life

Cycle life is a major and complex characteristic. It was measured as specific cumulated energy throughput until end of life in kWh/kg. It depends on the DOD window and the location of this window as well as on the charge and discharge-rates during cycling (see 3.2.4). Therefore, data in kWh/kg was collected together with these parameters, whereas details about the location of the DOD window were not provided by suppliers and thus neglected.

In order to compare cycle life data of different parameters, a relation between life and parameters was needed. A relation between life and only one of the two parameters, the DOD window, was found which is from Johnson Controls (JC) of the year 2003. *(Rosenkrank, 2003)* JC assumes hyperbolic functions as trade offs between the size of the DOD window and cycle numbers until end of life. The respective functions of three technologies – absorbed glass mat VRLA (Pb-AGM), Li-ion and Ni-MH are stated and plotted in Figure 3.17. Cycle life data of these functions base on *Rosenkranz, 2003*.

Collected data was also plotted in Figure 3.17. As can be seen data regarding batteries was given for 80% or 100% DOD windows, for supercapacitors for 50% and for flywheels for 100%. The area highlighted in Figure 3.17 mentioned as 'Batteries' is shown in Figure 3.18 whereas that mentioned as supercaps is shown in Figure 3.19. In Figure 3.18 packs are distinguished from cells.

As can be seen for batteries neither Li-ion nor Ni-MH batteries cross the hyperbolic trade-off functions developed by JC. Moreover it should be noticed, that a logarithmic scale was used which underlines this observation. Therefore, the model of JC could not be confirmed and thus was not used.

The development of an own model was not possible because of too little data, which corresponds to different parameters. Hence, such a model would be statistically too weak.

In order to compare data to derived goals of USABC (Table 3.4), goals were drawn in as shown in Figure 3.17. These goals were calculated of stated cycle number goals and the corresponding load profiles *(see Barnes et al, 2002)*. The respective DOD windows were calculated as the ratio of maximum energy swing measured from the initial charge level during a load profile (*Barnes et al, 2002*) to available energy of the storage.

As can be seen, derived goals are close to a DOD window of 10% whereas battery data was available for parameters of 80% or 100%. When the model of JC could be considered as right but it only had to be shifted to the left, a comparison would have been possible. This was done by replacing the multiplicator in the trade-off relation for Li-ion cells so that it crosses the area of batteries or in particular one representative cell: SAFT's VL6A cell. Following these considerations, the SAFT VL6A cell would have a cycle life of 5402 cycles for a DOD window of 10%. Hence, it would fulfill criteria of 675 cycles. The modified trade-off relation is plotted in Figure 3.17.

Cycle life of flywheels varies from 23000 to 96000 kWh. However, it is to mention, that life time of used bearings is a stochastic value. Rare events as the emergence of high gyroscopic forces as mentioned in 2.3.1 may play a critical role.

Regarding supercapacitors, life time data was available corresponding to 50% DOD swings. A comparison of all suppliers is illustrated in Figure 3.19.

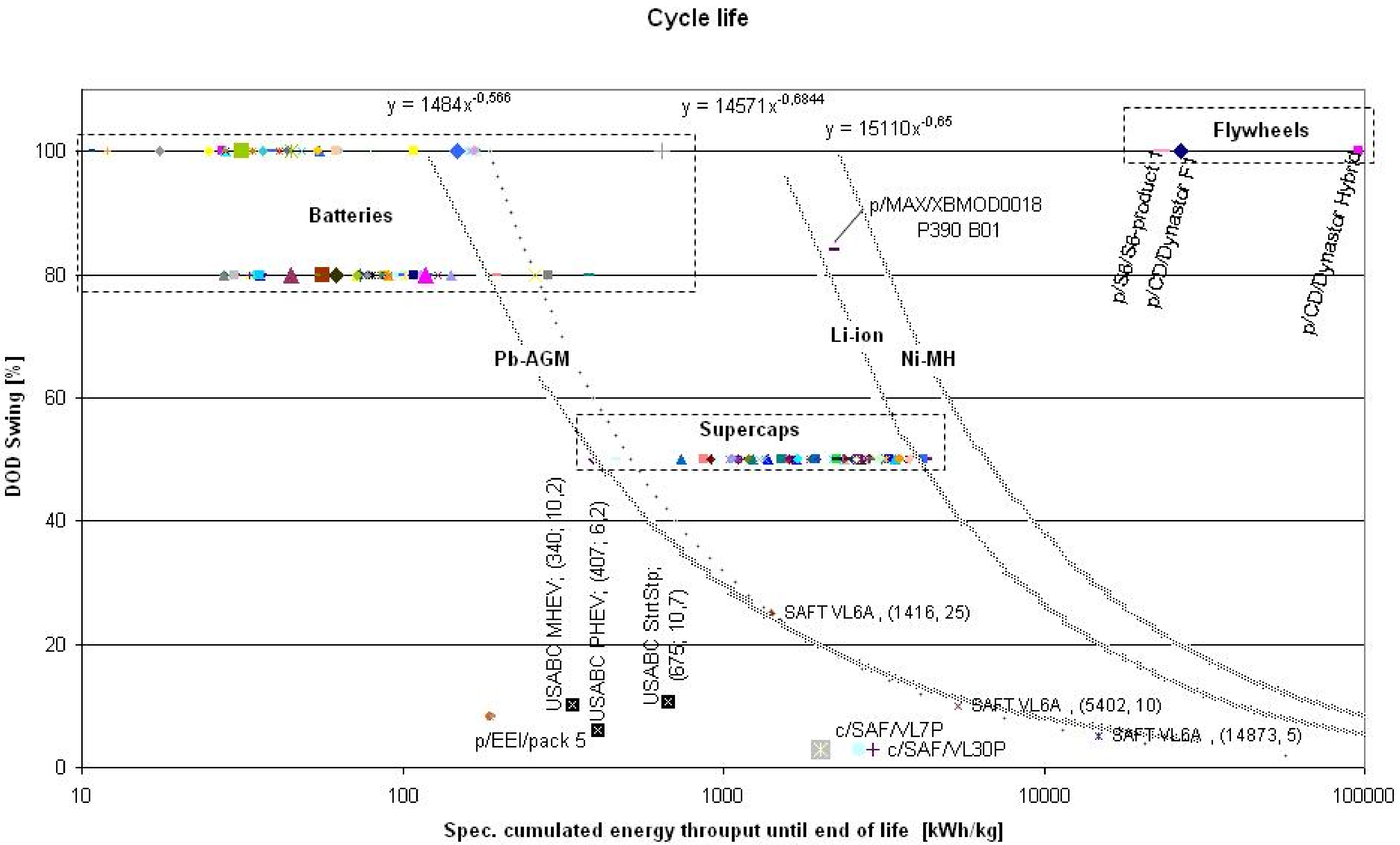


Figure 3.17 Cycle life (source: based on Rosenkranz, 2003)

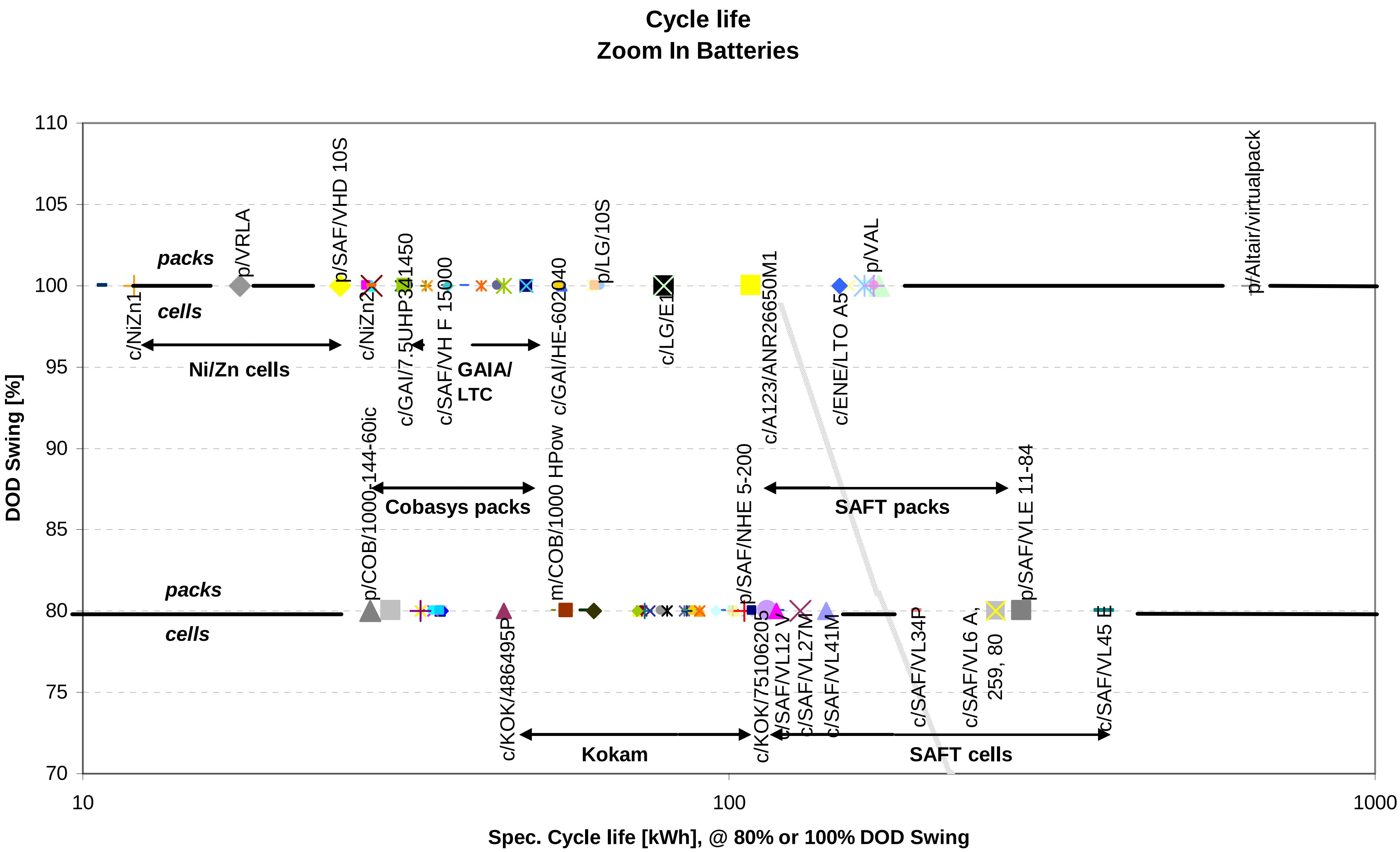


Figure 3.18 Cycle life – zoom in batteries

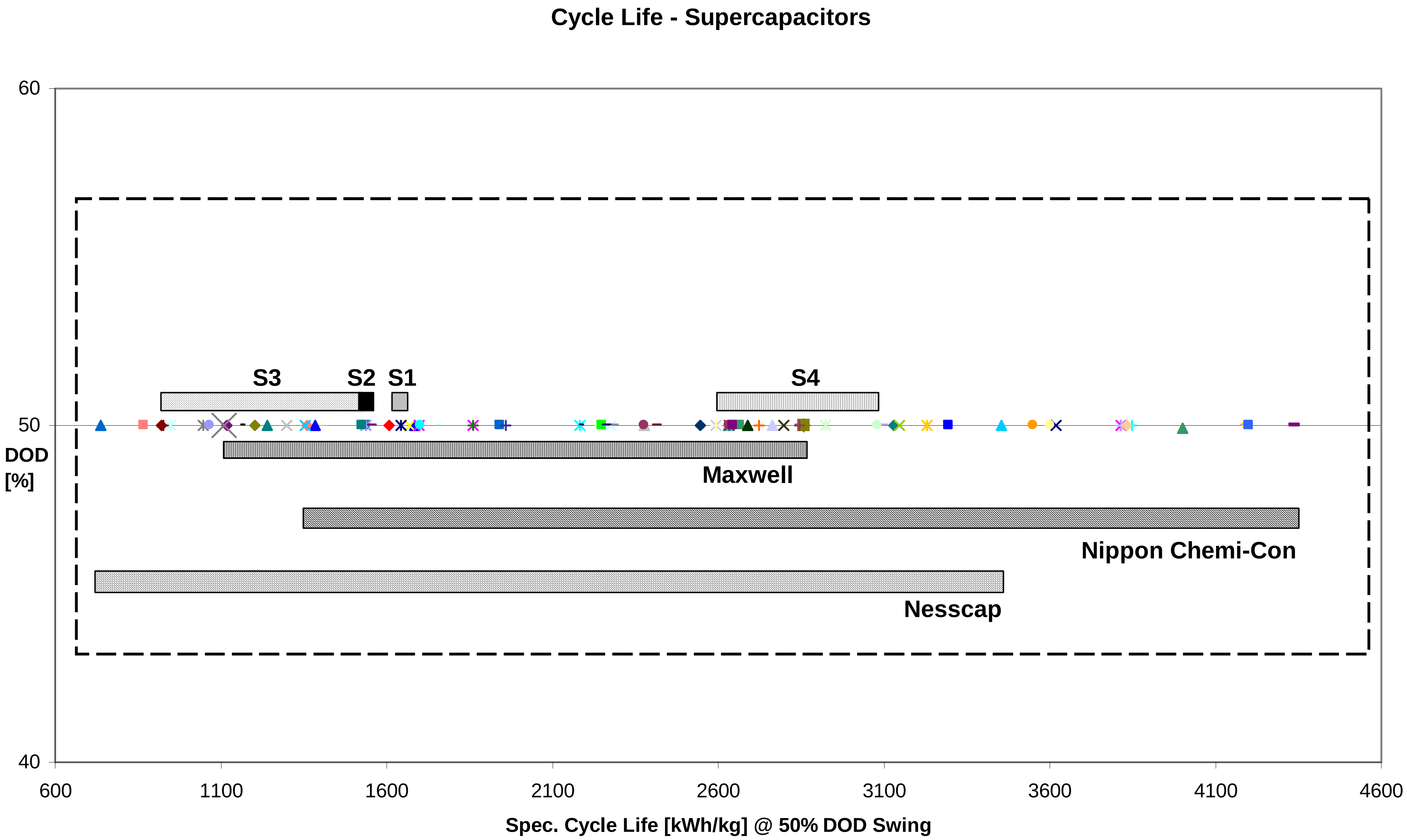


Figure 3.19 Cycle life - supercapacitors

3.4.3 Spec. Regenerative 2s pulse power

Regenerative 2s pulse power is shown in Figure 3.21 and Figure 3.22. The area highlighted in a rectangle in Figure 3.21 is shown in Figure 3.22. Only packages are shown in Figure C.3.

As mentioned in 3.4.1 concerning ragone plots, common P/E ratios are observable for various technologies and designs. Eye catching is the 20W/Wh ratio typical for various Ni-MH batteries as well as for some Li-ion batteries.

Derived USABC goals of 2,054kW/kg are met by supercapacitors (regenerative assumed to be equal to discharge pulse power capability) and by only one battery supplier regarding both cells and packages: Enerdel, using LMO/LTO lithium-ion technology.

3.4.4 Recharge rate

Similar to Regenerative 2s pulse power new lithium-ion technologies as those using LTO (Altair Nanotechnologies) as anode material show highest recharge rates of C48. Regarding the second supplier, Enerdel, also using these anodes, no data was available.

Figure 3.20 shows a plot of c-rates which indicates averages of the respective technologies. Besides Altair Nanotechnologies the group 'Lion NEW' implicates lithium iron phosphate cells of A123 (C4).

Figure 3.20 Recharge rate of various battery technologies

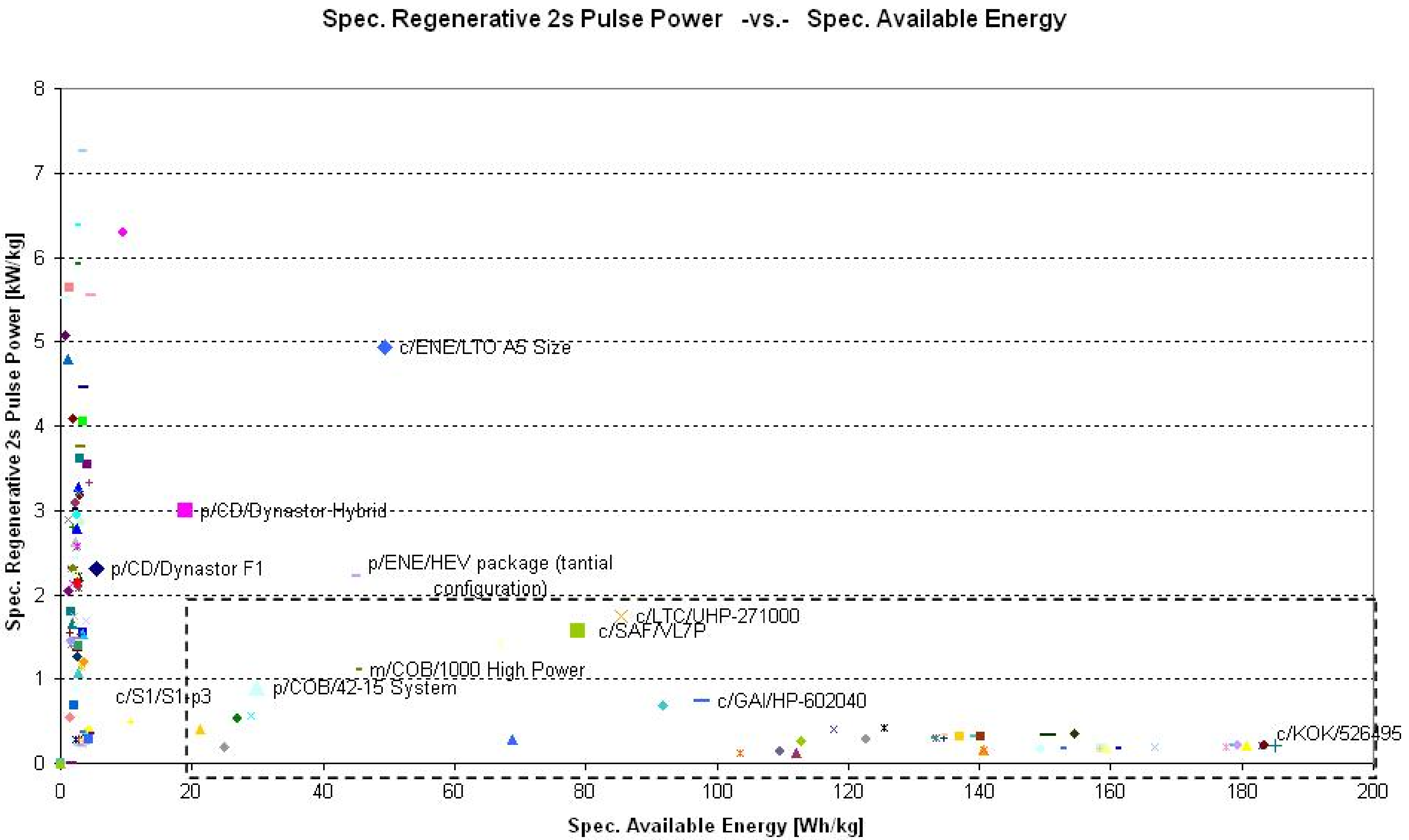


Figure 3.21 Spec. Regenerative 2s Pulse Power

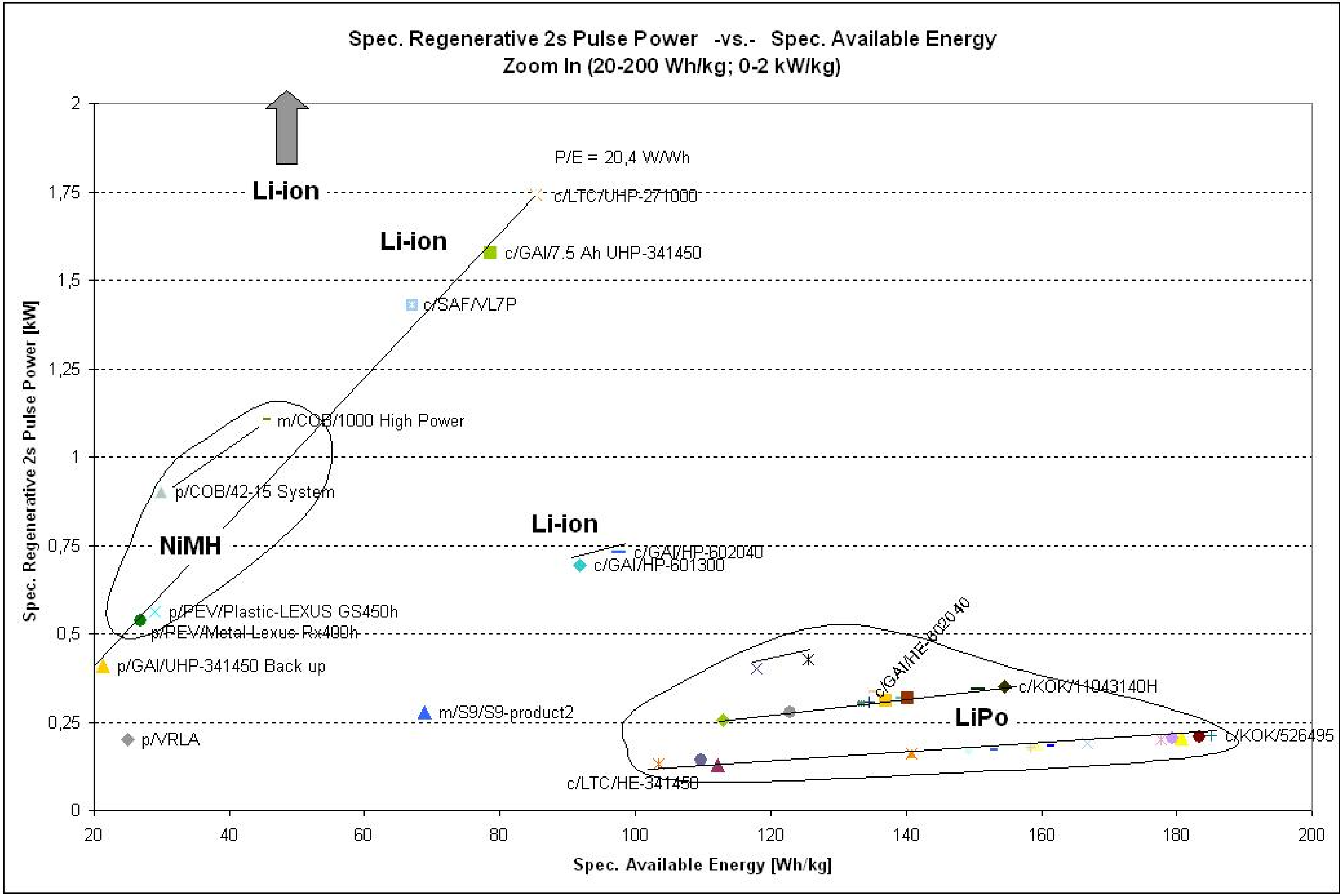


Figure 3.22 Spec. Regenerative 2s Pulse Power – Enlargement

3.4.5 Operating and Storage Temperature

As already mentioned operating temperature is the ambient temperature and not the temperature of the storage. Limits of the operating temperature range are indicated in Figure 3.23 and Figure 3.24 as blue triangles. The yellow rhombs indicate the respective storage temperature range. Data about operating temperature was available for nearly all storages (see Table B.2).

As can be seen, there are farley no operating temperature limits for flywheels. Supercaps as well as VRLA, ZEBRA, and some Li-ion batteries are capable to operate in a broad abient temperature range starting at minus 40°C.

Regarding low temperatures VRLA batteries and acetonitrile based supercaps as for instance those of Maxwell are appropriate for use, whereas nickel systems as Nickel-Metal hydride or Nickel-Zinc are limited at higher temperatures. Although ZEBRA is also mentioned regarding low temperature, it has to be underlined, that these systems need time to be heated up before usage.

Ranges of Li-ion depend on the respective technology. Li-ion batteries using LTO as anode show a broad range from minus 40 to 75 °C. Lithium-iron phosphate technology also operates in a broad range from -30 to 60°C.

Considering derived USABC goals (Table 3.5) of an operating temperature range from -30 to 52°C Li-ion-polymer batteries as well as Ni-MH or Ni-Zn batteries neither reach the lower boarder nor the upper boarder.

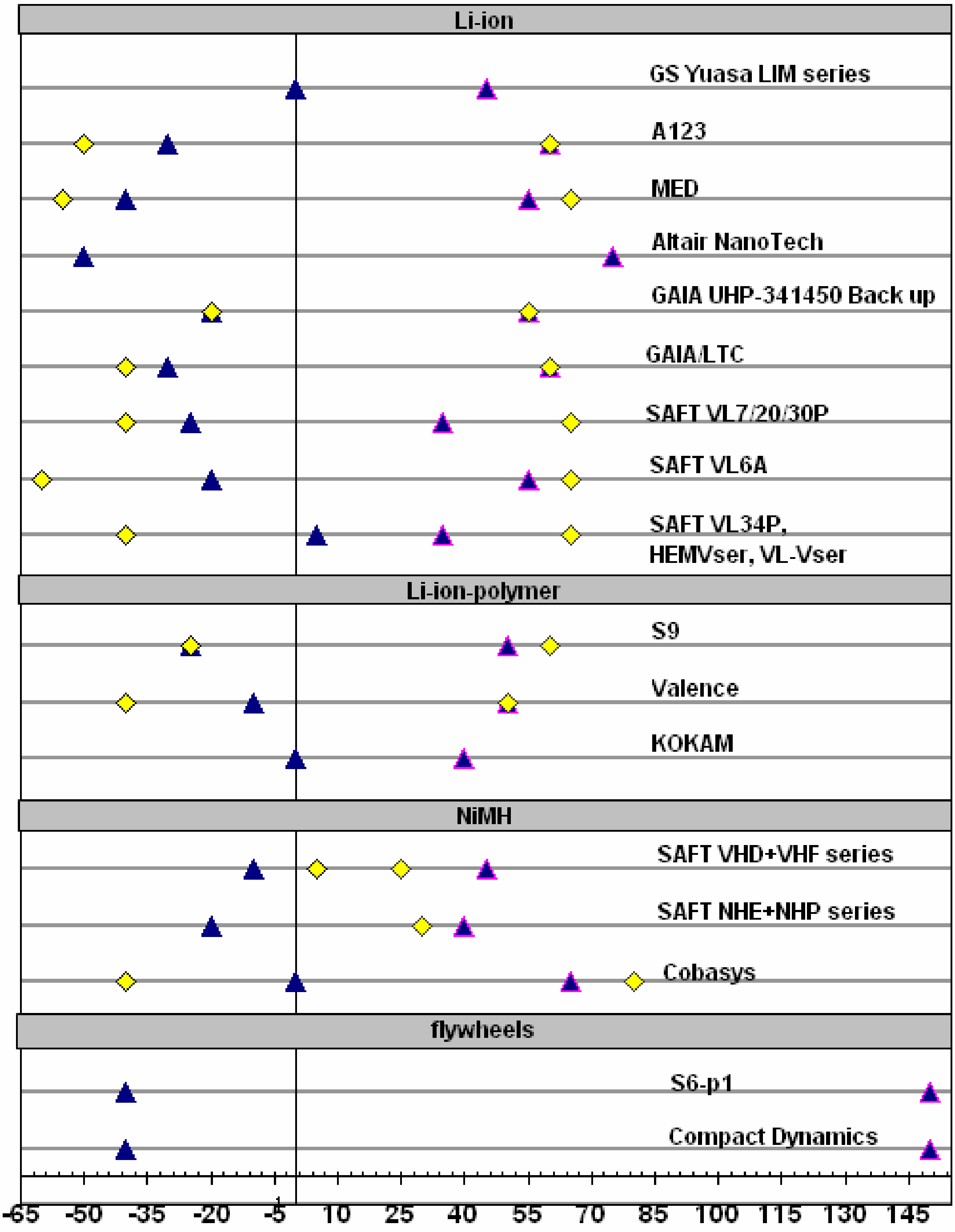


Figure 3.23 Operating and Storage Temperature 1/2

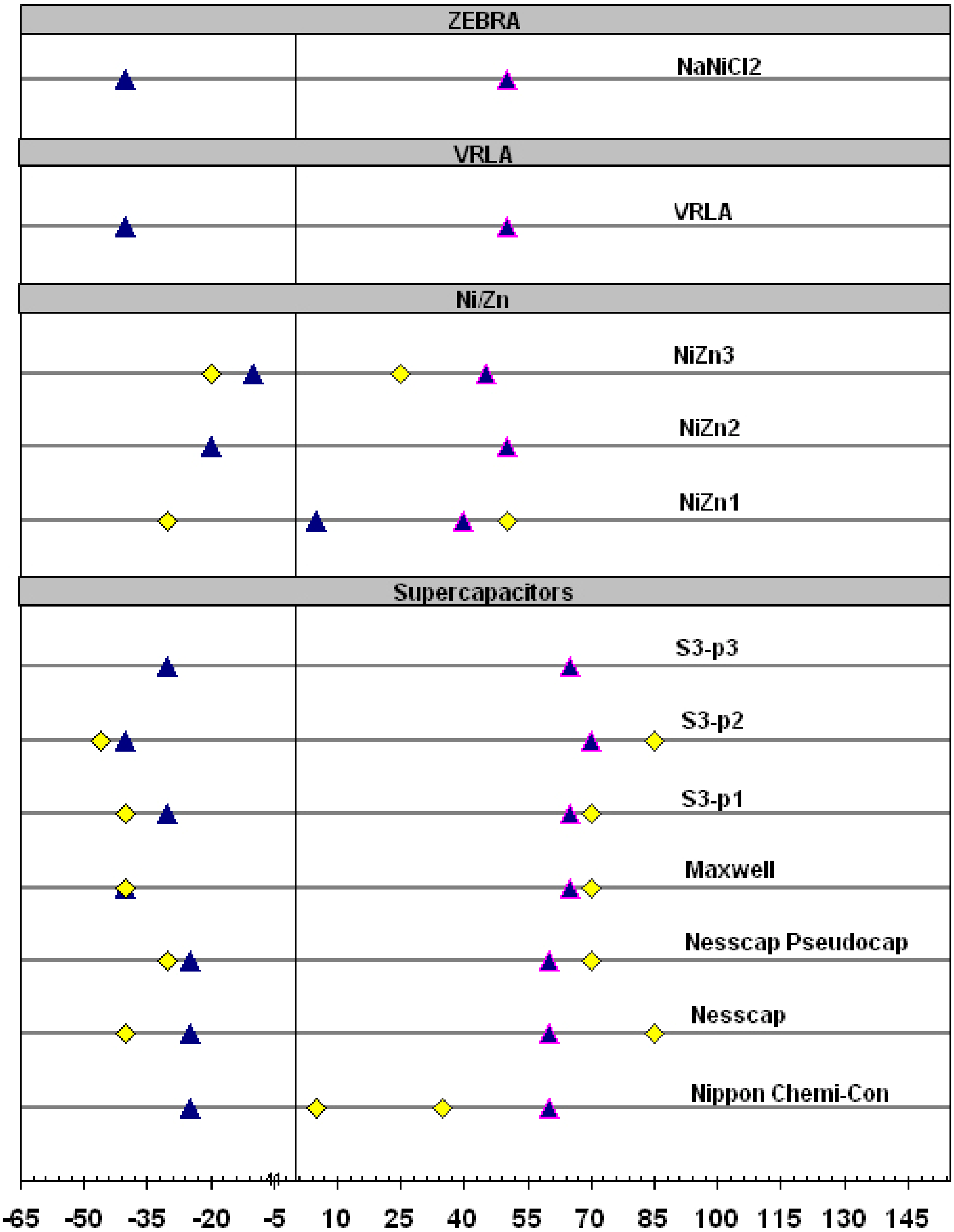


Figure 3.24 Operating and Storage Temperature 2/2

However, the operating temperature states the limits of ambient conditions but doesn't give an indication about power capability at these limits. For low temperatures at minus 30°C this is discussed in the next point.

3.4.6 -30°C Cold Cranking Power

In Figure 3.25 spec. cold cranking power at minus 30°C is illustrated over spec. 2s pulse power. In this plot, only storages are illustrated that are capable to operate at this temperature (compare 3.4.5) and hence, Ni-MH batteries of Cobasys and SAFT and some Li-ion-polymer batteries as those from KOKAM or supercaps from Nippon Chemi-Con and S4 are not included. Hence, these storages do not fulfill goals derived from USABC (Table 3.5). Moreover, storages are not included where data was not available (compare Table B.2).

Nearly all storages, which are plotted in Figure 3.25 fulfill derived USABC -30°C cold cranking power criterion of 0,32kW/kg (see Table 3.5). An exception are lithium-iron-phosphate cells from A123 with only 0,17 kW/kg (see Table B.2).

All supercaps from Maxwell lie on a line, which gives the ratio of 67% of -30°C cold cranking power in relation to 2s pulse power at 23°C ambient temperature. This ratio results from the fact, that Maxwell stated internal resistance increase at -30°C with 150% (compare supercaps, 3.3.3). An analogy holds for supercaps from NessCap.

As can be seen, supercaps and flywheels show the highest absolute values for -30°C. Regarding flywheels no difference between -30°C and 23°C was assumed. However, regarding cold cranking after having parked the car for some time, self discharge plays a major role. Although no data was available about self discharge of flywheels, it can be assumed that self discharge is high for long parking times. An auxiliary system as a starting battery or supercaps would be needed.

Hence, acetonitrile based supercaps perform best regarding low temperature power capability.

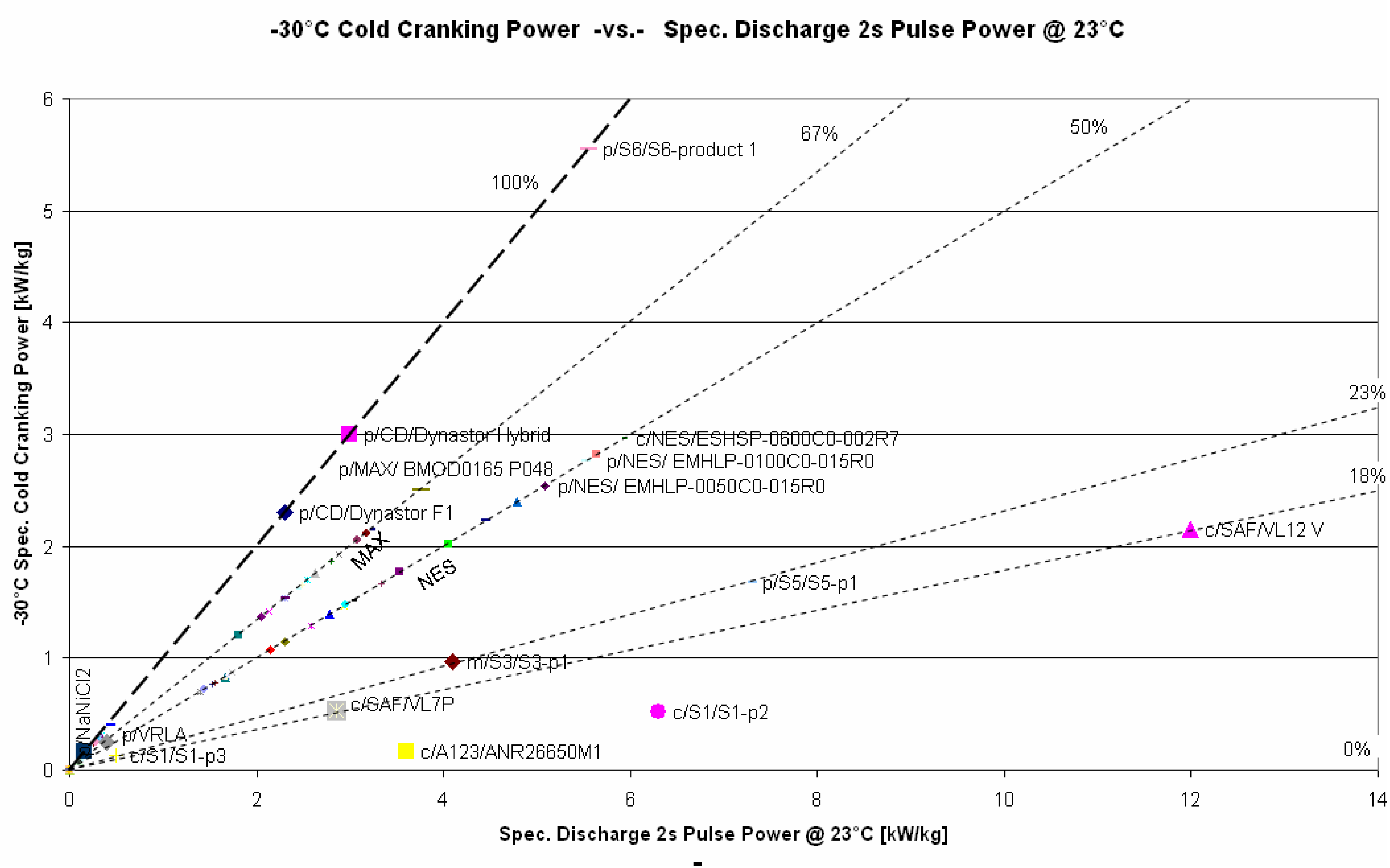


Figure 3.25 -30°C spec. cold cranking power over spec. 2s discharge pulse power

3.4.7 Self discharge

Regarding self discharge not much data was available. Concerning supercaps, it can be stated, that self discharge of available energy is about 2 to 7 % in the first 24 hours at standard conditions (23°C). This is roughly equal to the requirements derived from USABC criteria (compare Table 3.5).

3.5 Conclusion of analysis

Interpreting the development of start-stop systems, mild hybrids, plug-in hybrids to electric vehicles as a continuous process of the electrification of the car, concerning the various systems it can be concluded from 3.4.1 to 3.4.7:

Micro Hybrids (Start-Stop systems): Regarding start-stop systems high specific values and densities concerning all characteristics are more important than regarding mild or plug-in hybrids (compare 3.4.1.3). Moreover, concerning cold cranking, low temperature performance is very important in order to draw high discharge rates from compact sized energy storages.

Mild Hybrids: Regarding mild hybrids, batteries with higher P/E ratios are needed as for start-stop systems or plug-in hybrids. In contrast to start stop systems, cycle life becomes more important due to broader DOD windows.

Plug-in Hybrids: In Plug-in hybrids, large scale energy storage systems with low P/E ratios are needed. These systems will make up a high factor of total vehicle cost and thus, cost per Watt hour will play an essential role. Moreover, cycle life due to broad DOD windows and high recharge rates in order to quickly recharge the vehicle when plugged to the grid become very important. Due to low P/E ratios of supercapacitors, regarding Plug-in HEVs there may be no market for supercapacitors any more.

Regarding the various storage technologies discussed in chapter 3, it can be concluded:

Flywheels: Flywheels meet most of the USABC criteria, which were discussed in this work. Trusting on the suppliers' data, the flywheel is the best choice regarding lifetime (see 3.4.2). One criterion, which still is to analyze and may qualify the use of flywheels in hybrids, is cost.

Carbon EDLCs: 'Carbon EDLC'-supercaps do not fulfill derived USABC criteria regarding specific available energy. However, in mild and micro hybrids they can be used in combination with auxiliary battery systems. Regarding start-stop systems, this could be a conventional VRLA battery for instance. Life time is better than that of batteries on a kWh/kg basis (compare Figure 3.17) it is lower than expected. Carbon EDLCs, as one of few technologies, meet derived regenerative pulse power criteria. Together with LTO based lithium-ion technology acetonitrile based carbon EDLCs are the best choice regarding low temperature performance. Self discharge at 23°C is within the derived goals.

Ni-MH: Ni-MH batteries can currently be assumed as the predominant choice for Mild Hybrids (3.2.1). Considering a cycle life model developed by SAFT, Ni-MH batteries have higher spec. cycle life than Li-ion batteries. However, in this work, this couldn't be affirmed nor disproved.

Ni-MH batteries only operate in a narrow temperature range and show poor low temperature performance. Most products are not capable to operate at -30°C.

Li-ion: Li-ion batteries show attractive spec. power and energy values. Moreover they are available for P/E ratios needed for mild hybrids:

LMO/LTO lithium ion technology (Enerdel) meets or even tops most characteristics: A P/E ratio as derived from USABC goals with best values for Li-ion technology besides SAFT's LiNiCoAlO2 cathode technology. LMO/LTO products are the only batteries meeting derived regenerative pulse power criteria. Moreover LTO anodes developed by Altair Nanotechnology are stated with the highest recharge rates up to C48. Operation in broad temperature ranges is possible. LMO/LTO's safety is considered from moderately to high.

Lithium iron phosphate is the safest lithium-ion technology observed in this work but shows low power capability and lower P/E ratios in contrast to LMO/LTO or LiNiCoAlO2/Graphite technology. However, it fulfills derived USABC criteria regarding specific available energy and specific 2s discharge pulse power. Although operation is indicated from -30 to 60°C it shows poor low temperature performance not meeting the respective derived USABC criterion '-30°C specific cold cranking power'.

LiNiCoAlO2 utilized by SAFT shows best specific values regarding available energy and pulse power in an attractive P/E ratio. Regarding low temperature performance data was available for some cells which probably meets derived USABC criteria on package level. However safety is moderate to low *(compare Table 2.14)*.

Li-Ion-Polymer: In contrast to Li-ion batteries, Li-ion-polymer batteries show poor performance regarding most characteristics: Low power capability and an unattractive P/E-ratio, poor low temperature performance, low recharge rate and poor specific regenerative pulse power. Li-ion-polymer batteries may gain more respect considering high specific available energy demands in Plug-in hybrids or electric cars.

VRLA: Valve regulated lead-acid batteries show poor performance regarding most characteristics when compared to L-ion, Ni-MH batteries but have adequate low temperature performance.

Ni/Zn: Ni/Zn batteries show poor power capability (~0,9kW/kg) not meeting derived USABC goals and moderate specific available energy (55-60Wh/kg) (*see Table B.2*). Moreover, cycle life is low and operating temperature range is small. Ni/Zn systems represent an environmental friendly technology. *(see 2.7.8)*

NaNiCl2 (ZEBRA): High temperature ZEBRA batteries show lowest P/E ratios due to poor power capability (0,161kW/kg) and highest specific available energy content (118Wh/kg) on package level. At low temperatures they heat up autonomous consuming energy stored within the package and time. They may be attractive for large scale battery systems as used in Plug-in Hybrids, Electric Cars or in combination with fuel cells operating at same temperatures.

4 Selection Environment of battery development

The term 'selection environment' was established by *Nelson and Winter, 1977* in their paper 'In search of useful theory of innovation'. According to them, "*a firm, if it is to be profitable, then those at whom an innovation is aimed have to see it as important enough to value it at more than its cost; the innovation has to be 'selected'.*" The environment which decides about selection or sorting-out of an innovation is called the 'selection environment' *(Nelson, Winter, 1977).* It can be distinguished between a market and a nonmarket selection environment. The market selection environment consists of the set of market forces (chapter 4.2) whereas governmental institutions and regulations (chapter 4.3.1) as well as organizations (chapter 4.3.2) form the nonmarket selection environment. *(Nelson, Winter, 1977)*

In this section of this work, it is focused mainly on batteries. In the following sections, when it is referred to Li-ion technology, both, Li-ion and Li-ion-polymer technology is meant.

The selection environment should be explained on the example of one representative joint-venture, 'Johnson Controls-SAFT Advanced Power Solutions' ('JCS'). It was founded in January 2006 *(JCS, 2006)* by Johnson Controls which contributed know-how, technology licenses, contracts and $40m of cash and assets for a 51% stake and by SAFT S.A. which contributed know-how, technology licenses and contracts for a 49% stake *(SAFT, 2007b)*. The Joint Venture is "specialized in the development, production and selling of advanced technology batteries for hybrid and electric vehicles." *(JCS, 2006)*

Johnson Controls *"is a global leader in interior experience, building efficiency and power solutions. The company provides innovative automotive interiors …. For buildings, it offers products and services that optimize energy use and improve comfort and security. Johnson Controls also provides batteries for automobiles* (Optima, Varta, Heliar, and LTH) *and hybrid-electric vehicles, along with systems engineering and service expertise. Johnson Controls (NYSE: JCI) has 136,000 employees in more than 1,000 locations serving customers in 125 countries. Founded in 1885, the company is headquartered in Milwaukee, Wisconsin." (JCS, 2006)*

SAFT, Bagnolet, France *"(SAFT: Euronext) is a world specialist in the design and manufacture of high-tech batteries for industry. SAFT batteries are used in high performance applications such as industrial infrastructure and processes, transportation, space and* *defense. SAFT is the world's leading manufacturer of nickel-cadmium batteries for industrial applications and of primary lithium batteries for a wide range of end markets. The group is also the European leader for specialized advanced technologies for the defense and space industries. With approximately 3,800 employees worldwide, SAFT is present in 18 countries. …" (JCS, 2006)*

4.1 Relevant market and market segments

Generally, a relevant market can be evaluated by the method of 'the gap in the chain of substitutes' *(Robinson, 1933)*. According to this method, the relevant market consists of several products, which are substitutable. Boarders of the market can be detected where products can't be substituted by others or in other words where a gap in the chain of substitutes can be observed. Mathematically, substitution between two products can be expressed by the elasticity of demand which is determined as the ratio of percental change of demanded quantity of good 2 to the percental change in price of good 1 *(Shepherd, 1990, p.55)*. A gap in the chain exists where elasticity of demand is close to zero *(Robinson, 1933)*.

However, in real world, markets do not always show such clear boarders *(Shepherd, 1990)*. Moreover, this method has to be used carefully. Even if elasticity of demand between two products is bigger than zero, it also depends on the prices of good 1 and 2 if they can be seen as substitutes. If price of good 1 is a multiple of good two, then price of good 1 is not competitive to the price of good 2. Thus, they can not be seen as substitutes. *(Shepherd, 1990, p.56)*

Moreover, market shares of supplier 1 of good 1 and supplier 2 of good 2 also have to be considered. If both suppliers have small market shares and product 1 and 2 are substitutes, a major increase in price of good 2 would entail that supplier 2 loses all its sales but that would not result in a significant change in the demanded quantity of product 1 because the market share of supplier 1 is too small to make significantly more sales. Thus, considerations also have to be made at equal market shares *(Shepherd, 1990, p.56)*.

In the following, the relevant market of batteries for hybrid and electric vehicles should be defined differently just by considering a market's main dimensions. These are the product type and geographic area. *(Shepherd, 1990, p.54)*

Regarding product type, it can be assumed that batteries for hybrid or electric vehicles form a common market *(Anderman, 2006)* and that they differ essentially from batteries used in other applications *(compare chapter 3)* which thus cannot be seen as substitutes. Common batteries as used in notebooks or cellular phones or conventional 18650 consumer cells are not included although few exceptions exist, where manufacturers as Tesla Motors, San Carlos, California, USA use them in electric cars *(Berdichevsky et al, 2007).*

Hence, the observed relevant market is a submarket of the 'rechargeable battery market'. The latter can be segmented by customers from sectors as aviation, building, consumer, marine, medical, military, rail, road, space and telecommunication whereas the relevant market of 'hybrid and electric vehicle batteries' only covers the segment 'road' *(compare SAFT, 2005).* Other segments may be 'military' and 'aviation' but only concerning a minority of products.

Regarding the second dimension, geographic area, the market can be seen as global *(compare Anderman, 2006).*

For such a defined market, a survey *(Anderman, 2006)* estimated total market volume as \$600 million in 2006 which is expected to grow to \$1.4 billion in 2010 and \$2.3 billion in 2015. The market volume estimated for 2006 solely represents revenues of Ni-MH battery technology which is assumed to make out total market volume in 2006. The report states that in 2010 Li-ion batteries can capture 5% of the market.

4.1.1 Market Concentration

According to *Anderman, 2006* the 'hybrid and electric vehicle battery market' is dominated by two Japanese enterprises, Panasonic EV Energy Co Ltd., Tokyo followed by Sanyo Electric Co. Ltd., Osaka. Together, in 2006, they shared more than 85% of the total Ni-MH market, which can be assumed to approximately cover the total 'hybrid and electric vehicle battery market' in that year. Panasonic EV (see chapter 4.2) holds more than 75% and Sanyo Electrics about 10% *(Anderman, 2006).*

The battery manufacturer SAFT supplies both, Ni-MH and Li-ion batteries *(see Appendix B).* SAFT states revenue in the branch 'Electric and hybrid vehicles and new technologies' with € 10,6 million in 2004 (€/\$~1,12), € 7,5 million in 2003, and € 12,6mill in 2002 *(SAFT, 2005).* For the purpose of comparison, SAFT's total revenues are stated with €586.9 million in 2004 *(SAFT, 2005).* According to the study of *Anderman, 2006* SAFT would have a market share of ~2% in 2006 at constant revenues. Currently (2008), this share can be assumed as higher because SAFT together with Johnson Controls founded the JC-S Joint Venture to enhance production capabilities for this submarket. *(see JC-S, p.149)*

Data of manufacturers as Cobasys, GS Yuasa and Nissan were not available. However market concentration can be calculated sufficiently precisely for further investigations. The

Herfindahl-Hirschman Index HHI, a measure of market concentration, is defined as the sum of all squares of market shares of the relevant market *(Shepherd, 1990)* and is stated as

$$\textbf{HHI} = \sum_{i=1}^{n} s_i^2$$

Considering given data, the HHI lies in the interval of [5729, 5898]. (75^2 + 10^2 + 2^2 + 0 or (100-75-10-2)^2). A HHI below 1000 indicates a non concentrated market whereas values between 1000 and 1800 refer to moderate concentration. HHI values above 1800 refer to highly concentrated markets *(USDOJ, 1997).*

Another concentration measure, the C4-value, is defined as the sum of market shares of the 4 leading companies *(Perloff et al, 2007).* Hence, it can be concluded that C4 lies above 87% (75+10+MS3+MS4 with MS3 ≥ 2%, MS4 is unknown).

From both measures, it can be concluded that market concentration of the hybrid and electric vehicle battery market in 2006 was extremely high. The HHI between 5729 and 5898 equals to only 2 (10000/HHI = 1,7 to 1,75 ~ 2) equal sized companies which could supply the complete market. Such a low value can be reasoned either by a high value of the minimum efficient scale or by space for more enterprises.

The minimum efficient scale is the minimum of the long run average costs over output. Economies of scale lead to more efficient production and thus lower average costs at higher output. The lowest possible output level, where a company reaches this minimum with the best available technology is the MES. At a certain output level which lies over the MES, long run average costs begin to increase again due to diseconomies of scale. Starting from this output level, companies produce internally inefficiently (‘x-inefficiently’). This result in lower efficiency but the company may still make more profit at levels of diseconomy of scale due to higher sales. High values of the MES indicate that only some few companies are capable to produce efficiently and hence market concentration can be assumed to be high. *(Shepherd, 1990)*

As mentioned in 2.7.10.2 Ni-MH manufacturing processes are complex and need high investments. This could reason high output levels due to capacity effects in order to achieve economies of scale. Subsequently the need of high output levels reason high values of the MES. Thus, a high MES is thinkable but not enough information was available to make a precise statement. Hence, it cannot be concluded if only two enterprises would do the best job.

However, market demand is assumed to increase anyway within the next few years *(Anderman, 2006)* and thus concentration may vary significantly.

Moreover, market share of Li-ion technology is assumed to increase significantly *(Anderman, 2006)* and may displace the technological paradigm of Ni-MH gradually: Typical forms of the diffusion of new technologies over time are s-shaped *(Stepan, 2006)*, starting with a very promising exponential increase in the first years shown in Figure 4.1.

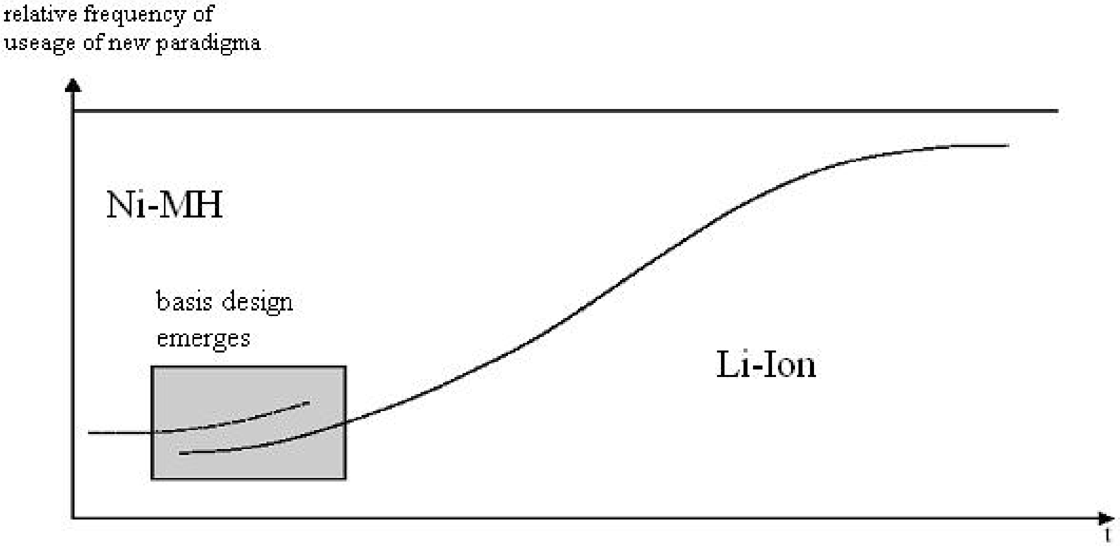


Figure 4.1 displacement of Ni-MH paradigm by Li-ion paradigm (source: based on Stepan, 2006)

Different potential in economies of scale of Li-ion technology as discussed in 4.1.3 may lead to different concentration and competition. In contrast to the quasi monopoly of the current Ni-MH market *(see Anderman, 2006)*, in an oligopoly of various Li-ion producers price of currently more costly (*Anderman, 2006*) Li-ion batteries would decrease.

4.1.2 Performance and structure

In a contestable market, no Market Entry Barriers (MEB) or barriers of exit exist. Regarding the HEV/EV battery market, this could not be observed *(see 4.5)*. In fact, it is assumed that, performance or structure depends on these barriers. Regarding Ni-MH technology, in this work the 'performance-follows-structure' model *(Shepherd, 1990)* is assumed due to high economies of scale and high market concentration observed. 'Performance follows structure' implicates that the market share of enterprises results from the branch's profits as well as from market concentration and market entry barriers. It is typical for established markets. *(Shepherd, 1990)*

Regarding Li-ion technology, currently the opposite - ‘structure-follows-performance’ - can be observed due to the fact that the market is not established yet. The latter paradigm is typical for small and innovative enterprises, as it can be observed for various Li-ion manufacturers in Asia *(see suppliers, Table 3.3)*. In this work, we assume that the Li-ion market, when fully established, changes to ‘Performance-follows-structure’.

4.1.3 Economies of Scale (EOS)

From the joint venture between Johnson Controls and SAFT both parties profit in their own way. Johnson Controls already entered the ‘hybrid and electric vehicle battery market’ earlier *(JCS, 2006)* but by cofounding the joint venture, it extended its access to lithium technology. SAFT, with Johnson Controls as strong partner, can profit from economies of scale due to corporate financed facilities and expertise in battery mass production. *(compare JCS, 2006)*

Regarding lithium-ion technology, potential in returns to scale exists for several stages of the manufacturing process. For further considerations, this process should be observed and potentials in economies of scale should be highlighted. The manufacturing process of cylindrical cells and in further stages of batteries is given in Figure 4.2.

A complete overview of manageable phenomena of economies of scale concerning lithium-ion batteries is summarized in Table 4.2 at the end of this section.

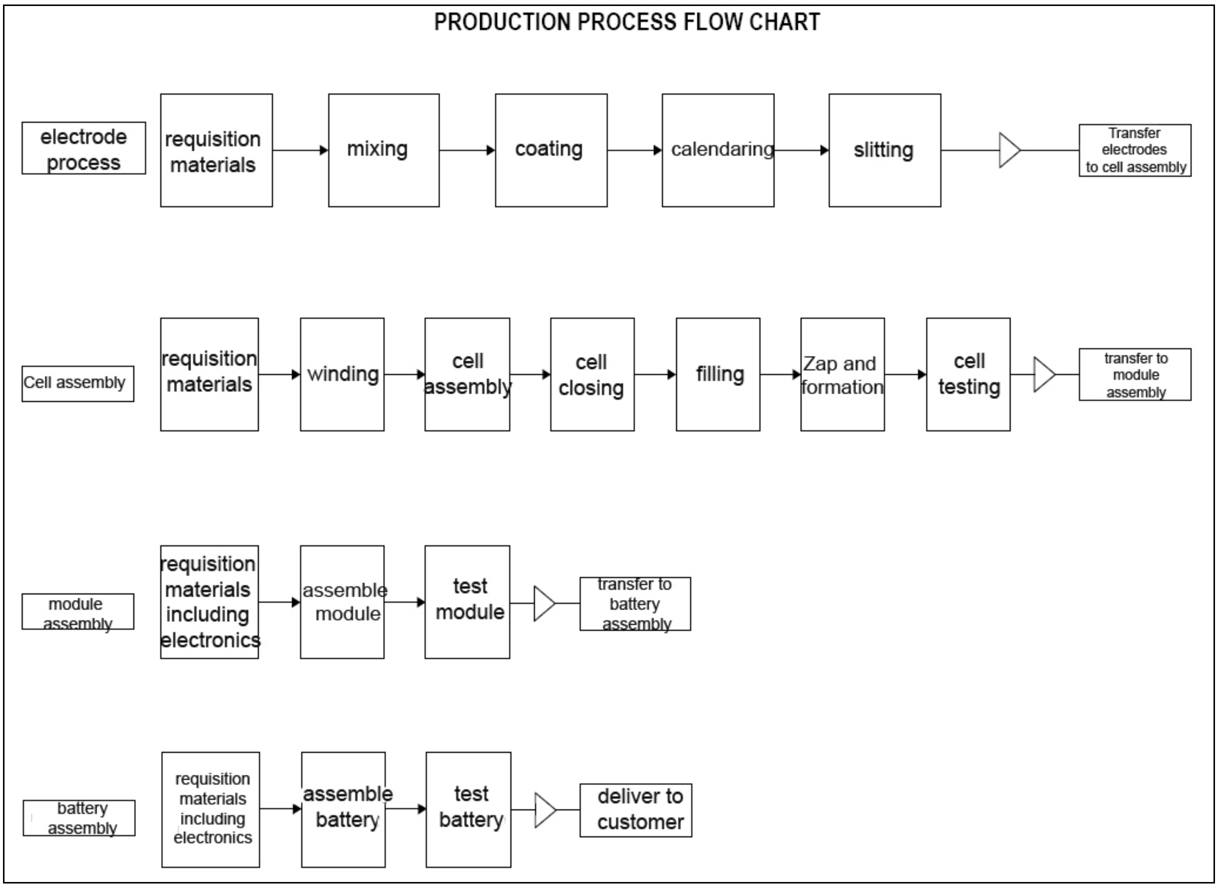


Figure 4.2 Production process of cylindrical batteries (source: SAFT, 2007c)

4.1.3.1 Returns to scale: Material production and assembly processes

According to a study of Argonne National Laboratory (ANL), Argonne, USA *(Cuenca, Gaines, 2000)* of the year 2000, when high costly lithium-cobalt-oxide was used as cathode material, material cost accounted for 75% - 80% of total cell product cost. Due to this fact, we focus on these costs in further considerations and outline alternative materials, which show cost reduction by economies of scale.

Regarding both, a high energy cell and a high power cell, the **cathode** material was the most costly. The respective stakes of various cell parts on total material costs are given in Figure 4.3.

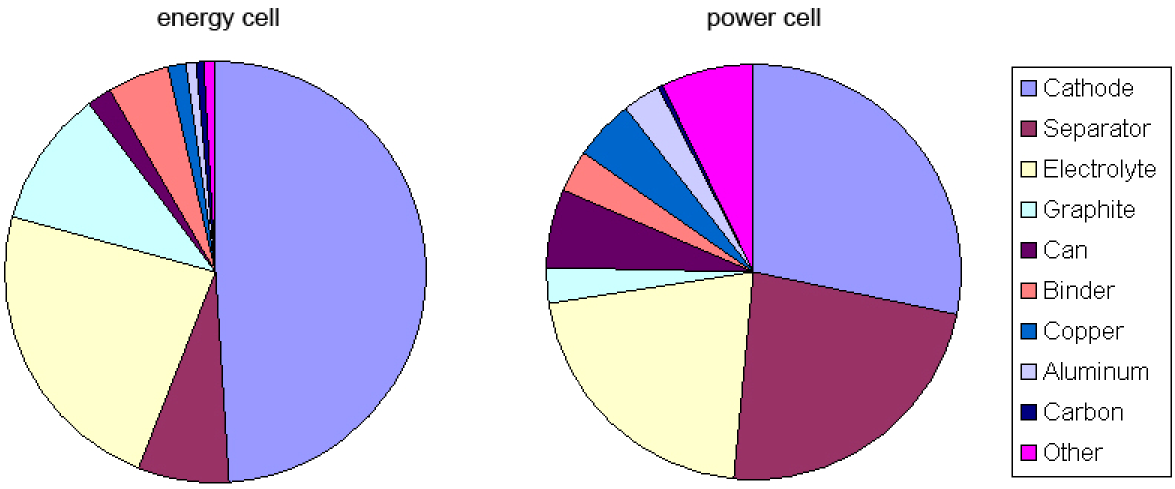


Figure 4.3 Material costs of high energy and high power cells using LCO cathodes (source: based on Cuenca, Gaines, 2000)

Currently, different cathode materials are used *(see 2.7.17.2.2, 2.7.17.2.6)* resulting in different costs, but it still can be assumed that cathode materials account for a major stake of total production cost.

Thus, regarding a broad commercialization of Li-ion batteries, material cost and in particular cathode material cost is a major issue. An overview of resources, mining activities and annual average cost is given in Table 4.1.

Resource	**Mining countries**	**Average price (1999)**	**Average price (2007)**
Cobalt	Congo, Canada, Australia, Zambia, Russia, Cuba	$48,5/kg ($ 22/lb, 1998)	$66,6/kg ($30,2/lb)
Nickel	Russia (Norilsk, Taimyrpeninsula), Canada, Australia, Indonesia, New Caledonia (France), Colombia, etc.	$4,4/kg ($2/lb, 1998)	$37,7/kg ($17,1/lb)

Li-Metal	Chile, Australia, Argentina, China, Russia, Canada	\$110, 2/kg (\$50/lb)	no data
Li-Carbonate (Li_2CO_3)		\$4,47/kg	
Manganese contained in ore (price per metric ton unit ore, 46-48% Mn content)	South Africa, Australia, China, Gabon, Brazil, Ukraine, etc.	\$0,49/kg contained (\$2,3/mtu)	\$0,71/kg contained (\$3,32/mtu)
1 lb = 0,45359237 kg; 1mtu = 10kg ore (100%) contained in 1 ton			

Table 4.1 Resources of cathode material, mining states ordered by annual production volume, average price (sources: Cuenca, Gaines, 2000; US Geological Survey, 2008)

As can be seen in Table 4.1, prices of manganese are indicated for ores. The reason is, that very little manganese is traded worldwide and thus the basis of quoting prices is that of ore. The manufacturing process of manganese electrode material as $LiMn_2O_4$ (LMO) is more difficult than of lithium cobalt oxide (LCO). As well as Lithium-nickel-cobalt-oxide, LMO shows potential for economies of scale. (*Cuenca, Gaines, 2000*)

Regarding **anode** material production of graphite, "*major production cost reductions associated with improved technology or economies of scale are not expected, because graphite is an established commercial product.*" Prices of graphite (year 2000) range from \$15 to \$30/kg. MCMB (compare 2.7.17.2.1) is most expensive with \$60/kg. (*Cuenca, Gaines, 2000*)

According to *Cuenca, Gaines, 2000*, economies of scale (EOS) are limited regarding the first stages of the electrode process indicated in Figure 4.2: "*As product demand increases, the maximum practical equipment size is reached (the limit of the economies of scale), and additional demand must be satisfied by means of duplicate production lines.*"

Regarding new processes, even if it is modeled on a similar process, experience is needed to optimize it. *"Each additional new plant incorporates minor improvements on the process' 'learning curve'. New technologies can bring larger improvements." (Cuenca, Gaines, 2000).*

However, according to the study, the 'coating' process offers flexibility. Concerning both processes, coating cathode material on aluminum foil and graphite on copper foil, the same machine can be used.

Regarding **separator** production, cost is expected to decrease significantly. Polyethylene and polypropylene are raw materials of separators. In spite that they are relatively inexpensive (less than $1.30/kg) the processing in turn makes separators expensive ($120-240/kg).

„*Although it is not very capital- or labor-intensive, productivity on a mass basis is inherently very low because the film is so thin. The prospects are good for reducing the costs somewhat for large-scale production; it is hoped that separator film could be made as cheaply as packaging film. It is possible that process modifications to allow coextrusion of the three layers could reduce manufacturing costs. New technology could potentially offer significant cost reductions.*" (*Cuenca, Gaines, 2000)*

Current **electrolytes** in lithium-ion batteries consist of salts and solvents. The salts are very expensive ($121/kg) whereas the solvent (DEC) is about $20/kg. (*Cuenca, Gaines, 2000)* Efforts in order to reduce cost may involve the replacement of recent electrolytes by cheaper ones (see 2.7.17.2.6).

Regarding **cell assembly**, Cuenca and Gaines, 2000 mention the increase of winding speed as further potential in order to increase EOS.

4.1.3.2 Pecuniary effects

4.1.3.2.1 Market power towards suppliers

Regarding the suppliers of the Johnson Controls – SAFT Joint Venture, the existence of a sufficient market for graphitic anode materials, separators, solvents, copper and aluminum substrates, cell cans, electronics for battery management systems (BMS) or housing of packages can be assumed.

In contrast, suppliers of cathode raw materials and electrolytic salts are raw. According to *Cuenca, Gaines, 2000* about 80% of the world's supply of electrolyte salts is produced by a single company: Stella Chemifa, Osaka, Japan (www.stella-chemifa.co.jp). Johnson Controls is a worldwide leading automotive battery supplier but cathode raw materials and electrolytic salts needed for lithium-ion batteries differ completely from raw material used for conventional automotive lead-acid batteries or Ni-MH systems. *(see 2.7.5)* Thus, market power towards these suppliers still has to be established. *(see also 4.5.4)*

4.1.3.2.2 Access to capital market

Both founding companies of the JC-S joint venture are quoted on the stock exchange (JCI on NYSE and SAFT on Euronext).

4.1.3.2.3 Standing towards public authorities

As leading supplier of military defense and space battery solutions (Ariane program) *(SAFT, 2005)*, SAFT enjoys special status. The European Union launched several programs whereas the following were coordinated by SAFT in cooperation with other organizations: LION HEART, POMEROL, EST, CAMELIAIA, SOS-PVI, NEGELIA, PAMLIB, HEALTHY AIMS, HYSYS, LIBERAL, PROFIBRE, AEROCELL, ELEDRIVE, INVESTIRE NETWORK, EU-DEEP.

Information about programs as well as regarding connections to other enterprises or institutions, about experts and publications, etc. is available in form of data mapping and several databases at www.ist-world.org (6th Framework Program of the European Union).

4.1.3.3 Overview of Economies of scale

An overview of returns to scale and pecuniary effects is given in Table 4.2.

Economies Of Scale		
Returns to scale	**possibilities**	**limits**
learning effects	each new product and new plant incorporates minor improvements on the process' learning curve, specially designed equipment is introduced	
effects of capacity	lower, non linear increase of cost with capacity size: - LMO, LNCO cathode production facilities - separator production facilities	- Cathode material production: additional demand must be satisfied by means of duplicate production lines
utilization of capacity	- LMO, LNCO cathode production - separator production - increase of winding speed of cell assembly	- EOS of anode production soon at its limits
flexibility	regarding new products and strategies of maintenance: - Coating process	
Pecuniary effects	**possibilities**	**limits**
Market power towards suppliers	using synergies of conventional automotive battery market	Li-ion raw materials
Access to capital market	stock market	
Standing towards public authorities	European Union projects	

Table 4.2 Manageable phenomena of Li-ion battery production

4.2 Competitors

Figure 4.4 gives an overview of the market selection environment in accordance to the five forces of competition of Porter. The nonmarket selection environment is also indicated as interacting with the market selection environment.

Battery manufacturing companies can be distinguished between vertical integrated companies and those which purchase complete cells from suppliers. The JC-S joint venture represents a vertical integrated example. *(see products, Appendix B)*

During research it turned out, that many holdings of competitors are located in Japan (*Table B.1*) whereas production plants and specified cell manufacturers are located overseas in China and Korea.

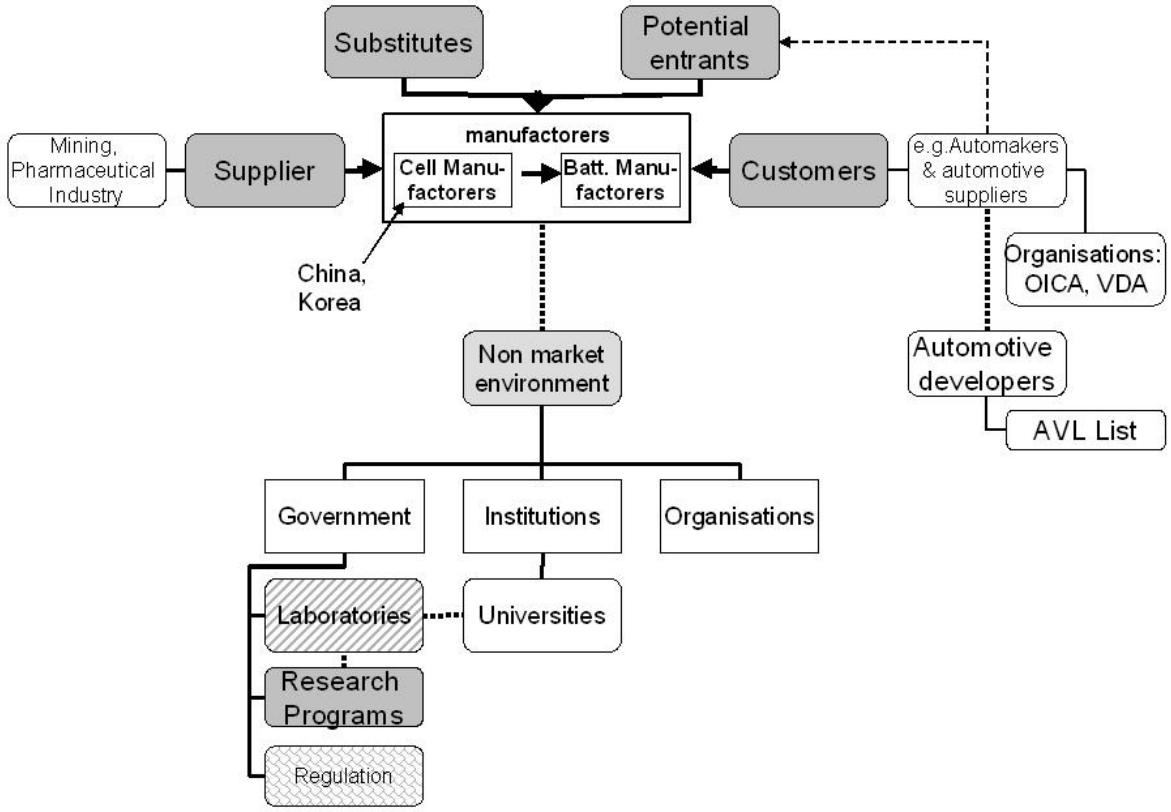


Figure 4.4 Porter's five forces applied on the storage market and in particular on the HEV/EV battery market, which interacts with the non market environment

Moreover, it can be stated that several companies which act on the hybrid and electric vehicle battery market form strategic alliances or joint ventures as Johnson Controls and SAFT did. This is a characteristic of an early stage *(Stepan, 2006)* of the adoption a new paradigm (compare Figure 4.1). In this case, the paradigm is the complete HEV/EV battery market and HEV technology.

For instance, Panasonic EV Energy, which dominates the HEV/EV battery market to 75 % *(see 4.1.1)* is a joint venture between Toyota (60% share) and the Matsushita Group (Panasonic Corp. from the 8th of Oct, 2008 on; 40% share) (*Toyota Motor Corp., 2005*). It supplies batteries for Toyota, Lexus, Daihatsu, Hino and Hyundai and formerly also for Honda or Ford *(Panasonic EV Energy, 2007)*. On 13th of January 2008 the Toyota Motor Corp. announced, that it plans to commence sales of lithium-ion battery-equipped plug-in hybrid vehicles in 2010. Toyota Motor Corp. and the Matsushita Group are currently investigating the feasibility of mass production of lithium-ion batteries at the plant of Panasonic EV Energy Co., Ltd in Omori, Japan (*Toyota Motor Corp., 2008*).

Another example of a joint venture is Cobasys, which was founded by the petrochemical giant Chevron (NYSE: CVX) and Energy Conversion Devices (ECD Ovonics) (NASDAQ: ENER). Chevron also operates coal and metal mines through its subsidiary Chevron Mining Inc. *(Chevron, 2008)* but no direct hint was found to a vertical integration of mining activity and battery manufacturing.

In 2001 ECD Ovonics and its subsidiary Ovonic Battery Company, Inc brought a patent infringement lawsuit against Matsushita, Toyota, and PEVE. Settlement in 2004 called for cross-licensing between parties of current and future Ni-MH-related patents until the end of 2014. It was not allowed to Matsushita, Toyota, and PEVE to sell certain Ni-MH batteries for transportation applications in North America until the second half of 2007, and commercial quantities of certain Ni-MH batteries in North America until the second half of 2010. Moreover, Ovonic Battery Co. and ECD Ovonics received a $10 million and Cobasys a $20 million patent license fee and $16 million to reimburse legal expenses. Furthermore Cobasys received royalties on certain batteries sold by Matsushita/PEVE in North America. *(ECD Ovonic, 2004)*

Licensing terms were expanded in 2005, with PEVE granted further license to sell Ni-MH batteries for certain transportation applications in North America, in exchange for royalties paid to Cobasys through 2014. *(Cobasys, 2005)*

Other characteristics indicating an early stage of the adoption of a new paradigm are R&D subsidies and innovation competition *(Stepan, 2006)*. These characteristics can be observed for the Li-ion paradigm in Northern America:

In the USA, in 2002 the US Government’s Department of Energy (DOE) teamed together with the United States Council for Automotive Research (USCAR) and established the ‘FreedomCar Partnership’ which then continued activities from the former ‘Partnership for a New Generation of Vehicles’ (PNGV). In 2003 this partnership was enhanced by five energy companies namely BP America, Chevron Corporation, ConocoPhillips, Exxon Mobil Corporation and Shell Hydrogen LLC and was renamed to ‘FreedomCar and Fuel Partnership’. *(USCAR, 2008)*

Among other things as hydrogen development, this partnership invests in five R&D programs concerning advanced batteries for plug-in HEVs. *(USDOE, 2007)* Programs consist of 3 phases. In September 2007 the DOE announced *(USDOE, 2007)*, that it provides capital of nearly $20 million for phase 2. Under the collaboration with the U.S. Advanced Battery

Consortium (USABC) (see also chapter 3.2), five lithium ion battery developers were selected for negotiation of awards. Combined with cost-share from the United States Advanced Battery Consortium (USABC), battery research and development budget is $38 million. The five developers are:

*„**3M of St. Paul, MN** – selected for an award of up to $1.14 million from DOE (total DOE/industry cost share: $ 2.28 million) over two years to screen nickel/manganese/cobalt (NMC) cathode materials through building and testing of small-sized cells;*

***A123Systems of Watertown, MA** – selected for an award of up to $6.25 million from DOE (total DOE/industry cost share: $12.5 million) over three years for a project to develop batteries based on nanophase iron-phosphate chemistry for 10- and 40-mile range PHEVs;*

***Compact Power Inc. of Troy, MI** – selected for an award of up to $4.45 million from DOE (total DOE/industry cost share: $12.7 million) over three years to develop batteries for 10-mile range PHEVs using high energy and high power Manganese-spinel;*

***EnerDel, Inc. of Indianapolis, IN** – selected for an award of up to $1.25 million from DOE (total DOE/industry cost share: $2.5 million) over two years to develop cells for 10- and 40-mile range PHEVs using nanophase lithium titanate coupled with a high voltage Nickel-Manganese cathode material;*

***Johnson Controls – SAFT Advanced Power Solutions of Milwaukee, WI** – selected for an award of up to $4.1 million from DOE (total DOE/industry cost-share: $8.2 million) over two years to develop batteries using a nickelate/layered chemistry for 10- and 40-mile range PHEVs. (USDOE, 2007)*

Moreover, *the University of Michigan's Michigan Memorial Phoenix Energy Institute (MMPEI) will receive nearly $2 million from DOE to coordinate efforts among DOE and its Pacific Northwest National Laboratory, General Motors, Ford Motor Company, and DTE Energy to conduct a two-year study on PHEVs.“ (USDOE, 2007)*

With exception of 3M, which acts as component supplier, products from all developers listed above where screened in this work. Compact Power Inc is a North American subsidiary of LG Chem Ltd. *(chapter 3.4)*

In Figure 4.4, substitutes and potential entrants are illustrated. As can be concluded from *USDOE, 2007,* the Li-ion technology can be assumed to be a substitute to Ni-MH technology, which is more desired.

Potential entrants may be suppliers (e.g. 3M) but in particular all automakers: Toyota already entered the market and holds controlling interest in the joint venture Panasonic EV Energy, which dominates market.

4.3 Non market selection environment

4.3.1 Governmental R&D and regulation

4.3.1.1 R&D

During research of this work, most R&D activities concerning energy storages for HEVs, EVs and Fuel Cell Vehicles (FCVs) were detected in Japan and the USA. Figure 4.5 illustrates an overview.

In Japan the responsible authority regarding governmental R&D activities in this area is the 'Ministry of Economics, Trade and Industry' (METI). These activities are delegated by the Council of Science and Technology to the 'New Energy and Industrial Technology Development Organization' (NEDO). NEDO is a public organization and is responsible for R&D project planning and formation, project management and post-project technology evaluation regarding new energy, industrial technology and environmental technology issues. Under its guidance several lithium-ion programs as indicated in Figure 4.5 in particular in respect to FCVs were carried out. *(NEDO, 2008).*

The Agency of Industrial Science & Technology (AIST) is a governmental funded R&D institution. The 'New Sunshine Program' should be mentioned here. *(Tatsumi, 2007)*

In the United States of America, R&D activities are concentrated in the 11 National Laboratories. Regarding energy storages and in particular regarding batteries, following five laboratories have to be mentioned *(USDOE-EERE, 2008)*:

Argonne National Laboratory (ANL):

- Standard protocols, benchmarking, validation
- Applied R&D; accelerated aging and diagnostics
- Hardware in the Loop (HIL) testing

Idaho National Laboratory (INL, formerly INEEL)

- Standard protocols, benchmarking, validation
- Applied R&D; accelerated aging and diagnostics

Lawrence Berkeley National Laboratory (LBNL):

- Long-term R&D; materials and electro-chemical couples

National Renewable Energy Laboratory (NREL):

- Thermal analysis

Sandia National Laboratories (SNL):

- Cell, module and battery abuse testing

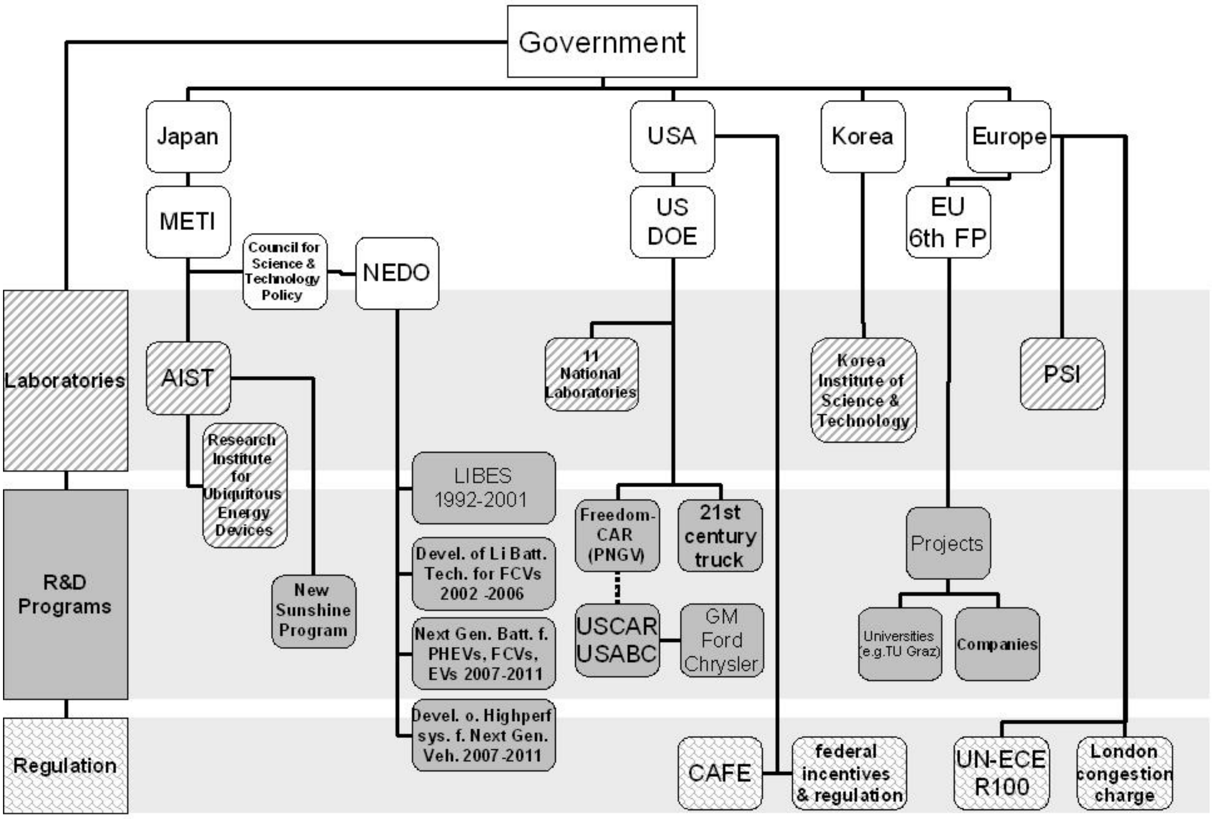


Figure 4.5 Governmental nonmarket selection environment of the storage market and in particular of the HEV/EV battery market

Regarding R&D programs, the FreedomCAR Program as discussed in 4.2 and the '21st Century Truck Partnership' have to be mentioned. The latter deals with 'Heavy Duty Hybrids'. Also hydraulic systems and thermal waste recovery (see 2.10) are key topics of this partnership program. *(USDOE EERE, 2007)*

In Korea, R&D activities concerning lithium-ion-(polymer) are concentrated in the Korea Institute of Science & Technology. *(KIST, 2008)*

In Europe, besides national R&D, activities are organized by the European Union. In several research projects as stated in Table 4.3, companies work together with institutions as the

Technical University of Graz, Austria or the Paul Scherrer Institute of the ETH (PSI), Switzerland. *(CORDIS, 2007)* Table 4.3 lists projects of the 6th Framework Program of the European Union. Abbreviations in the first column indicate Lithium (Li)-, Nickel (Ni)- and Supercap (SC) technology. No projects concerning mechanical storages were found.

Tech	**Title**	**Proj. Ref.**	**type**	**organisator**	**content**
Li	POMEROL - Power Oriented low cost and safe Materials for Li-ion batteries	19351	Specific Targeted Research Project	SAFT	high power, low-cost and intrinsically safe lithium-ion batteries by a breakthrough in materials
Li	ALISTORE - Advanced lithium energy storage systems based on the use of nano-powders and nano-composite electrodes/electrolytes	503532	Networks of Excellence	Centre nationale de la recherché scientifique, ICMCB (partner N°3) & CIRIMAT (partner N°11), Laboratoire de RÉACTIVITÉ et chimie des solides (LRCS)	Advanced lithium energy storage systems based on the use of nano-powders and nano-composite electrodes/electrolytes
Li	SUBAT	502490	-	VRIJE universiteit Brussel TW-ETEC	bility to maintain, or not, cadmium, in the exemption list of Directive 2000/53 on End-of-Life Vehicles
Ni	HYDRONANOPOL	32517	Specific Targeted Research Project	VARTA Microbattery GMBH	enhance the electrode material of Ni-MH batteries in a way that it is possible to replace ecological questionable NiCd batteries even in high current applications
Li	NANOPOLIBAT	33195	Specific Targeted Research Project	VARTA Microbattery GMBH, R&D Poliflex	lithium polymer microbatteries: NMP Nanotechnologies and nanosciences, knowledge based multifunctional materials and new production processes and devices
Li	ILLIBATT - Ionic liquid based Lithium batteries	33181	Specific Targeted Research Project	Technische Universität Graz - ICTAS - Prof. Winter	safer and better performing Li batteries that make use of solid-state electrolytes,

					containing non-volatile and thermally stable ionic liquids
SC	HI-CONDELEC	516975	Networks of Excellence	HEF R&D S.A.S	Design of highly conductive solid thin film electrolyte for stack integration within optical and energy storage applications
SC	ILHYPOS - Ionic Liquid-based Hybrid Power Supercapacitors	518307	Specific Targeted Research Project	Ente per le nuove tecnologie, l'energia e l'ambiente	green, safe, and high energy and power Hybrid SuperCapacitors for application as peak power smoothing device in fuel cell (PEM) powered electric vehicles and, as a second option, in delocalised energy production

Table 4.3 Energy storage development projects of the European Union's 6th Framework program (CORDIS, 2007)

4.3.1.2 Regulations

In the main, vehicle regulations in the European Union base on the *"Agreement concerning the adoption of uniform technical prescriptions for wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles and the conditions for reciprocal recognition of approvals granted on the basis of these prescriptions*" of the United Nations Economic Commission for Europe (UNECE). *(UNECE, 2005)* They are discussed in chapter 4.5.1. Several national or local incentives or regulations exist concerning HEVs/EVs. The 'central London congestion charging scheme' (*Transport for London, 2008*) as stated in Figure 4.5 is just an example. However, detailed discussion would go beyond the scope of this work.

In the US, 'Federal Motor Vehicle Safety Standards' are published by the 'National Highway Traffic Safety Administration of the United States Department of Transportation' (USDOT). *(NHTSA, 2008)* Significant are the Corporate Average Fuel Economy (CAFE) standards, which prescribe a manufacturer's fuel economy (miles per gallon), measured on the harmonically mean of its total fleet. Manufacturers which fall below the defined standard must pay a penalty, currently (2008) $5.50 USD per 0.1 mpg variation, multiplied by the manufacturer's total production for the U.S. domestic market. *(NHTSA, 2008)*

In California and several other states, there also exist additional regulations or public incentives. *(CARB, 2008)*

4.3.2 Organizations

Organizational structure of the branch can be explained by Figure 4.6. In first line, it can be distinguished between standard setters, organizing institutions of congresses and motorshows, specified HEV/EV organizations and the formula 1.

Regarding standard setters, see 2.7.2. USCAR and USABC is discussed in 4.2. As discussed in chapter 3.2, detailed standards are the basis for any data comparison and analysis. Thus, standard setters can be assumed to be the most important part of the organizational structure of the branch.

The formula 1 is the most important promoter regarding the development and diffusion of kinetic energy storages for vehicles. Comparing 2.3.1.6, all compact sized kinetic energy storages are primarily developed for purposes of the formula 1. New regulations allow the usage of Kinetic energy recovery systems (KERS) for the 2009 season *(FIA, 2006)*.

Congresses and motorshows are organized by several private organizations. The Society of Automotive Engineers (SAE) probably is the most famous example, which organizes both, congresses and several motorshows *(see SAE International, 2008).*

The ‘World Electric Vehicle Association’ (WEVA) organizes congresses through its subsidiaries ‘Electric Drive Transportation Association’ (EDTA), ‘European Electric Road Vehicle Association’ (AVERE), ‘Electric Vehicle Association of the Asia Pacific’ (EVAAP). *(EDTA, 2007)*

‘Advanced Automotive Batteries – Consulting’ (AABC) offers consulting services for the branch but also organizes congresses. *(Anderman, 2006)*

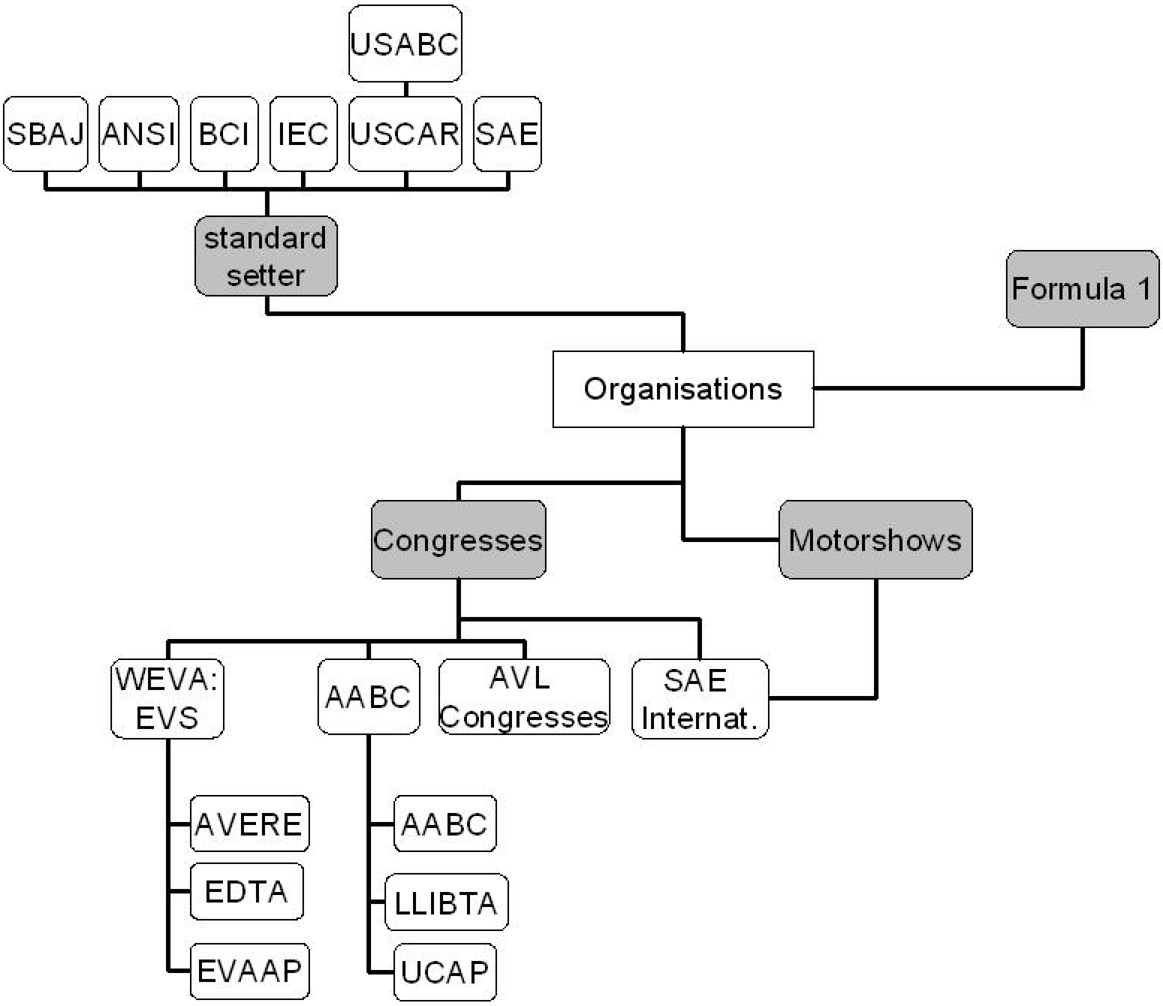


Figure 4.6 Organizational structure of the nonmarket selection environment of energy storages and in particular of HEV/EV batteries

AVL List, Graz, Austria, “*the world's largest privately owned and independent company for the development of powertrain systems with internal combustion engines as well as instrumentation and test systems*”, also organizes conferences as the ‘Engine and Environment’ conference. *(AVL List, 2008)* The hybrid division of AVL List offers several engineering services as well as technologies, tools, methodologies and products regarding hybrid vehicle development *(see 4.4.2).*

4.4 Inventions, Innovations and Innovation potential

*„**Invention** is the creation of a new idea. The act is intellectual: perception of a new image, of a new connection between old conditions, or of a new area for action. It can range from basic scientific concepts to strictly practical ideas.*

***Innovation** converts the idea to practical use. The innovator … brings the new product or process to the market. This often (not always) requires displacing previous products or processes.*

***Imitation** then follows as the innovation is copied by others. **Diffusion** of the innovation across the market may be rapid or slow. It is usually an easier and safer act than innovating. Yet imitation generally gives smaller rewards than innovation and often the **followers** act out of necessity, in order to survive.“ (Shepherd, 1990, p. 142)*

The displacement of previous products or processes mentioned by *Shepherd, 1990* may lead to fundamental changes regarding a predominant ‘*paradigm’*. Examples are the displacement of gasifier by intake-manifold fuel injection and subsequently by direct injection technology, the displacement of DVDs by Blu-Ray technology and that of common vehicles by HEVs. The characteristic S-shape of the diffusion process of a new paradigm displacing another one *(Stepan, 2006)* is indicated in Figure 4.1.

The process can be segmented into the phases of perception, seeking, testing and finally the phase of acquisition. Hence, adopters can be classified according to the stages of adoption by ‘early adopters, an early majority’, the ‘late majority’ and ‘laggards’. *(Stepan, 2006)*

When assuming that Li-ion technology is a new and successful paradigm for HEV energy storages, the Johnson Controls – SAFT joint venture may be seen as an early adopter.

4.4.1 Classification of innovations and the diffusion process

Innovations can be classified by product or process innovations, by the triggering source and by the degree of newness. *(Shepherd, 1990)*

Process innovations simply alter the way given products are made, whereas product innovations create a new good for sale, without any change in process. In real world, they often emerge as combinations. *(Shepherd, 1990, p.142)*

Product innovations tend to emerge frequently in the first stages of the diffusion of a new paradigm whereas process innovations tend to do later *(Utterback and Abernathy, 1975 at Stepan, 2006).* Regarding R&D of energy storages for HEVs, lithium-ion technology represents a relatively new technology *(see 4.1.1).* Recently, several new cathode materials emerge gradually *(see 2.7.17.2.6).* Hence, product innovation rates are high whereas process innovation rates may increase significantly at mass production *(see 4.1.1).* This would indicate an early stage of the diffusion process of Li-ion technology regarding the HEV battery market.

Regarding innovation triggers, it can be distinguished between, if a demanding source pulls (demand pull) or if a supplying source pushes (supply push) innovation to market *(Dosi, 1982 at Stepan, 2006)*. If sources can't be detected any more and the total market pulls or technology pushes, respectively, it is referred to market pull or technology push *(Dosi, 1982 at Stepan, 2006)*. Furthermore innovations may emerge autonomous or are induced by a distinct source. *(Scherer, 1990, at Shepherd, 1990)* Market pull and induced innovation characterize a higher level of diffusion of paradigms *(Stepan, 2006)*. Market pull innovations have good chances to be successful (*Scherer, 1990, at Shepherd, 1990*).

However, from the observed innovation competition as well as the subsidizing of Li-ion R&D mentioned in chapters 4.2 and 4.3.1.1, it can be concluded, that Li-ion technology gets prepared for the market but currently didn't diffuse very much so far.

Nevertheless, also market pull can be observed. This controversy may be explained that batteries represent a key technology for HEVs, which lag in comparison to the rest of HEV technology. Hence, a success in battery technology will lead to high diffusion rates of HEVs.

Regarding the degree of newness, it can be differentiated by basis innovations, improving-, adapting- and pseudo innovations. In this sequence they represent different levels of diffusion of a paradigm. *(Vahs, Burmester, 2005)*

Intensive cathode research can be assumed as basis or improving innovation, what also characterizes an early level of diffusion of Li-ion technology regarding the HEV/EV battery market.

4.4.2 Innovation potential

In our example of 'Johnson Controls-SAFT Advanced Power Solutions', innovation potential exists regarding several basis innovations of Li-ion cathode materials as mentioned in 4.4.1. In particular the usage of cheaper raw materials as manganese *(Cuenca, Gaines, 2000)* and higher safety *(see 2.7.17)* is desirable. Regarding Ni-MH, process innovations regarding the complex manufacturing process of anodes (*2.7.10.1*) is desirable to reduce cost.

Moreover, process innovations regarding various assembly processes Figure 4.2 are thinkable.

Furthermore, the usage of environmentally friendly materials, in particular of solvents, is important. Process innovations regarding recycling are in development concerning several technologies as Ni-MH and Li-ion. *(SAFT, 2006b)*

Another major issue regarding both, Li-ion and Ni-MH technology is life time and battery testing, which depends on the interaction of the battery with other components of the hybrid vehicle *(see 3.2.4)*. Hence, potential exists for several services and equipment, which for instance are offered by consulting and developing companies as discussed in the next section.

4.4.3 Role of the AVL List GmbH

Automotive developers as the AVL List GmbH (see also 4.3.2), employer of this thesis, have a special role in the selection environment of battery development and production as indicated in Figure 4.4.

AVL List offers several battery related test services and tools which are used in the development process of these storages as well as in the implementation process into entire systems. Products and services range from in-house battery simulation (AVL BTS-BS) to battery testbeds (AVL BTS-BT) *(AVL Group, 2007).*

AVL offers battery test beds for testing, characterization, verification and validation of current energy storage technologies as supercapacitors, Ni-MH, Li-Ion and Lead-Acid. AVL battery test beds are able to execute performance tests, calendar life tests and cycle life tests (*AVL Group, 2007*).

In this regard, Hardware in the loop (HIL) is a simulation technique to test complex embedded systems in a virtually environment *(AVL Group, 2008).* Institutions as Arsenal Research, Vienna, Austria *(Arsenal Research, 2007)* or Argonne National Laboratory *(4.3.1.1)* also use this technique concerning battery testing. The advantages of this simulation technique are to reduce development time and (subsequently) development cost due to the ability to feed back from a implementation in a virtual entire system before a real system is available *(AVL Group, 2008).*

As global automotive lead user, AVL List also was rewarded to license, distribute and enhance a tool developed by the *"U.S. Department of Energy's National Renewable Energy Laboratory (NREL). NREL first developed 'ADVISOR' in 1994. Between 1998 and 2003 it was downloaded by more than 7,000 individuals, corporations, and universities world-wide. In early 2003 NREL initiated the commercialization of ADVISOR through a public solicitation. AVL responded and was awarded the exclusive rights to license and distribute ADVISOR world-wide. AVL is committed to continuously enhance ADVISOR's capabilities. … ADVISOR provides rapid analysis of the performance and fuel economy of conventional* *and advanced, light and heavy-duty vehicle models as well as hybrid electric and fuel cell vehicle models." (NREL, 2008)*

Also other tools developed by AVL as AVL BOOST (entire engine modeling), AVL CRUISE (vehicle and powertrain analysis, control systems) and AVL Fire (computational fluid dynamics (CFD) problems) are used by NREL. (NREL, 2008)

Regarding battery packaging, the AVL Group is a specialist in offering logic and controls development with functional integration. Several solutions for total HEV conceptual design are available. *(AVL Group, 2007)*

4.5 Entry barriers and barriers to exit

4.5.4 Market selection environment

Entry barriers aroused by the market selection environment are price setting, price differentiation, economies of scale, absolute cost advantages and vertical integration *(Shepherd, 1990, pp.274).*

Regarding Li-ion technology, economies of scale are a key issue in order to purchase cathode raw material at low price because, according to *Cuenca and Gaines, 2000,* price increases significantly due to large volume shipments. However, prices also vary in broad ranges due to different price settings of the respective supplier (e.g. $29 to $59/kg manganese in 2000) (*Cuenca and Gaines, 2000).* According to *Ridgway, 1999 at C., G., 2000* some Japanese battery material producers also give preferential prices to some but not all Japanese battery manufacturers. Moreover, Japanese manufacturers have absolute cost advantages because major suppliers of cathode active material are in Japan whereas in North America material suppliers may give development of these products low priority.

Regarding vertical integration, no Li-ion manufacturers were detected which vertically integrated mining and manufacturing activities.

Regarding barriers to exit, high investment of production facilities as discussed for Ni-MH cathode manufacturing result in long payback periods (*2.7.10.2*). The rest value of purchased facilities may decrease significantly due to the displacement of Ni-MH by Li-ion technology.

4.5.1 Non market selection environment: regulations

Regarding our example of 'Johnson Controls-SAFT Advanced Power Solutions', competitors also face entry barriers of various regulations and standards:

In France, according to the decree 99-374 of May 12, 1999, "*all individuals or legal entities that manufacture, import, introduce, and/or distribute batteries under their own brand for household use are obliged to accept used rechargeable batteries…. The same individuals or legal entities have the responsibility for enhancing the value of the collected batteries, either directly or through third parties. For non-consumer applications, this responsibility is given to the final user*." *(SAFT, 2006c)*

In the **European Union**, the directive 2006/66/EC and the directive 2000/53/EC and 91/157 are the only European directives in force for batteries and accumulators. In article 9 of directive 91/157 it is stated, that member states may not impede, prohibit or restrict the marketing of batteries or accumulators covered by this directive and conforming to the provisions laid down herein (see also 2.7.9). *(SAFT, 2006c)*

Accepted **UN ECE** standards of the 'United Nations Economic Commission for Europe' define safety standards and test procedure of Battery Electric Vehicles in the UN ECE Regulation No. 100 'Uniform Provisions Concerning The Approval Of Battery Electric Vehicles With Regard To Specific Requirements For The Construction And Functional Safety'. *(UNECE, 2002)*

In the **United States** the 42 U.S.C 14301-14336 Act is to mention *(see 2.7.9)*.

5 Conclusion

The hybrid vehicle market grows steadily. At first sight, the range of energy storages which may be appropriate for hybrid vehicles seems to be broad but in a more detailed view, particularly electrochemical storages as Ni-MH and Li-Ion batteries and electrostatic storages as various types of supercapacitors (e.g. acetonitrile based EDLCs) meet most technical requirements. Li-ion batteries using lithium-manganese-spinel ($LiMn_2O_4$) cathodes in combination with lithium-titanate-oxide anodes as well as Li-ion batteries with lithium-iron phosphate ($LiFePO_4$) cathodes currently represent the most attractive battery solutions for HEVs.

Concerning mechanical storages, the installation of hydraulic storages in vehicles already equipped with a hydraulic system may have great potential regarding fuel economy and reduction of emissions. However, in this work hybrid electric vehicles were observed and thus these storages were not discussed in detail.

Kinetic storages meet most requirements up to mild hybrids but their usage may be qualified by their complex construction and higher cost than batteries or supercapacitors.

Regarding benchmarking, storages have to be compared on the basis of similar defined characteristics, in particular at equal degrees of energy efficiency. Any small variations are misleading.

Regarding characteristics, USABC goals of specific and volumetric power and energy capabilities are met by various types of current storage technologies. The most complex characteristic is cycle life. It depends on a set of various parameters as Depth Of Discharge (DOD) and charge-rate. Recent storages meet USABC lifetime criteria.

However, specific and volumetric energy storage capability of all storages discussed differs significantly from that of chemical storages. A wide range of various fuels, including hydrogen, is indicated in Figure 5.1. The latter, hydrogen, may be used in both, Electric Vehicles equipped with Fuel Cells and Internal Combustion Vehicles (see BMW, chapter 2.6).

Figure 5.1 reflects the vision of the National Renewable Energy Laboratory (NREL), Golden, Colorado, USA and illustrates the state of diffusion of various fuels at the bottom of the plot. The corresponding roadmap of various vehicle types is also illustrated. Currently (2008) the milestone ‘Consumers asking for Plug-In Capabilities’ is reached.

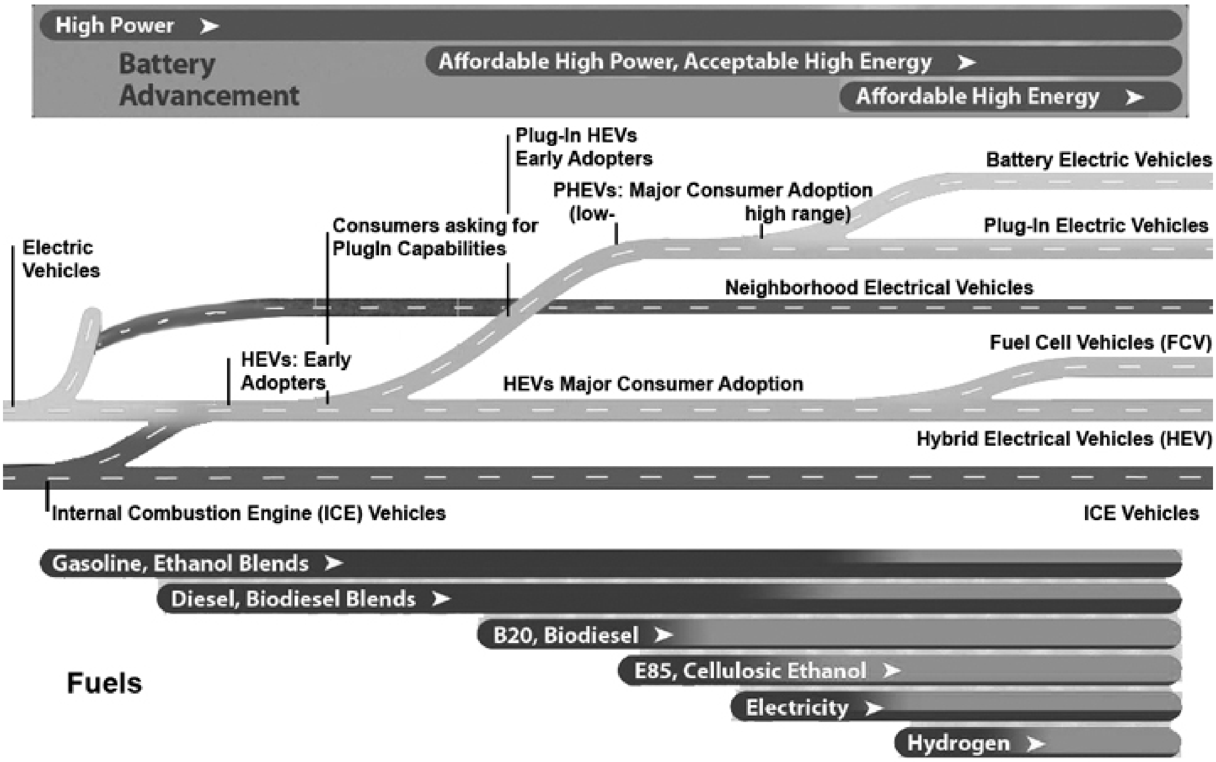


Figure 5.1 NREL's vision of future transportation (source: Pesaran 2006b)

Batteries play a key role regarding all types of HEVs but also regarding FCVs and of course concerning Battery Electric Vehicles. The current HEV/EV battery market is still dominated by Ni-MH technology. Toyota Motor Corporation and the Matsushita Group together hold a quasi monopoly in the highly concentrated market (HHI about 5800). Major efforts in the commercialization of Li-ion batteries for HEV are made by battery producers as e.g. the Joint Venture Johnson Controls-SAFT, public R&D programs funded by the US Department of Energy (USDOE) and by automakers, which consider Li-ion battery mass production for Plug-In hybrids as Toyota. In this market, which is expected to grow from $600 million in 2006 to $1.4 billion in 2010 and $2.3 billion in 2015, Li-ion technology is assumed to displace Ni-MH technology gradually (5% in 2010). Market concentration is assumed to decrease within the next 5 to 10 years.

A major issue is cost reduction and in particular the reduction of cathode raw material cost. Regarding the manufacturing process, potential for economies of scale, in particular concerning certain cathodes as LMO and LNCO exists.

Currently, Japan is the leading country concerning battery manufacturing due to a high concentration of suppliers of battery components. Japanese manufacturers also benefit from absolute cost advantages.

Due to the present scarcity and high cost of some minerals, recycling becomes a major issue. Moreover, the choice of environmental friendly materials (e.g. regarding solvents) are important in order to support the green image of hybrid vehicles and their marketing strategy.

AVL List, client of this diploma thesis, faces various potentials of innovations, which in first line do not concern battery manufacturing but the process of implementation of storages into vehicles. Various AVL simulation and testing tools (e.g. AVL ADVISOR) as well as an entire Hybrid Development Platform (HDP) are used in the hybrid vehicle development process world wide and became standard development tools.

Appendix A

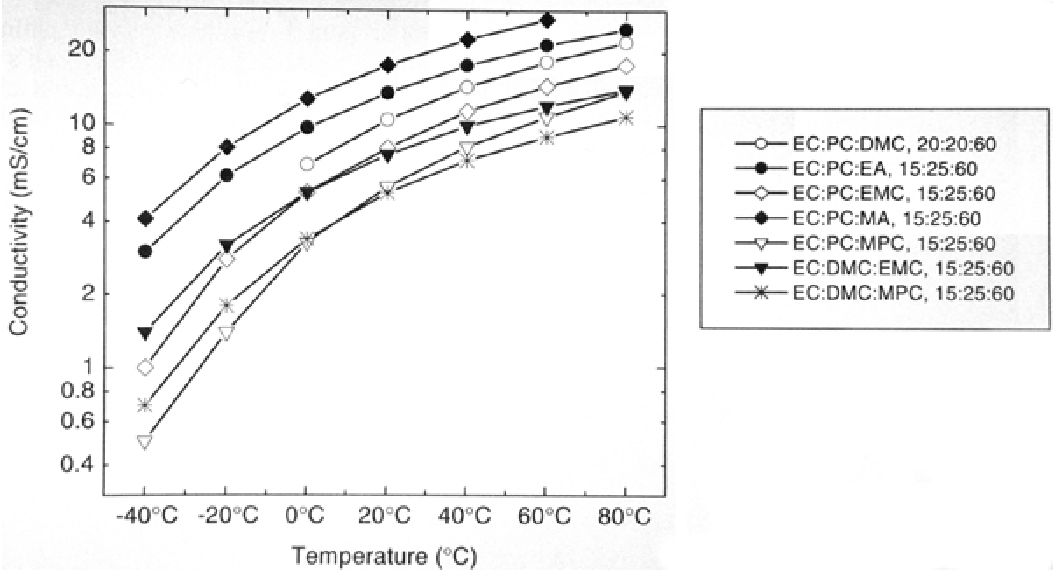
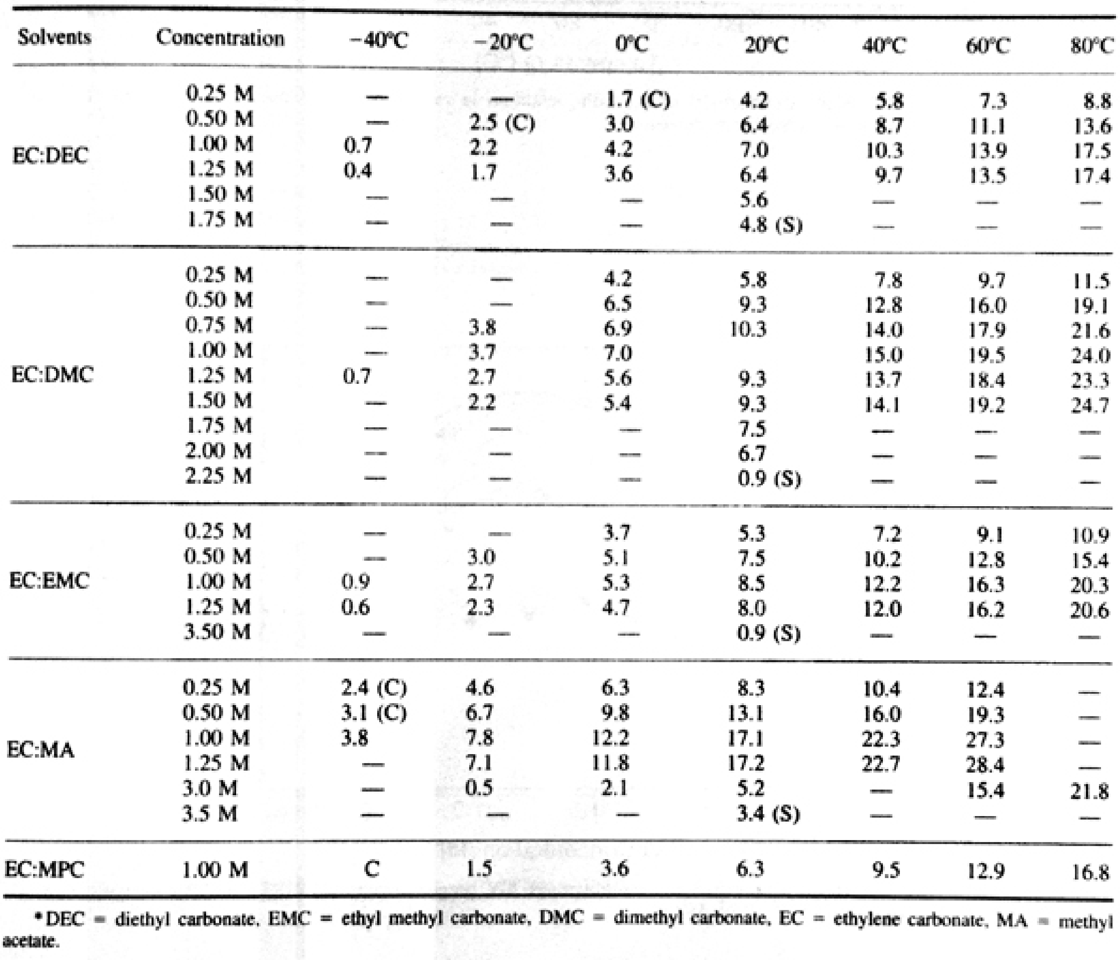


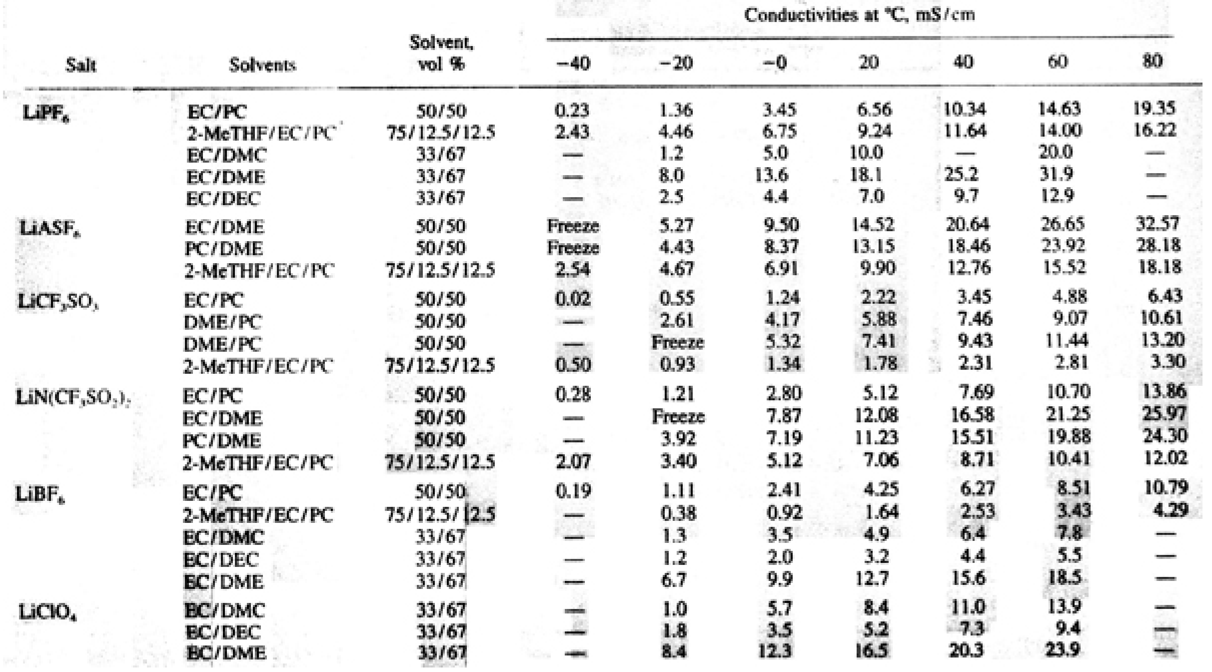
Figure A.1 Conductivity (mS/cm) of 1M LiPF6 salt in various blends of solvents over temperature (source: Ehrlich, 2002, figure 35.26)



Solvents	Concentration	−40°C	−20°C	0°C	20°C	40°C	60°C	80°C
EC:DEC	0.25 M	—	—	1.7 (C)	4.2	5.8	7.3	8.8
	0.50 M	—	2.5 (C)	3.0	6.4	8.7	11.1	13.6
	1.00 M	0.7	2.2	4.2	7.0	10.3	13.9	17.5
	1.25 M	0.4	1.7	3.6	6.4	9.7	13.5	17.4
	1.50 M	—	—	—	5.6	—	—	—
	1.75 M	—	—	—	4.8 (S)	—	—	—
EC:DMC	0.25 M	—	—	4.2	5.8	7.8	9.7	11.5
	0.50 M	—	—	6.5	9.3	12.8	16.0	19.1
	0.75 M	—	3.8	6.9	10.3	14.0	17.9	21.6
	1.00 M	—	3.7	7.0		15.0	19.5	24.0
	1.25 M	0.7	2.7	5.6	9.3	13.7	18.4	23.3
	1.50 M	—	2.2	5.4	9.3	14.1	19.2	24.7
	1.75 M	—	—	—	7.5	—	—	—
	2.00 M	—	—	—	6.7	—	—	—
	2.25 M	—	—	—	0.9 (S)	—	—	—
EC:EMC	0.25 M	—	—	3.7	5.3	7.2	9.1	10.9
	0.50 M	—	3.0	5.1	7.5	10.2	12.8	15.4
	1.00 M	0.9	2.7	5.3	8.5	12.2	16.3	20.3
	1.25 M	0.6	2.3	4.7	8.0	12.0	16.2	20.6
	3.50 M	—	—	—	0.9 (S)	—	—	—
EC:MA	0.25 M	2.4 (C)	4.6	6.3	8.3	10.4	12.4	—
	0.50 M	3.1 (C)	6.7	9.8	13.1	16.0	19.3	—
	1.00 M	3.8	7.8	12.2	17.1	22.3	27.3	—
	1.25 M	—	7.1	11.8	17.2	22.7	28.4	—
	3.0 M	—	0.5	2.1	5.2	—	15.4	21.8
	3.5 M	—	—	—	3.4 (S)	—	—	—
EC:MPC	1.00 M	C	1.5	3.6	6.3	9.5	12.9	16.8

*DEC = diethyl carbonate, EMC = ethyl methyl carbonate, DMC = dimethyl carbonate, EC = ethylene carbonate, MA = methyl acetate.

Table A.1 Conductivity (mS/cm) of various blends of solvents given for the stated concentration of LiPF6 at various temperatures (source: Ehrlich, 2002, table 35.8)



Salt	Solvents	Solvent, vol %	Conductivities at °C, mS/cm						
			−40	−20	−0	20	40	60	80
$LiPF_6$	EC/PC	50/50	0.23	1.36	3.45	6.56	10.34	14.63	19.35
	2-MeTHF/EC/PC	75/12.5/12.5	2.43	4.46	6.75	9.24	11.64	14.00	16.22
	EC/DMC	33/67	—	1.2	5.0	10.0	—	20.0	—
	EC/DME	33/67	—	8.0	13.6	18.1	25.2	31.9	—
	EC/DEC	33/67	—	2.5	4.4	7.0	9.7	12.9	—
$LiASF_6$	EC/DME	50/50	Freeze	5.27	9.50	14.52	20.64	26.65	32.57
	PC/DME	50/50	Freeze	4.43	8.37	13.15	18.46	23.92	28.18
	2-MeTHF/EC/PC	75/12.5/12.5	2.54	4.67	6.91	9.90	12.76	15.52	18.18
$LiCF_3SO_3$	EC/PC	50/50	0.02	0.55	1.24	2.22	3.45	4.88	6.43
	DME/PC	50/50	—	2.61	4.17	5.88	7.46	9.07	10.61
	DME/PC	50/50	—	Freeze	5.32	7.41	9.43	11.44	13.20
	2-MeTHF/EC/PC	75/12.5/12.5	0.50	0.93	1.34	1.78	2.31	2.81	3.30
$LiN(CF_3SO_2)_2$	EC/PC	50/50	0.28	1.21	2.80	5.12	7.69	10.70	13.86
	EC/DME	50/50	—	Freeze	7.87	12.08	16.58	21.25	25.97
	PC/DME	50/50	—	3.92	7.19	11.23	15.51	19.88	24.30
	2-MeTHF/EC/PC	75/12.5/12.5	2.07	3.40	5.12	7.06	8.71	10.41	12.02
$LiBF_4$	EC/PC	50/50	0.19	1.11	2.41	4.25	6.27	8.51	10.79
	2-MeTHF/EC/PC	75/12.5/12.5	—	0.38	0.92	1.64	2.53	3.43	4.29
	EC/DMC	33/67	—	1.3	3.5	4.9	6.4	7.8	—
	EC/DEC	33/67	—	1.2	2.0	3.2	4.4	5.5	—
	EC/DME	33/67	—	6.7	9.9	12.7	15.6	18.5	—
$LiClO_4$	EC/DMC	33/67	—	1.0	5.7	8.4	11.0	13.9	—
	EC/DEC	33/67	—	1.8	3.5	5.2	7.3	9.4	—
	EC/DME	33/67	—	8.4	12.3	16.5	20.3	23.9	—

Figure A.2 Conductivity (in mS/cm) of various salts in various blends of solvents at various temperatures (source: Hossain, Reddy, 2002, table 34.14)

Appendix B

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
1	p/CD/Dynastor F1	Compact Dynamics	http://www.compact-dynamics.de/entwicklung_motoren0.html	Compact Dynamics GmbH	Dynastor F1	flywheel	electric-output	metal sheets	-		p	n
2	p/CD/Dynastor Hybrid	Compact Dynamics	Datasheet		Dynastor Hybrid	flywheel	electric-output	metal sheets	-		p	n
3	c/KOK/356495	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html	EaglePicher Kokam Co., Ltd	356495	Lithium	LiPolymer	LCO		graphite	c	y
4	c/KOK/456495	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		456495	Lithium	LiPolymer	LCO		graphite	c	y
5	c/KOK/396495	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		396495	Lithium	LiPolymer	LCO		graphite	c	y
6	c/KOK/486495	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		486495	Lithium	LiPolymer	LCO		graphite	c	y
7	c/KOK/526495	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		526495	Lithium	LiPolymer	LCO		graphite	c	y
8	c/KOK/50106100	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		50106100	Lithium	LiPolymer	LCO		graphite	c	y
9	c/KOK/75106100	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		75106100	Lithium	LiPolymer	LCO		graphite	c	y
10	c/KOK/60216216	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		60216216	Lithium	LiPolymer	LCO		graphite	c	y
11	c/KOK/65216216	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		65216216	Lithium	LiPolymer	LCO		graphite	c	y
12	c/KOK/70460330	Kokam Co. Ltd	http://kokam.com/product/product_pdf/high_energy_density/EL-402_SLPB70460330_100Ah_Grade.pdf		70460330	Lithium	LiPolymer	LCO		graphite	c	y
13	c/KOK/140460330	Kokam Co. Ltd	http://kokam.com/product/product_pdf/high_energy_density/EL-403_SLPB140460330_200Ah_Grade.pdf		140460330	Lithium	LiPolymer	LCO		graphite	c	y
14	c/KOK/160460330	Kokam Co. Ltd	http://kokam.com/product/product_pdf/high_energy_density/EL-404_SLPB160460330_240Ah_Grade.pdf		160460330	Lithium	LiPolymer	LCO		graphite	c	y
15	c/KOK/75106205	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		75106205	Lithium	LiPolymer	LCO		graphite	c	y
16	c/KOK/90216216	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		90216216	Lithium	LiPolymer	LCO		graphite	c	y

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
17	c/KOK/53460330	Kokam Co. Ltd	http://kokam.com/product/product_pdf/high_energy_density/El-401_SLPB53460330_70Ah_Grade.pdf		53460330	Lithium	LiPolymer	LCO		graphite	c	y
18	c/KOK/55205130H	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		55205130H	Lithium	LiPolymer	LCO		graphite	c	y
19	c/KOK/30205130H	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		30205130H	Lithium	LiPolymer	LCO		graphite	c	y
20	c/KOK/80460330H	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		80460330H	Lithium	LiPolymer	LCO		graphite	c	y
21	c/KOK/160460330H	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		160460330H	Lithium	LiPolymer	LCO		graphite	c	y
22	c/KOK/78216216H	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		78216216H	Lithium	LiPolymer	LCO		graphite	c	y
23	c/KOK/41205130H	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		41205130H	Lithium	LiPolymer	LCO		graphite	c	y
24	c/KOK/100216216H	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		100216216H	Lithium	LiPolymer	LCO		graphite	c	y
25	c/KOK/60460330H	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		60460330H	Lithium	LiPolymer	LCO		graphite	c	y
26	c/KOK/5043128H3	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		5043128H3	Lithium	LiPolymer	LCO		graphite	c	y
27	c/KOK/11043140H	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		11043140H	Lithium	LiPolymer	LCO		graphite	c	y
28	c/KOK/8043128H	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		8043128H	Lithium	LiPolymer	LCO		graphite	c	y
29	c/KOK/486495P	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		486495P	Lithium	LiPolymer	LCO		graphite	c	y
30	c/KOK/45205130P	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		45205130P	Lithium	LiPolymer	LCO		graphite	c	y
31	c/KOK/70205130P	Kokam Co. Ltd	http://www.kokam.com/english/product/battery_main.html		70205130P	Lithium	LiPolymer	LCO		graphite	c	y
32	p/SAF/NHE 10-100	SAFT	http://www.saft.fr/130-Catalogue/PDF/NHE_en.pdf	Johnson Controls– Saft Advanced Power Solutions - Joint Venture	NHE 10-100	Nickel	Ni-MH	NiOOH	Alkaline	(AB5)H	p	n
33	p/SAF/NHE 5-200	SAFT	http://www.saft.fr/130-Catalogue/PDF/NHE_en.pdf		NHE 5-200	Nickel	Ni-MH	NiOOH	Alkaline	(AB5)H	p	n
34	p/SAF/NHP 10-340	SAFT	http://www.saft.fr/130-Catalogue/PDF/NHP_en.pdf		NHP 10-340	Nickel	Ni-MH	NiOOH	Alkaline	(AB5)H	p	n
35	p/SAF/NHP 5-680	SAFT	http://www.saft.fr/130-		NHP 5-680	Nickel	Ni-MH	NiOOH	Alkaline	(AB5)H	p	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
			Catalogue/PDF/NHP_en.pdf									
36	p/SAF/VHD 10S	SAFT	http://www.saft.fr/130-Catalogue/PDF/VH_module.pdf	Johnson Controls– Saft Advanced Power Solutions - Joint Venture	VHD 10S	Nickel	Ni-MH	NiOOH			p	y
37	p/SAF/VHD 20S	SAFT	http://www.saft.fr/130-Catalogue/PDF/VH_module.pdf		VHD 20S	Nickel	Ni-MH	NiOOH			p	y
38	p/SAF/VHD 30S	SAFT	http://www.saft.fr/130-Catalogue/PDF/VH_module.pdf		VHD 30S	Nickel	Ni-MH	NiOOH			p	y
39	p/SAF/VHF 10S	SAFT	http://www.saft.fr/130-Catalogue/PDF/VH_module.pdf		VHF 10S	Nickel	Ni-MH	NiOOH			p	y
40	p/SAF/VHF 20S	SAFT	http://www.saft.fr/130-Catalogue/PDF/VH_module.pdf		VHF 20S	Nickel	Ni-MH	NiOOH			p	y
41	p/SAF/VHF 30S	SAFT	http://www.saft.fr/130-Catalogue/PDF/VH_module.pdf		VHF 30S	Nickel	Ni-MH	NiOOH			p	y
42	c/SAF/VH D 9500	SAFT	http://www.saft.fr/130-Catalogue/PDF/VH_D_9500.pdf		VH D 9500	Nickel	Ni-MH	NiOOH			c	y
43	c/SAF/VH F 15000	SAFT	http://www.saft.fr/130-Catalogue/PDF/VH_F_15000.pdf		VH F 15000	Nickel	Ni-MH	NiOOH			c	y
44	c/SAF/VL45 E	SAFT	http://www.saft.fr/120-Techno/20-10_produit.asp?sSegment=&sSegmentLien=&sSecteurLien=&secteur=&Intitule_Produit=VLEcells&page=2		VL45 E	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	c	y
45	p/SAF/VLE 22-42	SAFT	http://www.saft.fr/130-Catalogue/PDF/VLE_module.pdf		VLE 22-42	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	p	n
46	p/SAF/VLE 11-84	SAFT	http://www.saft.fr/130-Catalogue/PDF/VLE_module.pdf		VLE 11-84	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	p	n
47	c/SAF/VL41M	SAFT	http://www.saft.fr/130-Catalogue/PDF/vlm_cells.pdf		VL41M	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvent	graphite based	c	y

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
									s + LiPF6			
48	c/SAF/VL27M	SAFT	http://www.saft.fr/130-Catalogue/PDF/vlm_cells.pdf	Johnson Controls–Saft Advanced Power Solutions - Joint Venture	VL27M	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF7	graphite based	c	y
49	c/SAF/VL7P	SAFT	http://www.saft.fr/130-Catalogue/PDF/VLP_cells.pdf		VL7P	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	c	y
50	c/SAF/VL20P	SAFT	http://www.saft.fr/130-Catalogue/PDF/VLP_cells.pdf		VL20P	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	c	y
51	c/SAF/VL30P	SAFT	http://www.saft.fr/130-Catalogue/PDF/VLP_cells.pdf		VL30P	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	c	y
52	c/SAF/VL34P	SAFT	http://www.saft.fr/130-Catalogue/PDF/VL-34-P.pdf		VL34P	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	c	y
53	m/SAF/VL34P module	SAFT	http://www.saft.fr/130-Catalogue/PDF/VL34P_Module.pdf		VL34P module	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	m	y
54	p/SAF/HEMV-5	SAFT	http://www.saft.fr/130-		HEMV-5	Lithium	LiIon	LiNiCo	blend of	graphite	p	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
			Catalogue/PDF/HEMV.pdf					AlO2	carbonate solvents + LiPF6	based		
55	p/SAF/HEMV-7	SAFT	http://www.saft.fr/130-Catalogue/PDF/HEMV.pdf	Johnson Controls–Saft Advanced Power Solutions - Joint Venture	HEMV-7	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	p	n
56	c/SAF/VL12 V	SAFT	http://www.saft.fr/130-Catalogue/PDF/VL12V.pdf		VL12 V	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	c	y
57	c/SAF/VL6 A	SAFT	http://www.saft.fr/130-Catalogue/PDF/VL6A.pdf		VL6 A	Lithium	LiIon	LiNiCoAlO2	blend of carbonate solvents + LiPF6	graphite based	c	y
58	p/VAL/U1-12XP	Valence Technologies Inc.	http://www.valence.com/assets/pdf/ucharge_xp_data_sheet.pdf	Valence Technologies Inc.	U1-12XP	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
59	p/VAL/U24-12XP	Valence Technologies Inc.	http://www.valence.com/assets/pdf/ucharge_xp_data_sheet.pdf		U24-12XP	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
60	p/VAL/U27-12XP	Valence Technologies Inc.	http://www.valence.com/assets/pdf/ucharge_xp_data_sheet.pdf		U27-12XP	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
61	p/VAL/UEV-18XP	Valence Technologies Inc.	http://www.valence.com/assets/pdf/ucharge_xp_data_sheet.pdf		UEV-18XP	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
62	p/VAL/U1-12RTL	Valence Technologies Inc.	http://www.valence.com/assets/pdf/ucharge_rt_data_sheet.pdf		U1-12RTL	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
63	p/VAL/U1-12RT	Valence	http://www.valence.com/assets/pdf/uc		U1-12RT	Lithium	LiPolymer	LiFePO	DC:EC	black	p	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
		Technologies Inc.	harge_rt_data_sheet.pdf					4	= 2:1, gelled	carbon		
64	p/VAL/U24-12RT	Valence Technologies Inc.	http://www.valence.com/assets/pdf/ucharge_rt_data_sheet.pdf	Valence Technologies Inc.	U24-12RT	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
65	p/VAL/U27-12RT	Valence Technologies Inc.	http://www.valence.com/assets/pdf/ucharge_rt_data_sheet.pdf		U27-12RT	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
66	p/VAL/EU1	Valence Technologies Inc.	http://www.valence.com/assets/pdf/vlnc_epoch_data_sheet.pdf		EU1	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
67	p/VAL/E24	Valence Technologies Inc.	http://www.valence.com/assets/pdf/vlnc_epoch_data_sheet.pdf		E24	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
68	p/VAL/E27	Valence Technologies Inc.	http://www.valence.com/assets/pdf/vlnc_epoch_data_sheet.pdf		E27	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
69	p/VAL/EEV	Valence Technologies Inc.	http://www.valence.com/assets/pdf/vlnc_epoch_data_sheet.pdf		EEV	Lithium	LiPolymer	LiFePO4	DC:EC = 2:1, gelled	black carbon	p	n
70	c/GAI/HE-602040	GAIA Akkumulatorren-werke, GmbH	http://www.gaia-akku-online.de/SEITEN/60_Ah_HE_602040.lasso?-Token.Menu=Produkte&-Token.Link=Link1	Lithium Technology Corporation	60 Ah HE-602040	Lithium	LiIon	Li(NiCo)O2		hard carbon	c	y
71	c/GAI/HP-602040	GAIA Akkumulatorren-werke, GmbH	http://www.gaia-akku-online.de/SEITEN/45_Ah_HP_602040.lasso?-Token.Menu=Produkte&-Token.Link=Link1		45 Ah HP-602040	Lithium	LiIon	Li(NiCo)O2		hard carbon	c	y
72	c/GAI/HP-601300	GAIA Akkumulatorren-werke, GmbH	http://www.gaia-akku-online.de/SEITEN/27_Ah_HP_601300.lasso?-Token.Menu=Produkte&-Token.Link=Link1		27 Ah HP-601300	Lithium	LiIon	Li(NiCo)O2		hard carbon	c	y
73	c/GAI/7.5 Ah UHP-341450	GAIA Akkumulatorren-werke, GmbH	http://www.gaia-akku-online.de/SEITEN/7.5_Ah_UHP_341450.lasso?-Token.Menu=Produkte&-Token.Link=Link1		7.5 Ah UHP-341450	Lithium	LiIon	Li(NiCo)O2		hard carbon	c	y
74	p/GAI/UHP-341450 Back up	GAIA Akkumulatorren-werke,	http://www.gaia-akku-online.de/SEITEN/pitch_control.lasso?-Token.Menu=Produkte&-		7.5 Ah UHP-341450 Back up	Lithium	LiIon	Li(NiCo)O2		hard carbon	p	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
		GmbH	Token.Link=Link1									
75	c/LTC/UHP-271000	Lithium Technology Corporation	http://www.lithiumtech.com/35AhCCUHP.pdf	Lithium Technology Corporation	3,5 Ah UHP-271000	Lithium	LiIon	Li(NiCo)O2		hard carbon	c	y
76	c/LTC/HE-341450	Lithium Technology Corporation	http://www.lithiumtech.com/341450HE.pdf		10 Ah HE-341450	Lithium	LiIon	Li(NiCo)O2		hard carbon	c	y
77	c/LTC/HE-601300	Lithium Technology Corporation	http://www.lithiumtech.com/33AhHE.pdf		33 Ah HE-601300	Lithium	LiIon	Li(NiCo)O2		hard carbon	c	y
78	p/Altair Nanotechnologies/ virtualpack	Altair Nanotechnologies	http://www.altairnano.com/documents/NanoSafe_Datasheet.pdf	Altair Nanotechnologies, Inc	Optimisation of Anode	Lithium	LiIon	-	-	LTO, nanostructured	p	n
79	p/MED/PNU100 C3	Modular Energy Devices, Inc	http://www.modenergy.com/DS-PNU100-001E%20high%20power%20panel%20mount%20data%20sheet.pdf	EnerSys	PNU100 C3	Lithium	LiIon	LCO		graphite	p	n
80	p/MED/PNU100 C5	Modular Energy Devices, Inc	http://www.modenergy.com/DS-PNU100-001E%20high%20power%20panel%20mount%20data%20sheet.pdf		PNU100 C5	Lithium	LiIon	LCO		graphite	p	n
81	p/MED/PNU100 C7	Modular Energy Devices, Inc	http://www.modenergy.com/DS-PNU100-001E%20high%20power%20panel%20mount%20data%20sheet.pdf		PNU100 C7	Lithium	LiIon	LCO		graphite	p	n
82	p/MED/PNU100 C9	Modular Energy Devices, Inc	http://www.modenergy.com/DS-PNU100-001E%20high%20power%20panel%20mount%20data%20sheet.pdf		PNU100 C9	Lithium	LiIon	LCO		graphite	p	n
83	p/MED/PNU100 C10	Modular Energy Devices, Inc	http://www.modenergy.com/DS-PNU100-001E%20high%20power%20panel%20mount%20data%20sheet.pdf		PNU100 C10	Lithium	LiIon	LCO		graphite	p	n
84	p/MED/PNU100 C12	Modular Energy Devices, Inc	http://www.modenergy.com/DS-PNU100-001E%20high%20power%20panel%20mount%20data%20sheet.pdf		PNU100 C12	Lithium	LiIon	LCO		graphite	p	n
85	p/MED/PNU100 C14	Modular Energy	http://www.modenergy.com/DS-PNU100-		PNU100 C14	Lithium	LiIon	LCO		graphite	p	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
		Devices, Inc	001E%20high%20power%20panel%20mount%20data%20sheet.pdf									
86	p/MED/PNU100 C16	Modular Energy Devices, Inc	http://www.modenergy.com/DS-PNU100-001E%20high%20power%20panel%20mount%20data%20sheet.pdf	EnerSys	PNU100 C16	Lithium	LiIon	LCO		graphite	p	n
87	p/MED/PNU100 C18	Modular Energy Devices, Inc	http://www.modenergy.com/DS-PNU100-001E%20high%20power%20panel%20mount%20data%20sheet.pdf		PNU100 C18	Lithium	LiIon	LCO		graphite	p	n
88	p/Magna/Heavy Duty	Magna Steyr	Papers	Magna International	Heavy Duty projected series	Lithium	LiIon	uncertain	uncertain	uncertain	p	n
89	p/Magna/Full HEV	Magna Steyr	Papers		Full HEV projected series	Lithium	LiIon	uncertain	uncertain	uncertain	p	n
90	p/Magna/Mild hybrid	Magna Steyr	Papers		Mild hybrid projected series	Lithium	LiIon	uncertain	uncertain	uncertain	p	n
91	c/A123/ANR26650 M1	A123systems	http://www.a123systems.com/newsite/index.php#/products/	A123systems, MIT Spinoff	ANR26650M1	Lithium	LiIon	LiFePO4, nanophase	LiPF6 in ?	graphite	c	y
92	m/PEV/Plastic Prismatic - Gen III	Panasonic EV Energy Co.	http://www.peve.jp/e/hevkinzoku.html	Toyota (majority) - Matsushita Electric Industrial Co. JointVenture	Plastic Case Prismatic Module - Gen III	Nickel	Ni-MH	NiOOH	KOH, NaOH, (pH 13,5), gelled	(AB5)H	m	y
93	p/PEV/Plastic Prismatic - Gen III LEXUS GS450h	Panasonic EV Energy Co.	datasheet		Plastic Case Prismatic Module - Gen III in LEXUS GS450h	Nickel	Ni-MH	NiOOH	KOH, NaOH, (pH 13,5), gelled	(AB5)H	p	n
94	m/PEV/Metal Prismatic - Gen III	Panasonic EV Energy Co.	http://www.peve.jp/e/hevjyusi.html		Metal Case Prismatic Module - Gen III	Nickel	Ni-MH	NiOOH	KOH, NaOH, (pH 13,5), gelled	(AB5)H	m	y

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
95	p/PEV/Metal Prismatic - Gen III Lexus Rx400h	Panasonic EV Energy Co.	datasheet	Toyota (majority) - Matsushita Electric Industrial Co. JointVenture	Metal Case Prismatic Module - Gen III in Lexus Rx400h and Toyota Highlander Hybrid	Nickel	Ni-MH	NiOOH	KOH, NaOH, (pH 13,5), gelled	(AB5)H	p	n
96	m/COB/1000 High Power	Cobasys	http://www.cobasys.com/pdf/transportation/Series1000Brochure.pdf	Chevron Technology Ventures LCC (Chevron) +ECD Ovonics Joint Venture, Cobasys was Texaco Ovonic Battery Systems	series 1000 High Power	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	m	y
97	p/COB/1000 - 144-30	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 144-30	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	y
98	p/COB/1000 - 144-30 ic	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 144-30 ic	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n
99	p/COB/1000 - 144-60	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 144-60	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	y
100	p/COB/1000 - 144-60 ic	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 144-60 ic	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n
101	p/COB/1000 - 288-60	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 288-60	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	y
102	p/COB/1000 - 288-60 ic	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 288-60 ic	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n
103	p/COB/1000 - 288-120	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 288-120	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	y
104	p/COB/1000 - 288-120 ic	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 288-120 ic	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n
105	p/COB/1000 - 336-70	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 336-70	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	y
106	p/COB/1000 - 336-	Cobasys	http://www.cobasys.com/pdf/transport		Series 1000	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
	70 ic		ation/Ni-MHax_HEV_Brochure.pdf		- Ni-MHax 336-70 ic							
107	p/COB/1000 - 336-140	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf	Chevron Technology Ventures LCC (Chevron) +ECD Ovonics Joint Venture, Cobasys was Texaco Ovonic Battery Systems	Series 1000 - Ni-MHax 336-140	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	y
108	p/COB/1000 - 336-140 ic	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 336-140 ic	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n
109	p/COB/1000 - 576-120	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 576-120	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	y
110	p/COB/1000 - 576-120 ic	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 576-120 ic	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n
111	p/COB/1000 - 576-240	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 576-240	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	y
112	p/COB/1000 - 576-240 ic	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 576-240 ic	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n
113	p/COB/1000 - 672-140	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 672-140	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	y
114	p/COB/1000 - 672-140 ic	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 672-140 ic	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n
115	p/COB/1000 - 672-280	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 672-280	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	y
116	p/COB/1000 - 672-280 ic	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax_HEV_Brochure.pdf		Series 1000 - Ni-MHax 672-280 ic	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n
117	p/COB/42-15 System	Cobasys	http://www.cobasys.com/pdf/transportation/Ni-MHax%2042V%20Brochure.pdf		42-15 System	Nickel	Ni-MH	NiOOH	KOH	(AB5)H	p	n
118	c/LG/E1	LGChem/CompactPowerInc	http://www.compactpower.com/batterypack.html	LG	E1-10Ah LiIonPolymer	Lithium	LiPolymer	Lithium-manganese-based		graphite	c	y

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
								oxides				
119	p/LG/7S	LGChem/CompactPowerInc	http://www.extraenergy.org/files/Pretest-LG-Chem.pdf	LG	7S Standard Soft Pack	Lithium	LiPolymer	Lithium-manganese-based oxides		graphite	p	n
120	p/LG/10S	LGChem/CompactPowerInc	http://www.extraenergy.org/files/Pretest-LG-Chem.pdf		10S Standard Soft Pack	Lithium	LiPolymer	Lithium-manganese-based oxides		graphite	p	n
121	p/LG/152V	LGChem/CompactPowerInc	http://www.extraenergy.org/files/Pretest-LG-Chem.pdf		152V Compact Power 'typical Battery Pack	Lithium	LiIon	LMO-spinel		graphite	p	n
122	p/ENE/HEV package (tantial configuration)	EnerDel	http://enerdel.com	Ener1	HEV package (tantial)	Lithium	LiIon	LMO-spinel		LTO spinel (L4Ti5O12)	p	n
123	c/ENE/LTO CD Size	EnerDel	http://enerdel.com		LTO CD Size	Lithium	LiIon	LMO-spinel		LTO spinel (L4Ti5O12)	c	y
124	c/ENE/LTO A5 Size	EnerDel	http://enerdel.com		LTO A5 Size	Lithium	LiIon	LMO-spinel		LTO spinel (L4Ti5O12)	c	y
125	c/ENE/HC CD Size	EnerDel	http://enerdel.com		HC CD Size	Lithium	LiIon	LMO-spinel		hard carbon	c	y
126	c/ENE/HC A5 Size	EnerDel	http://enerdel.com		HC A5 Size	Lithium	LiIon	LMO-spinel		hard carbon	c	y
127	p/EEI/pack 1	Electro Energy Inc.	http://www.electroenergyinc.com/products.html	Electro Energy Inc (EEI)	pack 1	Nickel	Ni-MH	NiOOH	KOH	(AB5)H - LaNi5class	p	
128	p/EEI/pack 2	Electro Energy Inc.	http://www.electroenergyinc.com/products.html		pack 2	Nickel	Ni-MH	NiOOH	KOH	(AB5)H - LaNi5class	p	
129	p/EEI/pack 3	Electro	http://www.electroenergyinc.com/prod		pack 3	Nickel	Ni-MH	NiOOH	KOH	(AB5)H -	p	

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
		Energy Inc.	ucts.html							LaNi5class		
130	p/EEI/pack 4	Electro Energy Inc.	http://www.electroenergyinc.com/products.html	Electro Energy Inc (EEI)	pack 4	Nickel	Ni-MH	NiOOH	KOH	(AB5)H - LaNi5class	p	
131	p/EEI/pack 5	Electro Energy Inc.	http://www.electroenergyinc.com/products.html		pack 5	Nickel	Ni-MH	NiOOH	KOH	(AB5)H - LaNi5class	p	
132	c/GSY/LIM 30H	GS Yuasa	http://www.gsyuasa-lp.com/Products.html	GS Yuasa	LIM 30H	Lithium	LiIon	LMO-spinel	Li salt in blend of alkyl carbonates	graphite	c	y
133	c/GSY/LIM 60H	GS Yuasa	http://www.gsyuasa-lp.com/Products.html		LIM 60H	Lithium	LiIon	LMO-spinel	Li salt in blend of alkyl carbonates	graphite	c	y
134	m/GSY/LIM 40-6	GS Yuasa	http://www.gsyuasa-lp.com/Products.html; http://home.gyps.gs-yuasa.com/products/catalog.html		LIM 40-6	Lithium	LiIon	LMO-spinel	Li salt in blend of alkyl carbonates	graphite	m	y
135	m/GSY/LIM 40-7	GS Yuasa	http://www.gsyuasa-lp.com/Products.html; http://home.gyps.gs-yuasa.com/products/catalog.html		LIM 40-7	Lithium	LiIon	LMO-spinel	Li salt in blend of alkyl carbonates	graphite	m	y
136	m/GSY/LIM 40-7	GS Yuasa	http://www.gsyuasa-lp.com/Products.html; http://home.gyps.gs-yuasa.com/products/catalog.html		LIM 40-7	Lithium	LiIon	LMO-spinel	Li salt in blend of alkyl carbonates	graphite	m	y
137	m/GSY/LIM 80-3	GS Yuasa	http://www.gsyuasa-lp.com/Products.html; http://home.gyps.gs-yuasa.com/products/catalog.html		LIM 80-3	Lithium	LiIon	LMO-spinel	Li salt in blend of alkyl carbonates	graphite	m	y
138	m/GSY/LIM 80-4	GS Yuasa	http://www.gsyuasa-		LIM 80-4	Lithium	LiIon	LMO-	Li salt	graphite	m	y

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
			lp.com/Products.html; http://home.gyps.gs-yuasa.com/products/catalog.html					spinel	in blend of alkyl carbonates			
139	m/GSY/LIM 80-7	GS Yuasa	http://www.gsyuasa-lp.com/Products.html; http://home.gyps.gs-yuasa.com/products/catalog.html	GS Yuasa	LIM 80-7	Lithium	LiIon	LMO-spinel	Li salt in blend of alkyl carbonates	graphite	m	y
140	c/GSY/LVP 65	GS Yuasa	http://www.gsyuasa-lp.com/Products.html		LVP 65	Lithium	LiIon	LCO		graphite	c	y
141	c/GSY/LFC 40	GS Yuasa	http://www.gsyuasa-lp.com/Products.html		LFC 40	Lithium	LiIon	LCO		graphite	c	y
142	c/GSY/LSE 50	GS Yuasa	http://www.gsyuasa-lp.com/Products.html		LSE 50	Lithium	LiIon	LCO		graphite	c	y
143	c/GSY/LSE 100	GS Yuasa	http://www.gsyuasa-lp.com/Products.html		LSE 100	Lithium	LiIon	LCO		graphite	c	y
144	c/GSY/LSE 175	GS Yuasa	http://www.gsyuasa-lp.com/Products.html		LSE 175	Lithium	LiIon	LCO		graphite	c	y
145	p/MAX/BMOD0083 E048	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_energy_series_48_1009364_rev5.pdf	Maxwell Technologies Corp	BCAP1500 E270 T04 - BMOD0083 E048	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
146	p/MAX/ BMOD0110 E048	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_energy_series_48_1009364_rev5.pdf		BCAP2000 E270 T04 - BMOD0110 E048	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
147	p/MAX/ BMOD0165 E048	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_energy_series_48_1009364_rev5.pdf		BCAP3000 E270 T04 - BMOD0165 E048	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
148	p/MAX/ BMOD0083 P048	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_energy_series_48_1009364_rev5.pdf		BCAP1500 P270 T04 - BMOD0083 P048	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
149	p/MAX/ BMOD0110 P048	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_energy_series_48_1009364_rev5.pdf		BCAP2000 P270 T04 - BMOD0110 P048	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
150	p/MAX/ BMOD0165 P048	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_energy_series_48_1009364_rev5.pdf	Maxwell Technologies Corp	BCAP3000 P270 T04 - BMOD0165 P048	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
151	p/MAX/ BMOD0110 E016	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_power_series_16v_1009363_rev5.pdf		BCAP0650 E270 T04 - BMOD0110 E016	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
152	p/MAX/ BMOD0250 E016	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_power_series_16v_1009363_rev5.pdf		BCAP1500 E270 T04 - BMOD0250 E016	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
153	p/MAX/ BMOD0500 E016	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_power_series_16v_1009363_rev5.pdf		BCAP3000 E270 T04 - BMOD0500 E016	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
154	p/MAX/ BMOD0110 P016	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_power_series_16v_1009363_rev5.pdf		BCAP0650 P270 T04 - BMOD0110 P016	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
155	p/MAX/ BMOD0250 P016	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_power_series_16v_1009363_rev5.pdf		BCAP1500 P270 T04 - BMOD0250 P016	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
156	p/MAX/ BMOD0500 P016	Maxwell Technologies	http://www.maxwell.com/pdf/uc/datasheets/mc_power_series_16v_1009363_rev5.pdf		BCAP3000 P270 T04 - BMOD0500 P016	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
157	p/MAX/ BMOD0094 E075 B02	Maxwell Technologies	http://www.maxwell.com/ultracapacitors/products/modules/bmod0094-75v.asp		BCAP3000 E270 - BMOD0094 E075 B02	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
158	p/MAX/XBMOD0063 P125 B11/B21	Maxwell Technologies	http://www.maxwell.com/ultracapacitors/products/modules/bmod0063-125v.asp		X - BMOD0063 P125 B11/B21	Supercap	EDLC	activated carbon	organic acetonitrile based	activated carbon	p	n
159	p/MAX/XBMOD0018 P390 B01	Maxwell Technologies	http://www.maxwell.com/ultracapacitors/products/modules/bmod0018-390v.asp		X - BMOD0018 P390 B01	Supercap	EDLC	activated carbon	organic acetonitrile	activated carbon	p	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
									based			
160	p/NIP/MDLA15R0V058F	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html	Nippon Chemi-Con Corporation	MDLA15R0V058F	Supercap	EDLC	activated carbon	PC based	activated carbon	p	
161	p/NIP/MDLA15R0V116F	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		MDLA15R0V116F	Supercap	EDLC	activated carbon	PC based	activated carbon	p	
162	c/NIP/DDLB2R5LGN401KA65S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDLB2R5LGN401KA65S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
163	c/NIP/DDLB2R5LGN741KA95S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDLB2R5LGN741KA95S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
164	c/NIP/DDLB2R5LGN112KBA5S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDLB2R5LGN112KBA5S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
165	c/NIP/DDLB2R5LGN172KBF0S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDLB2R5LGN172KBF0S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
166	c/NIP/DDLB2R5LGN172KCA5S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDLB2R5LGN172KCA5S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
167	c/NIP/DDLB2R5LGN272KCF0S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDLB2R5LGN272KCF0S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
168	c/NIP/DDLC2R5LGN351KA65S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDLC2R5LGN351KA65S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
169	c/NIP/DDLC2R5LGN641KA95S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDLC2R5LGN641KA95S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
170	c/NIP/DDLC2R5LGN951KBA5S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDLC2R5LGN951KBA5S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
171	c/NIP/DDLC2R5LGN142KBF0S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDLC2R5LGN142KBF0S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
172	p/NIP/MDLC15R0V233F	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.h		MDLC15R0V233F	Supercap	EDLC	activated	PC based	activated carbon	p	

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
			tml					carbon				
173	c/NIP/DDMB2R3L GN501KA65S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html	Nippon Chemi-Con Corporation	DDMB2R3L GN501KA65S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
174	c/NIP/DDMB2R3L GN871KA95S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDMB2R3L GN871KA95S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
175	c/NIP/DDMB2R3L GN132KBA5S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDMB2R3L GN132KBA5S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
176	c/NIP/DDMB2R3L GN202KBF0S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDMB2R3L GN202KBF0S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
177	p/NIP/MDMB13R8 V500F	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		MDMB13R8 V500F	Supercap	EDLC	activated carbon	PC based	activated carbon	p	
178	c/NIP/DDMB2R3L GN202KCA5S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDMB2R3L GN202KCA5S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
179	c/NIP/DDMB2R3L GN312KCF0S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDMB2R3L GN312KCF0S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
180	c/NIP/DDMC2R3L GN451KA65S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDMC2R3L GN451KA65S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
181	c/NIP/DDMC2R3L GN761KA95S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDMC2R3L GN761KA95S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
182	c/NIP/DDMC2R3L GN112KBA5S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDMC2R3L GN112KBA5S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
183	c/NIP/DDMC2R3L GN172KBF0S	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDMC2R3L GN172KBF0S	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
184	c/NIP/DDSC2R5L GN182K54AS	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDSC2R5L GN182K54AS	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
185	c/NIP/DDSC2R5L GN242K54BS	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.h		DDSC2R5L GN242K54B	Supercap	EDLC	activated	PC based	activated carbon	c	

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
			tml		S			carbon				
186	p/NIP/MDSC15R0 V400F	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html	Nippon Chemi-Con Corporation	MDSC15R0 V400F	Supercap	EDLC	activated carbon	PC based	activated carbon	p	
187	c/NIP/DDSC2R5L GN901K30AS	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDSC2R5L GN901K30AS	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
188	c/NIP/DDSC2R5L GN122K30BS	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDSC2R5L GN122K30BS	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
189	c/NIP/DDTC2R3L GN212K54AS	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDTC2R3L GN212K54AS	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
190	c/NIP/DDTC2R3L GN282K54BS	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDTC2R3L GN282K54BS	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
191	c/NIP/DDTC2R3L GN112K30AS	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDTC2R3L GN112K30AS	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
192	c/NIP/DDTC2R3L GN142K30BS	Nippon ChemiCon	http://www.chemi-con.co.jp/english/catalog_e/top_dl_e.html		DDTC2R3L GN142K30BS	Supercap	EDLC	activated carbon	PC based	activated carbon	c	
193	c/NES/ESLSR-0120C0-002R3	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf	NESSCAP Co., Ltd	ESLSR-0120C0-002R3	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	c	n
194	c/NES/ESLLP-1200C0-002R3	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESLLP-1200C0-002R3	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	c	n
195	c/NES/ESLLP-2500C0-002R3	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESLLP-2500C0-002R3	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	c	n
196	c/NES/ESLLP-3500C0-002R3	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESLLP-3500C0-002R3	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	c	n
197	c/NES/ESHSR-0100C0-002R7	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSR-0100C0-002R7	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	c	n
198	p/NES/ EMHSR-0033C0-015R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet		ESHSR-0100C0-	Supercap	EDLC	activated	PC or AC	activated carbon	p	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
			.pdf		002R7 cells in EMHSR-0033C0-015R0 package			carbon	based			
199	p/NES/ EMHSR-0014C2-017R5	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf	NESSCAP Co., Ltd	ESHSR-0100C0-002R7 cells in EMHSR-0014C2-017R5 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
200	p/NES/ EMHSR-0057C8-017R5	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSR-0100C0-002R7 cells in EMHSR-0057C8-017R5 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
201	p/NES/ EMHSR-0010C0-050R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSR-0100C0-002R7 cells in EMHSR-0010C0-050R0 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
202	p/NES/ EMHSR-0002C8-090R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSR-0100C0-002R7 cells in EMHSR-0002C8-090R0 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
203	c/NES/ESHSP-0600C0-002R7	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSP-0600C0-002R7	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	c	n
204	c/NES/ESHSP-1700C0-002R7	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSP-1700C0-002R7	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	c	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
205	p/NES/ EMHSP-0094C0-045R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf	NESSCAP Co., Ltd	ESHSP-1700C0-002R7 cells in EMHSP-0094C0-045R0 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
206	c/NES/ESHSP-3500C0-002R7	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSP-3500C0-002R7	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	c	n
207	p/NES/ EMHSP-0194C0-045R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSP-3500C0-002R7cells in EMHSP-0194C0-045R0 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
208	p/NES/ EMHSP-0166C0-052R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSP-3500C0-002R7cells in EMHSP-0166C0-052R0 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
209	p/NES/ EMHSP-0205C0-042R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSP-3500C0-002R7cells in EMHSP-0205C0-042R0 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
210	p/NES/ EMHSP-0051C0-340R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHSP-3500C0-002R7cells in EMHSP-0051C0-340R0 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
211	c/NES/ESHSP-5000C0-002R7	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet		ESHSP-5000C0-	Supercap	EDLC	activated	PC or AC	activated carbon	c	n

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
			.pdf		002R7			carbon	based			
212	p/NES/ EMHSP-0238C0-052R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf	NESSCAP Co., Ltd	ESHSP-5000C0-002R7 in EMHSP-0238C0-052R0 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
213	c/NES/ESHLP-0300C0-002R7	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHLP-0300C0-002R7	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	c	n
214	p/NES/ EMHLP-0050C0-015R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHLP-0300C0-002R7 cells in EMHLP-0050C0-015R0 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
215	p/NES/ EMHLP-0100C0-015R0	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHLP-0300C0-002R7 cells in EMHLP-0100C0-015R0 package	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	p	n
216	c/NES/ESHLP-0600C0-002R7	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		ESHLP-0600C0-002R7	Supercap	EDLC	activated carbon	PC or AC based	activated carbon	c	n
217	c/NES/PSHLR-0120C0-002R3	Nesscap	http://www.nesscap.com/data_nesscap/Download%20full%20data%20sheet.pdf		PSHLR-0120C0-002R3	Supercap	PseudoCap				c	n
218	p/S1/S1-p1	S1	confidential list	S1	S1-product1	Supercap	EDLC	activated carbon	AC based	activated carbon	p	n
219	c/S1/S1-p2	S1	confidential list	S1	S1-product2	Supercap	Hybrid				c	y
220	c/S1/S1-p3	S1	confidential list	S1	S1-product3	Supercap	?	activated carbon	Aqueous Electrolyte	activated carbon	c	y

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
									(research)			
221	m/S1/S1-p4	S1	confidential list	S1	S1-product4	Supercap	?	activated carbon	AC based	activated carbon	m	n
222	p/S2/S2-p1	S2	confidential list	S2	S2-product1	Supercap	EDLC	activated carbon	PC based	activated carbon	p	n
223	m/S3/S3-p1	S3	confidential list	S3	S3-product1	Supercap	EDLC	activated carbon	PC based	activated carbon	m	n
224	p/S3/S3-P2	S3	confidential list		S3-Product2	Supercap	EDLC	activated carbon	AC based	activated carbon	p	n
225	p/S3/S3-P3	S3	confidential list		S3-Product3	Supercap	EDLC	activated carbon	AC based	activated carbon	p	n
226	p/S3/S3-P4	S3	confidential list		S3-Product4	Supercap	EDLC	activated carbon	AC based	activated carbon	p	n
227	p/S3/S3-P5	S3	confidential list		S3-Product5	Supercap	EDLC	activated carbon	AC based	activated carbon	p	n
228	c/S4/S4-p1	S4	confidential list	S4	S4-product1	Supercap	EDLC	activated carbon	PC based	activated carbon	c	y
229	p/S4/S4-p2	S4	confidential list		S4-product2	Supercap	EDLC	activated carbon	PC based	activated carbon	p	n
230	p/S5/S5-p1	S5	confidential list	S5	S5-product1	Supercap	EDLC	activated carbon	developed PC	activated carbon	p	n
231	p/S6/S6-product 1	S6	confidential list	S6	S6-product 1	flywheel	-	metal sheets			p	n
232	c/S8/S8-p1	S8	confidential list	S8	S8-product1	Lithium	LiIon				c	y
233	m/S9/S9-product1	S9	Datasheet	S9	S9-product1	Lithium	LiIon	$Li(NiCo)O_2$		hard carbon	m	y
234	m/S9/S9-product2	S9	Datasheet	S9	S9-product2	Lithium	LiIon	$Li(NiCo)O_2$		hard carbon	m	y

#	Abbreviation	Distributing Company/ Brand	www	Holding	product	technology	Tech. subgroup	Cathode/rotor	Electrolyte	Anode/housing	Cell/module/pack.	external cooling
235	c/S9/S9-product3	S9	Datasheet	S9	S9-product3	Lithium	LiIon	Li(NiCo)O2		hard carbon	c	y
236	p/S9/S9-product4	S9	Datasheet	S9	S9-product4	Lithium	LiIon	Li(NiCo)O2		hard carbon	p	n
237	c/S9/S9-product5	S9	Datasheet	S9	S9-product5	Lithium	LiIon	Li(NiCo)O2		hard carbon	c	y
238	c/NiZn1	Powergenix	http://www.powergenix.com/		Nickel-Zinc batteries	Nickel	Nickel-Zinc	NiOOH	KOH	Zn	c	n
239	c/NiZn2	Evercel	HBoB 2004		Nickel-Zinc batteries	Nickel	Nickel-Zinc	NiOOH	KOH	Zn	c	n
240	c/NiZn3	Xellerion	Datasheet	Evionyx	Xellerion Xell-12	Nickel	Nickel-Zinc	NiOOH	KOH	Zn	c	n
241	p/VRLA	Leadacid	NREL: "Battery Choices and Potential Requirements for Plug-In Hybrids", 2007	-	LA	LeadAcid	VRLA	PbO2	H2SO4	Pb	p	n
242	p/NaNiCl2	MES-DEA	http://www.cebi.com/cebi/content/index_html?a=5&b=9&c=19&d=72&docID=159&info=1	MES-DEA	Z33-93-ML3P-152	High Temp-erature	ZEBRA	NiCl2	ceramic beta"/ NaAlCl4	Na	p	n

Table B.1 dataset 1/2

#	System Voltage	Cells in System	Spec. Disch. 2s Pulse Power, Max. [kW/kg]	Disch. 2s Pulse Power dens. Max. [kW/l]	Spec. Reg. 2s Pulse Power, Max. [kW/kg]	Reg. 2s Pulse Power dens., Max. [kW/l]	Spec. Cold Crank. 2s Power @ -30°C, Max. [kW/kg]	Cold Crank. 2s Power dens. @ -30°C, Max. [kW/l]	Spec. Avail. Energy @3 kW [Wh/kg]	Avail. Energy Dens. @3 kW [Wh/l]	C-rate @any eta [1/h]	Spec. Cyc.Life @ 23°C, (80% capacity) [kWh/kg]	@ C-rate	@ % DOD	Cyc.Life Dens. (80% capacity) [kWh / l]	Calendar Life [Yrs]	Self Disch., 23°C [%/1^{st} day]	Operating Temp. Range [°C]		Storage Temp. Range [°C]		System Weight [kg]	System Volume [Liters]
	max 48		**2,670**	**3,338**	**1,643**	**2,540**	**0,32**	**0,4**	**12**	**15**	**2,6**	**339,96**	**7**	**10,2**	**425**	**15**	**6,7**	**-30**	**52**	**-46**	**66**	**25**	**20**
1	-	4	2,308	11,806	2,308	11,806	2,308	11,806	5,34	27,33		26709		100	136648			-40	150	-	-	26,00	5,08
2	-	4	3,000	5,261	3,000	5,261	3,000	5,261	19,10	33,49		95486		100	167449			-40	150	-	-	40,00	22,81
3	3,7	1	0,659	1,332	0,205	0,414	fail	fail	180,70	365,13	1,0	72	1,0	80	146			0	40			0,04	0,02
4	3,7	1	0,669	1,378	0,208	0,429	fail	fail	183,30	377,72	1,0	73	1,0	80	151			0	40			0,05	0,03
5	3,7	1	0,668	1,349	0,208	0,420	fail	fail	183,09	369,75	1,0	73	1,0	80	148			0	40			0,05	0,02
6	3,7	1	0,669	1,388	0,208	0,432	fail	fail	183,47	380,35	1,0	73	1,0	80	152			0	40			0,06	0,03
7	3,7	1	0,675	1,357	0,210	0,422	fail	fail	185,00	371,89	1,0	74	1,0	80	149			0	40			0,07	0,03
8	3,7	1	0,587	1,274	0,183	0,396	fail	fail	160,87	349,06	1,0	103	1,0	80	223			0	40			0,12	0,05
9	3,7	1	0,653	1,274	0,203	0,396	fail	fail	179,03	349,06	1,0	115	1,0	80	223			0	40			0,16	0,08
10	3,7	1	0,544	1,098	0,169	0,342	fail	fail	149,19	300,86	1,0	95	1,0	80	193			0	40			0,62	0,31
11	3,7	1	0,579	1,259	0,180	0,392	fail	fail	158,57	345,11	1,0	101	1,0	80	221			0	40			0,70	0,32
12	3,7	1	0,349	0,761	0,181	0,394	fail	fail	159,48	347,52	1,0	102	1,0	80	222			0	40			2,32	1,06
13	3,7	1	0,243	0,522	0,189	0,406	fail	fail	166,67	357,44	1,0	107	1,0	80	229			0	40			4,44	2,07
14	3,7	1	0,259	0,548	0,202	0,426	fail	fail	177,60	375,32	1,0	114	1,0	80	240			0	40			5,00	2,37
15	3,7	1	0,655	1,325	0,204	0,412	fail	fail	179,39	363,25	1,0	115	1,0	80	232			0	40			0,33	0,16
16	3,7	1	0,578	1,268	0,180	0,395	fail	fail	158,29	347,66	1,0	101	1,0	80	223			0	40			0,94	0,43
17	3,7	1	0,556	1,206	0,173	0,375	fail	fail	152,35	330,47	1,0	98	1,0	80	211			0	40			1,70	0,78
18	3,7	1	1,017	1,980	0,316	0,616	fail	fail	139,38	271,39	2,0	89	1,0	80	174			0	40			0,29	0,15
19	3,7	1	0,823	1,626	0,256	0,506	fail	fail	112,80	222,84	2,0	72	1,0	80	143			0	40			0,16	0,08
20	3,7	1	0,800	1,803	0,311	0,701	fail	fail	137,04	308,90	2,0	88	1,0	80	198			0	40			2,70	1,20
21	3,7	1	0,411	0,859	0,160	0,334	fail	fail	140,68	294,37	1,0	90	1,0	80	188			0	40			5,26	2,51
22	3,7	1	0,973	2,107	0,303	0,655	fail	fail	133,37	288,68	2,0	85	1,0	80	185			0	40			0,86	0,40
23	3,7	1	0,896	1,800	0,279	0,560	fail	fail	122,79	246,72	2,0	79	1,0	80	158			0	40			0,23	0,11
24	3,7	1	0,982	2,134	0,305	0,664	fail	fail	134,55	292,43	2,0	86	1,0	80	187			0	40			1,10	0,51
25	3,7	1	0,969	2,204	0,302	0,686	fail	fail	132,82	301,98	2,0	85	1,0	80	193			0	40			1,95	0,86
26	3,7	1	3,295	7,175	0,342	0,744	fail	fail	150,51	327,75	2,0	60	1,0	80	131			0	40			0,06	0,03

#	System Voltage	Cells in System	Spec. Disch. 2s Pulse Power, Max. [kW/kg]	Disch. 2s Pulse Power dens. Max. [kW/l]	Spec. Reg. 2s Pulse Power, Max. [kW/kg]	Reg. 2s Pulse Power dens., Max. [kW/l]	Spec. Cold Crank. 2s Power @ -30°C, Max. [kW/kg]	Cold Crank. 2s Power dens. @ -30°C, Max. [kW/l]	Spec. Avail. Energy @3 kW [Wh/kg]	Avail. Energy Dens. @3 kW [Wh/l]	C-rate @any eta [1/h]	Spec. Cyc.Life @ 23°C, (80% capacity) [kWh/kg]	@ C-rate	@ % DOD	Cyc.Life Dens. (80% capacity) [kWh / l]	Calendar Life [Yrs]	Self Disch., 23°C [%/1^{st} day]	Operating Temp. Range [°C]		Storage Temp. Range [°C]		System Weight [kg]	System Volume [Liters]
	max 48		**2,670**	**3,338**	**1,643**	**2,540**	**0,32**	**0,4**	**12**	**15**	**2,6**	**339,96**	**7**	**10,2**	**425**	**15**	**6,7**	**-30**	**52**	**-46**	**66**	**25**	**20**
27	3,7	1	4,508	7,921	0,351	0,616	fail	fail	154,43	271,35	2,0	62	1,0	80	109			0	40			0,12	0,07
28	3,7	1	4,090	8,392	0,318	0,653	fail	fail	140,12	287,50	2,0	56	1,0	80	115			0	40			0,08	0,04
29	3,7	1	3,273	6,888	0,127	0,268	fail	fail	112,12	235,97	1,0	45	1,0	80	94			0	40			0,07	0,03
30	3,7	1	1,720	3,226	0,401	0,753	fail	fail	117,88	221,06	3,0	75	1,0	80	141			0	40			0,23	0,12
31	3,7	1	1,831	3,457	0,427	0,807	fail	fail	125,42	236,85	3,0	80	1,0	80	152			0	40			0,35	0,19
32	12,0	10	0,230	0,469					66,00	137,00		106	0,3	80	215		4,0	-20	40	0	30	18,60	9,13
33	6,0	5	0,230	0,469					66,00	137,00		106	0,3	80	215		4,0	-20	40	0	30	18,60	9,13
34	12,0	10	0,667	1,244					50,00	90,00							4,0	-20	40	0	30	9,00	4,82
35	6,0	5	0,667	1,244					50,00	90,00							4,0	-20	40	0	30	9,00	4,82
36	12,0	10	0,181	0,292			fail	fail	50,00	81,00	0,3	25		100	41			-10	45	5	25	2,10	1,30
37	24,0	20	0,200	0,361			fail	fail	55,00	101,00	0,3	28		100	51			-10	45	5	25	3,80	2,10
38	36,0	30	0,203	0,393			fail	fail	56,00	110,00	0,3	28		100	55			-10	45	5	25	5,60	2,90
39	12,0	10	0,193	0,352			fail	fail	56,00	102,00	0,2	28		100	51			-10	45	5	25	3,10	1,70
40	24,0	20	0,210	0,413			fail	fail	62,00	120,00	0,2	31		100	60			-10	45	5	25	5,70	2,90
41	36,0	30	0,222	0,449			fail	fail	64,00	128,00	0,2	32		100	64			-10	45	5	25	8,10	4,00
42	1,2	1	0,687	2,441			fail	fail	67,86	241,28	0,5	34		100	121			-10	45	5	25	0,17	0,05
43	1,2	1	0,436	1,513			fail	fail	72,00	249,69	0,3	36		100	125			-10	45	5	25	0,25	0,07
44	3,6	1							149,00	313,00		381	0,3	80	801							1,07	0,51
45	21,6	6	0,663	0,937					110,00	158,00		282	0,3	80	404							8,00	5,66
46	10,8	6	0,663	0,937					111,00	158,00		284	0,3	80	404							8,00	5,66
47	3,6	1	1,298	2,724					136,00	285,00	1,0	141	0,3	80	296							1,07	0,51
48	3,6	1	1,188	2,407					124,00	252,00	1,0	129	0,3	80	262							0,77	0,38
49	3,6	1	2,856	5,561	1,430	2,790	0,529	1,125	67,00	131,00		2010		3	3930	15		-25	35	-40	65	0,37	0,19
50	3,6	1	3,774	7,945					89,00	187,00		2670		3	5610	15		-25	35	-40	65	0,80	0,38
51	3,6	1	4,117	8,879					97,00	209,00		2910		3	6270	15		-25	35	-40	65	1,10	0,51
52	3,6	1	3,934	9,019					120,00	280,00		192		80	448	15		5	35	-40	65	0,94	0,41
53	43,2	12	2,773	5,006					75,00	139		120		80	222	15		5	35	-40	65	16	8,86

#	System Voltage	Cells in System	Spec. Disch. 2s Pulse Power, Max. [kW/kg]	Disch. 2s Pulse Power dens. Max. [kW/l]	Spec. Reg. 2s Pulse Power, Max. [kW/kg]	Reg. 2s Pulse Power dens., Max. [kW/l]	Spec. Cold Crank. 2s Power @ -30°C, Max. [kW/kg]	Cold Crank. 2s Power dens. @ -30°C, Max. [kW/l]	Spec. Avail. Energy @3 kW [Wh/kg]	Avail. Energy Dens. @3 kW [Wh/l]	C-rate @any eta [1/h]	Spec. Cyc.Life @ 23°C, (80% capacity) [kWh/kg]	@ C-rate	@ % DOD	Cyc.Life Dens. (80% capacity) [kWh / l]	Calendar Life [Yrs]	Self Disch., 23°C [%/1st day]	Operating Temp. Range [°C]		Storage Temp. Range [°C]		System Weight [kg]	System Volume [Liters]
	max 48		**2,670**	**3,338**	**1,643**	**2,540**	**0,32**	**0,4**	**12**	**15**	**2,6**	**339,96**	**7**	**10,2**	**425**	**15**	**6,7**	**-30**	**52**	**-46**	**66**	**25**	**20**
54	219,0	60	1,707	2,497					68,00	99,50		109		80	159	15		5	35	-40	65	100	68,35
55	307,0	84	1,827	2,670					68,00	99,17		109		80	159	15		5	35	-40	65	140	95,79
56	3,6	1	12,000	29,000			2,150	5,096	74,00	175,00	15,0	118		80	280	15		5	35	-40	65	0,64	0,27
57	3,7	1	7,850	16,681					64,71	137,50	15,0	259		80	550	15		-20	55	-60	65	0,34	0,16
58	12,8		0,333	0,436			0,303	0,396	84,00	110,00	0,5	168	0,5	100	220			-10	50	-40	50	6,10	4,66
59	12,8		0,321	0,501			0,292	0,456	81,00	126,00	0,5	162	0,5	100	253			-10	50	-40	50	15,80	10,12
60	12,8		0,260	0,426			0,237	0,387	85,00	140,00	0,5	171	0,5	100	279			-10	50	-40	50	19,50	11,91
61	19,2								84,00	117,00	0,5	169	0,5	100	234			-10	50	-40	50	14,80	10,67
62	12,8		0,439	0,386			0,399	0,351	73,00	66,00	0,5	150	0,5	100	132			-10	50	-40	50	4,10	4,66
63	12,8		0,295	0,386			0,268	0,351	84,00	110,00	0,5	168	0,5	100	220			-10	50	-40	50	6,10	4,66
64	12,8		0,114	0,178			0,104	0,162	81,00	126,00	0,2	162	0,5	100	253			-10	50	-40	50	15,80	10,12
65	12,8		0,092	0,151			0,084	0,137	85,00	140,00	0,2	171	0,5	100	279			-10	50	-40	50	19,50	11,91
66	12,8		0,296	0,428			0,269	0,390	76,80	111,15	1,0	154	0,5	100	222			-10	45	-40	75	7,00	4,84
67	12,8		0,328	0,497			0,298	0,451	81,01	122,66	1,0	162	0,5	100	245			-10	45	-40	75	15,80	10,44
68	12,8		0,279	0,422			0,253	0,384	83,96	127,15	0,8	168	0,5	100	254			-10	45	-40	75	18,60	12,28
69	19,2								83,69	119,70	1,0	167	0,5	100	239			-10	45	-40	75	15,60	10,91
70	3,6	1	1,260	2,881	0,336	0,768			134,40	307,33	1,0	54	0,5	100	123			-30	60	-40	60	1,50	0,66
71	3,6	1	1,761	4,162	0,732	1,729			97,55	230,50	2,0	39	0,5	100	92			-30	60	-40	60	1,55	0,66
72	3,6	1	1,854	4,066	0,694	1,523			91,84	201,46	2,0	37	0,5	100	81			-30	60	-40	60	0,98	0,45
73	3,6	1	6,563	13,537	1,575	3,249			78,75	162,45	10,0	32	0,5	100	65			-30	60	-40	60	0,32	0,16
74	86,4	24	0,258	0,305	0,407	0,480			21,37	25,20	10,0		0,5	100				-20	55	-20	55	28,30	24,00
75	3,6	1	0,871	1,640	1,742	3,280			85,33	160,67	10,0	34	0,2	100	64			-30	60	-30	60	0,14	0,07
76	3,6	1			0,131	0,271			103,50	213,50	0,2	41	0,2	100	85			-30	60	-30	60	0,32	0,16
77	3,6	1			0,141	0,310			109,64	241,75	0,2	44	0,2	100	97			-30	60	-30	60	0,99	0,45
78	13,8	48	7,144	8,581					71,44	85,81	48,0	643		100	772	20		-50	75			17,00	14,15
79	48,0		0,488	0,728					35,12	52,39	1,7	11		100	16	7		-40	55	-55	65	4,10	2,75
80	48,0								42,86	63,30	1,4	13		100	19	7		-40	55	-55	65	5,60	3,79

#	System Voltage	Cells in System	Spec. Disch. 2s Pulse Power, Max. [kW/kg]	Disch. 2s Pulse Power dens. Max. [kW/l]	Spec. Reg. 2s Pulse Power, Max. [kW/kg]	Reg. 2s Pulse Power dens., Max. [kW/l]	Spec. Cold Crank. 2s Power @ -30°C, Max. [kW/kg]	Cold Crank. 2s Power dens. @ -30°C, Max. [kW/l]	Spec. Avail. Energy @3 kW [Wh/kg]	Avail. Energy Dens. @3 kW [Wh/l]	C-rate @any eta [1/h]	Spec. Cyc.Life @ 23°C, (80% capacity) [kWh/kg]	@ C-rate	@ % DOD	Cyc.Life Dens. (80% capacity) [kWh / l]	Calendar Life [Yrs]	Self Disch., 23°C [%/1st day]	Operating Temp. Range [°C]		Storage Temp. Range [°C]		System Weight [kg]	System Volume [Liters]
	max 48		**2,670**	**3,338**	**1,643**	**2,540**	**0,32**	**0,4**	**12**	**15**	**2,6**	**339,96**	**7**	**10,2**	**425**	**15**	**6,7**	**-30**	**52**	**-46**	**66**	**25**	**20**
81	48,0								46,67	69,86		14		100	21	7		-40	55	-55	65	7,20	4,81
82	48,0								49,66	73,81	0,8	15		100	22	7		-40	55	-55	65	8,70	5,85
83	48,0								47,06	69,60	1,5	14		100	21	7		-40	55	-55	65	10,20	6,90
84	48,0								48,81	72,78	1,3	15		100	22	7		-40	55	-55	65	11,80	7,91
85	48,0								50,53	75,02	1,1	15		100	23	7		-40	55	-55	65	13,30	8,96
86	48,0								51,89	76,99	1,4	16		100	23	7		-40	55	-55	65	14,80	9,98
87	48,0								52,68	78,41	1,3	16		100	24	7		-40	55	-55	65	16,40	11,02
88	630,0	576							30,43	20,00												230,00	350,00
89	200-400	100							48,33	38,67												60,00	75,00
90	115,0	36																				8,50	15,00
91	3,3	1	3,600	7,370			0,171	0,350	108,43	221,98	4,0	108	10,0	100	222			-30	60	-50	60	0,07	0,03
92	7,2	6	1,250	2,196					46,00	80,79												1,04	0,59
93	288,0	240	0,682	0,287	0,561	0,236			28,99	12,22												66,00	156,66
94	9,6	8	1,192	2,668					41,00	91,75												1,51	0,67
95	288,0	240	0,652	0,294	0,536	0,241			26,92	12,12												69,00	153,21
96	12,0	10	1,687	3,239	1,104	2,120	fail	fail	45,00	86,00	4,0	53		80	102		5,0	0	65	-40	80	18,20	7,20
97	144,0	120	0,588	0,484			fail	fail	23,53	19,38	4,0	30		80	25		5,0	0	65	-40	80	51,00	61,92
98	144,0	120	0,545	0,560			fail	fail	21,82	22,41	4,0	28		80	29		5,0	0	65	-40	80	55,00	53,54
99	144,0	240	0,588	0,484			fail	fail	23,53	19,38	4,0	30		80	25		5,0	0	65	-40	80	102,00	123,85
100	144,0	240	0,545	0,560			fail	fail	21,82	22,41	4,0	28		80	29		5,0	0	65	-40	80	110,00	107,09
101	288,0	240	0,682	0,683			fail	fail	27,27	27,32	4,0	35		80	35		5,0	0	65	-40	80	88,00	87,84
102	288,0	240	0,652	0,825			fail	fail	26,09	33,02	4,0	33		80	42		5,0	0	65	-40	80	92,00	72,69
103	288,0	480	0,682	0,683			fail	fail	27,27	27,32	4,0	35		80	35		5,0	0	65	-40	80	176,00	175,67
104	288,0	480	0,652	0,825			fail	fail	26,09	33,02	4,0	33		80	42		5,0	0	65	-40	80	184,00	145,39
105	336,0	280	0,707	0,714			fail	fail	28,28	28,57	4,0	36		80	36		5,0	0	65	-40	80	99,00	97,99
106	336,0	280	0,700	0,878			fail	fail	28,00	35,12	4,0	36		80	45		5,0	0	65	-40	80	100,00	79,73
107	336,0	560	0,707	0,714			fail	fail	28,28	28,57	4,0	36		80	36		5,0	0	65	-40	80	198,00	195,99

#	System Voltage	Cells in System	Spec. Disch. 2s Pulse Power, Max. [kW/kg]	Disch. 2s Pulse Power dens. Max. [kW/l]	Spec. Reg. 2s Pulse Power, Max. [kW/kg]	Reg. 2s Pulse Power dens., Max. [kW/l]	Spec. Cold Crank. 2s Power @ -30°C, Max. [kW/kg]	Cold Crank. 2s Power dens. @ -30°C, Max. [kW/l]	Spec. Avail. Energy @3 kW [Wh/kg]	Avail. Energy Dens. @3 kW [Wh/l]	C-rate @any eta [1/h]	Spec. Cyc.Life @ 23°C, (80% capacity) [kWh/kg]	@ C-rate	@ % DOD	Cyc.Life Dens. (80% capacity) [kWh / l]	Calendar Life [Yrs]	Self Disch., 23°C [%/1st day]	Operating Temp. Range [°C]		Storage Temp. Range [°C]		System Weight [kg]	System Volume [Liters]
	max 48		**2,670**	**3,338**	**1,643**	**2,540**	**0,32**	**0,4**	**12**	**15**	**2,6**	**339,96**	**7**	**10,2**	**425**	**15**	**6,7**	**-30**	**52**	**-46**	**66**	**25**	**20**
108	336,0	560	0,700	0,878			fail	fail	28,00	35,12	4,0	36		80	45		5,0	0	65	-40	80	200,00	159,46
109	576,0	480	0,682	0,683			fail	fail	27,27	27,32	4,0	35		80	35		5,0	0	65	-40	80	176,00	175,67
110	576,0	480	0,652	0,825			fail	fail	26,09	33,02	4,0	33		80	42		5,0	0	65	-40	80	184,00	145,39
111	576,0	960	0,682	0,683			fail	fail	27,27	27,32	4,0	35		80	35		5,0	0	65	-40	80	352,00	351,34
112	576,0	960	0,652	0,825			fail	fail	26,09	33,02	4,0	33		80	42		5,0	0	65	-40	80	368,00	290,77
113	672,0	560	0,707	0,714			fail	fail	28,28	28,57	4,0	36		80	36		5,0	0	65	-40	80	198,00	195,99
114	672,0	560	0,700	0,878			fail	fail	28,00	35,12	4,0	36		80	45		5,0	0	65	-40	80	200,00	159,46
115	672,0	1120	0,707	0,714			fail	fail	28,28	28,57	4,0	36		80	36		5,0	0	65	-40	80	396,00	391,98
116	672,0	1120	0,700	0,878			fail	fail	28,00	35,12	4,0	36		80	45		5,0	0	65	-40	80	400,00	318,91
117	42,0		0,750	0,631	0,900	0,757	fail	fail	30,00	25,23	4,0			5			5,0	0	65	-40	80	20,00	23,78
118	3,9	1	1,196	2,385			fail	fail	158,44	315,92	1,0	79	1,0	100	158			0	40	-10	30	0,24	0,12
119	27,0	7	0,925	1,313			fail	fail	122,73	174,24	1,0	61	1,0	100	87			0	40	-10	30	2,20	1,55
120	38,0	12	1,163	1,694			fail	fail	126,67	184,61	1,0	63	1,0	100	92			0	40	-10	30	3,00	2,06
121	152,0								28,15	19,00												27,00	40,00
122	200,0	80							44,44							15						45,00	
123	2,5	1		4,706				53,050		47,75			5,0	100	143	15							0,09
124	2,5	1	4,872	9,569	4,943	9,708			49,43	97,08		148	5,0	100	291	15						0,25	0,13
125	3,6	1		6,594						76,39			5,0	100	229	15							0,09
126	3,6	1		12,068						139,79			5,0	100	419	15							0,13
127	24,0	20	0,540	1,080					18,00	36,00	0,3	188	0,7	8,3	375	15						8,00	4,00
128	36,0	30	0,568	1,258					18,95	41,94	0,3	188	0,7	8,3	375	15						11,40	5,15
129	48,0	40	0,584	1,374					19,46	45,79	0,3	188	0,7	8,3	375	15						14,80	6,29
130	72,0	60	0,597	1,510					19,91	50,35	0,3	188	0,7	8,3	375	15						21,70	8,58
131	96,0	80	0,606	1,590					20,21	52,99	0,3	188	0,7	8,3	375	15						28,50	10,87
132	3,8	1	1,316	3,008					54,00	107,00	10,0	124			246			0	45			2,10	0,92
133	3,8	1	1,417	3,073					58,00	110,00	6,7	133			253			0	45			3,90	1,80
134	22,8	6	0,619	0,688					56,70	54,81	3,0	130			126			0	45			16,00	14,38

#	System Voltage	Cells in System	Spec. Disch. 2s Pulse Power, Max. [kW/kg]	Disch. 2s Pulse Power dens. Max. [kW/l]	Spec. Reg. 2s Pulse Power, Max. [kW/kg]	Reg. 2s Pulse Power dens., Max. [kW/l]	Spec. Cold Crank. 2s Power @ -30°C, Max. [kW/kg]	Cold Crank. 2s Power dens. @ -30°C, Max. [kW/l]	Spec. Avail. Energy @3 kW [Wh/kg]	Avail. Energy Dens. @3 kW [Wh/l]	C-rate @any eta [1/h]	Spec. Cyc.Life @ 23°C, (80% capacity) [kWh/kg]	@ C-rate	@ % DOD	Cyc.Life Dens. (80% capacity) [kWh / l]	Calendar Life [Yrs]	Self Disch., 23°C [%/1^{st} day]	Operating Temp. Range [°C]		Storage Temp. Range [°C]		System Weight [kg]	System Volume [Liters]
	max 48		**2,670**	**3,338**	**1,643**	**2,540**	**0,32**	**0,4**	**12**	**15**	**2,6**	**339,96**	**7**	**10,2**	**425**	**15**	**6,7**	**-30**	**52**	**-46**	**66**	**25**	**20**
135	26,6	7	0,642	0,709					58,80	56,48	3,0	135			130			0	45			18,00	16,28
136	26,6	7	0,679	0,889					62,26	70,81	3,0	143			163			0	45			17,00	12,99
137	11,4	3	0,707	0,963					65,19	76,62	3,0	150			176			0	45			14,00	10,28
138	15,2	4	0,733	1,001					67,60	79,63	3,0	155			183			0	45			18,00	13,19
139	26,6	7	0,770	1,054					70,98	83,87	3,0	163			193			0	45			30,00	21,92
140	3,7	1	1,492	3,398			fail	fail	101,00	232,00	1,0					4		-18	70			2,75	1,21
141	3,6	1	1,492	3,398			fail	fail	102,00	224,00	0,5							10	30			1,60	0,70
142	3,6	1	1,492	3,398					136,00	277,00	0,5											1,50	0,80
143	3,6	1	1,492	3,398					146,00	328,00	0,5											2,80	1,35
144	3,6	1	1,492	3,398					146,00	334,00	0,5											4,60	2,17
145	48,6	18	2,132	2,759	2,132	2,759	1,421	1,839	1,86	2,41	-	1860		50	2407	10	1,6	-40	65	-40	70	11,00	8,50
146	48,6	18	2,548	3,224	2,548	3,224	1,699	2,149	2,18	2,76	-	2183		50	2762	10	1,6	-40	65	-40	70	12,40	9,80
147	48,6	18	3,180	3,583	3,180	3,583	2,120	2,389	2,86	3,22	-	2858		50	3220	10	1,6	-40	65	-40	70	14,20	12,60
148	48,6	18	2,797	3,619	2,797	3,619	1,864	2,413	1,86	2,41	-	1860		50	2407	10	1,6	-40	65	-40	70	11,00	8,50
149	48,6	18	3,224	4,079	3,224	4,079	2,149	2,720	2,18	2,76	-	2183		50	2762	10	1,6	-40	65	-40	70	12,40	9,80
150	48,6	18	3,761	4,238	3,761	4,238	2,507	2,826	2,86	3,22	-	2858		50	3220	10	1,6	-40	65	-40	70	14,20	12,60
151	16,2	6	2,050	1,677	2,050	1,677	1,366	1,118	1,12	0,91	-	1118		50	1522	10	1,6	-40	65	-40	70	2,70	3,30
152	16,2	6	1,803	2,588	1,803	2,588	1,202	1,725	1,54	2,21	-	1538		50	3133	10	1,6	-40	65	-40	70	4,45	3,10
153	16,2	6	2,633	3,221	2,633	3,221	1,755	2,147	2,38	2,91	-	2378		50	3496	10	1,6	-40	65	-40	70	5,75	4,70
154	16,2	6	2,889	2,364	2,889	2,364	1,926	1,576	1,11	0,91	-	1110		50	1522	10	1,6	-40	65	-40	70	2,70	3,30
155	16,2	6	2,302	3,304	2,302	3,304	1,535	2,203	1,54	2,21	-	1538		50	3133	10	1,6	-40	65	-40	70	4,45	3,10
156	16,2	6	3,085	3,774	3,085	3,774	2,057	2,516	2,38	2,91	-	2378		50	3496	10	1,6	-40	65	-40	70	5,75	4,70
157	75,0	32	2,487	2,132	2,487	2,132	1,658	1,422	2,24	1,92	-	2245		50	1924	17,36	1,6	-40	55	-40	70	24,50	28,58
158	125,0		2,432	1,644	2,432	1,644	1,621	1,096	1,75	1,19	-	1753		50	1185	17,36	1,6	-40	65	-40	70	58,00	85,82
159	390,0		2,305	1,749	2,305	1,749	1,536	1,166	1,71	1,30	-	2220		83,97	1685	17,36	1,6	-40	65	-40	70	165,00	217,38

#	System Voltage	Cells in System	Spec. Disch. 2s Pulse Power, Max. [kW/kg]	Disch. 2s Pulse Power dens. Max. [kW/l]	Spec. Reg. 2s Pulse Power, Max. [kW/kg]	Reg. 2s Pulse Power dens., Max. [kW/l]	Spec. Cold Crank. 2s Power @ -30°C, Max. [kW/kg]	Cold Crank. 2s Power dens. @ -30°C, Max. [kW/l]	Spec. Avail. Energy @3 kW [Wh/kg]	Avail. Energy Dens. @3 kW [Wh/l]	C-rate @any eta [1/h]	Spec. Cyc.Life @ 23°C, (80% capacity) [kWh/kg]	@ C-rate	@ % DOD	Cyc.Life Dens. (80% capacity) [kWh / l]	Calendar Life [Yrs]	Self Disch., 23°C [%/1^{st} day]	Operating Temp. Range [°C]		Storage Temp. Range [°C]		System Weight [kg]	System Volume [Liters]
	max 48		**2,670**	**3,338**	**1,643**	**2,540**	**0,32**	**0,4**	**12**	**15**	**2,6**	**339,96**	**7**	**10,2**	**425**	**15**	**6,7**	**-30**	**52**	**-46**	**66**	**25**	**20**
160	15,0	6	0,538	0,526	0,538	0,526	fail	fail	1,36	1,33	-	1359		50	1329		6,9	-25	60	5	35	1,00	1,02
161	15,0	6	0,687	0,668	0,687	0,668	fail	fail	1,94	1,89	-	1942		50	1888		6,9	-25	60	5	35	1,40	1,44
162	2,5	1	0,269	0,406	0,269	0,406	fail	fail	2,76	4,16	-	2763		50	4164		6,9	-25	60	5	35	0,09	0,06
163	2,5	1	0,347	0,505	0,347	0,505	fail	fail	3,62	5,27	-	3619		50	5271		6,9	-25	60	5	35	0,13	0,09
164	2,5	1	0,361	0,513	0,361	0,513	fail	fail	3,82	5,43	-	3815		50	5428		6,9	-25	60	5	35	0,19	0,13
165	2,5	1	0,385	0,539	0,385	0,539	fail	fail	4,19	5,87	-	4195		50	5872		6,9	-25	60	5	35	0,26	0,19
166	2,5	1	0,353	0,493	0,353	0,493	fail	fail	3,85	5,37	-	3848		50	5368		6,9	-25	60	5	35	0,29	0,21
167	2,5	1	0,357	0,493	0,357	0,493	fail	fail	4,32	5,97	-	4323		50	5968		6,9	-25	60	5	35	0,41	0,29
168	2,5	1	1,347	2,030	1,347	2,030	fail	fail	2,42	3,64	-	2417		50	3644		6,9	-25	60	5	35	0,09	0,06
169	2,5	1	1,526	2,222	1,526	2,222	fail	fail	3,13	4,56	-	3130		50	4559		6,9	-25	60	5	35	0,13	0,09
170	2,5	1	1,546	2,199	1,546	2,199	fail	fail	3,29	4,69	-	3295		50	4687		6,9	-25	60	5	35	0,19	0,13
171	2,5	1	1,540	2,155	1,540	2,155	fail	fail	3,45	4,84	-	3454		50	4835		6,9	-25	60	5	35	0,26	0,19
172	15,0	6	0,896	0,868	0,896	0,868	fail	fail	2,28	2,21	-	2275		50	2205		6,9	-25	60	5	35	2,40	2,48
173	2,3	1	0,203	0,305	0,203	0,305	fail	fail	2,92	4,41	-	2923		50	4406		6,9	-25	60	5	35	0,09	0,06
174	2,3	1	0,258	0,376	0,258	0,376	fail	fail	3,60	5,25	-	3601		50	5245		6,9	-25	60	5	35	0,13	0,09
175	2,3	1	0,229	0,326	0,229	0,326	fail	fail	3,82	5,43	-	3816		50	5429		6,9	-25	60	5	35	0,19	0,13
176	2,3	1	0,296	0,415	0,296	0,415	fail	fail	4,18	5,85	-	4177		50	5847		6,9	-25	60	5	35	0,26	0,19
177	13,8	6	0,220	0,212	0,220	0,212	fail	fail	3,10	2,99	-	3100		50	2989		6,9	-25	60	5	35	3,20	3,32
178	2,3	1	0,272	0,379	0,272	0,379	fail	fail	3,83	5,35	-	3831		50	5346		6,9	-25	60	5	35	0,29	0,21
179	2,3	1	0,282	0,389	0,282	0,389	fail	fail	4,20	5,80	-	4201		50	5800		6,9	-25	60	5	35	0,41	0,29
180	2,3	1	1,073	1,617	1,073	1,617	fail	fail	2,63	3,97	-	2631		50	3965		6,9	-25	60	5	35	0,09	0,06
181	2,3	1	1,174	1,710	1,174	1,710	fail	fail	3,15	4,58	-	3146		50	4582		6,9	-25	60	5	35	0,13	0,09
182	2,3	1	1,145	1,629	1,145	1,629	fail	fail	3,23	4,59	-	3229		50	4594		6,9	-25	60	5	35	0,19	0,13
183	2,3	1	1,207	1,689	1,207	1,689	fail	fail	3,55	4,97	-	3550		50	4970		6,9	-25	60	5	35	0,26	0,19
184	2,5	1	0,295	0,399	0,295	0,399	fail	fail	2,72	3,69	-	2723		50	3687		2,9	-25	60	5	35	0,43	0,32
185	2,5	1	0,368	0,501	0,368	0,501	fail	fail	2,83	3,85	-	2833		50	3855		2,9	-25	60	5	35	0,55	0,41
186	15,0	6	1,486	1,563	1,486	1,563	fail	fail	2,29	2,41	-	2287		50	2405		2,9	-25	60	5	35	4,10	3,90

#	System Voltage	Cells in System	Spec. Disch. 2s Pulse Power, Max. [kW/kg]	Disch. 2s Pulse Power dens. Max. [kW/l]	Spec. Reg. 2s Pulse Power, Max. [kW/kg]	Reg. 2s Pulse Power dens., Max. [kW/l]	Spec. Cold Crank. 2s Power @ -30°C, Max. [kW/kg]	Cold Crank. 2s Power dens. @ -30°C, Max. [kW/l]	Spec. Avail. Energy @3 kW [Wh/kg]	Avail. Energy Dens. @3 kW [Wh/l]	C-rate @any eta [1/h]	Spec. Cyc.Life @ 23°C, (80% capacity) [kWh/kg]	@ C-rate	@ % DOD	Cyc.Life Dens. (80% capacity) [kWh / l]	Calendar Life [Yrs]	Self Disch., 23°C [%/1st day]	Operating Temp. Range [°C]		Storage Temp. Range [°C]		System Weight [kg]	System Volume [Liters]
	max 48		**2,670**	**3,338**	**1,643**	**2,540**	**0,32**	**0,4**	**12**	**15**	**2,6**	**339,96**	**7**	**10,2**	**425**	**15**	**6,7**	**-30**	**52**	**-46**	**66**	**25**	**20**
187	2,5	1	1,260	1,674	1,260	1,674	fail	fail	2,55	3,38	-	2545		50	3380		2,9	-25	60	5	35	0,23	0,17
188	2,5	1	1,386	1,858	1,386	1,858	fail	fail	2,67	3,57	-	2666		50	3572		2,9	-25	60	5	35	0,29	0,22
189	2,3	1	2,219	3,005	2,219	3,005	fail	fail	2,69	3,64	-	2689		50	3641		2,9	-25	60	5	35	0,43	0,32
190	2,3	1	2,226	3,030	2,226	3,030	fail	fail	2,80	3,81	-	2797		50	3807		2,9	-25	60	5	35	0,55	0,41
191	2,3	1	2,074	2,755	2,074	2,755	fail	fail	2,63	3,50	-	2633		50	3497		2,9	-25	60	5	35	0,23	0,17
192	2,3	1	2,095	2,808	2,095	2,808	fail	fail	2,63	3,53	-	2632		50	3527		2,9	-25	60	5	35	0,29	0,22
193	2,3	1	1,528	2,011	1,528	2,011	0,764	1,005	2,94	3,87	-	1959	120,0	50	2578	6,7		-25	60	-40	85	0,02	0,02
194	2,3	1	3,016	4,138	3,016	4,138	1,508	2,069	1,74	2,39	-	1160	120,0	50	1591	6,7		-40	60	-40	70	0,38	0,28
195	2,3	1	2,204	2,782	2,204	2,782	1,102	1,391	2,12	2,67	-	1413	120,0	50	1783	6,7		-40	60	-40	70	0,65	0,52
196	2,3	1	2,149	2,411	2,149	2,411	1,075	1,206	2,41	2,70	-	1607	120,0	50	1803	6,7		-40	60	-40	70	0,80	0,71
197	2,7	1	4,050	5,329	4,050	5,329	2,025	2,664	3,38	4,44	-	2250	120,0	50	2961	6,7		-40	60	-40	70	0,02	0,02
198	15,0	12	2,779	3,922	2,779	3,922	1,389	1,961	2,53	3,57	-	1685	120,0	50	2378	6,7		-40	60	-40	70	0,31	0,22
199	17,5	7	2,935	4,142	2,935	4,142	1,467	2,071	2,50	3,53	-	1668	120,0	50	2354	6,7		-40	60	-40	70	0,18	0,13
200	17,5	28	2,581	3,643	2,581	3,643	1,291	1,822	2,55	3,59	-	1698	120,0	50	2396	6,7		-40	60	-40	70	0,71	0,51
201	50,0	40	2,950	4,164	2,950	4,164	1,475	2,082	2,55	3,60	-	1702	120,0	50	2402	6,7		-40	60	-40	70	1,02	0,72
202	90,0	36	1,549	0,878	1,549	0,878	0,774	0,439	1,39	0,79	-	926	120,0	50	525	6,7		-40	60	-40	70	1,70	3,00
203	2,7	1	5,923	7,845	5,923	7,845	2,962	3,923	2,28	3,02	-	1519	120,0	50	2012	6,7		-40	60	-40	70	0,20	0,15
204	2,7	1	4,453	6,109	4,453	6,109	2,227	3,055	3,40	4,66	-	2265	120,0	50	3107	6,7		-40	60	-40	70	0,38	0,28
205	45,0	18	2,301	3,050	2,301	3,050	1,151	1,525	1,80	2,39	-	1202	120,0	50	1593	6,7		-40	60	-40	70	11,00	8,30
206	2,7	1	3,536	4,600	3,536	4,600	1,768	2,300	3,97	5,16	-	2645	120,0	50	3441	6,7		-40	60	-40	70	0,67	0,52
207	45,0	18	1,662	1,463	1,662	1,463	0,831	0,731	1,86	1,64	-	1240	120,0	50	1091	6,7		-40	60	-40	70	22,00	25,00
208	52,0	21	1,744	1,414	1,744	1,414	0,872	0,707	1,95	1,58	-	1299	120,0	50	1053	6,7		-40	60	-40	70	24,00	29,60
209	42,0	17	1,405	1,297	1,405	1,297	0,703	0,649	1,57	1,45	-	1046	120,0	50	966	6,7		-40	60	-40	70	24,00	26,00
210	340,0	272	1,439	1,328	1,439	1,328	0,719	0,664	1,60	1,48	-	1066	120,0	50	984	6,7		-40	60	-40	70	384,00	416,00
211	2,7	1	3,328	4,154	3,328	4,154	1,664	2,077	4,27	5,33	-	2844	120,0	50	3550	6,7		-40	60	-40	70	0,89	0,71
212	52,0	21	1,635	1,369	1,635	1,369	0,817	0,685	2,09	1,75	-	1397	120,0	50	1170	6,7		-40	60	-40	70	32,00	38,20
213	2,7	1	5,523	6,579	5,523	6,579	2,761	3,290	0,69	0,82	-	460	120,0	50	548	6,7		-40	60	-40	70	0,33	0,28

#	System Voltage	Cells in System	Spec. Disch. 2s Pulse Power, Max. [kW/kg]	Disch. 2s Pulse Power dens. Max. [kW/l]	Spec. Reg. 2s Pulse Power, Max. [kW/kg]	Reg. 2s Pulse Power dens., Max. [kW/l]	Spec. Cold Crank. 2s Power @ -30°C, Max. [kW/kg]	Cold Crank. 2s Power dens. @ -30°C, Max. [kW/l]	Spec. Avail. Energy @3 kW [Wh/kg]	Avail. Energy Dens. @3 kW [Wh/l]	C-rate @any eta [1/h]	Spec. Cyc.Life @ 23°C, (80% capacity) [kWh/kg]	@ C-rate	@ % DOD	Cyc.Life Dens. (80% capacity) [kWh / l]	Calendar Life [Yrs]	Self Disch., 23°C [%/1st day]	Operating Temp. Range [°C]		Storage Temp. Range [°C]		System Weight [kg]	System Volume [Liters]
	max 48		**2,670**	**3,338**	**1,643**	**2,540**	**0,32**	**0,4**	**12**	**15**	**2,6**	**339,96**	**7**	**10,2**	**425**	**15**	**6,7**	**-30**	**52**	**-46**	**66**	**25**	**20**
214	15,0	6	5,083	6,090	5,083	6,090	2,542	3,045	0,59	0,70	-	391	120,0	50	468	6,7		-40	60	-40	70	2,00	1,67
215	15,0	6	5,641	7,128	5,641	7,128	2,821	3,564	1,30	1,64	-	868	120,0	50	1097	6,7		-40	60	-40	70	0,35	0,28
216	2,7	1	4,795	6,090	4,795	6,090	2,398	3,045	1,11	1,41	-	738	120,0	50	937	6,7		-40	60	-40	70	2,12	1,67
217	2,3	1	1,686	2,809	1,686	2,809	0,843	1,405	3,89	6,48	-	2593	120,0	50	4322	6,7		-25	60	-30	70	0,02	0,01
218	42,0	16	0,285	0,398	0,285	0,398	0,854	1,194	2,19	3,06	-	1642	90,0	50	2295918			-30	65	-46	66	13,70	9,80
219	3,8	1	6,294	10,475	6,294	10,475	0,525	0,873	9,40	15,64	-						1,5					0,23	0,14
220	1,6	1	0,496	0,495	0,496	0,495	0,129	0,129	10,70	15,24	-											1,40	1,40
221	21,6	8	6,371	5,158	6,371	5,158			2,32	1,88	-											1,70	2,10
222		10							1,56	1,45	-	1557		50	1452	10						2,80	3,00
223	28,0	12	4,097	4,464	4,097	4,464	0,964	1,050	1,84	2,01	-	921	90,0	50	1004	10		-30	65	-40	70	8,50	7,80
224	48,6	18	3,614	3,774	3,614	3,774			3,05	3,19	-	1525	90,0	50	1593	10		-40	70	-46	85	11,80	11,30
225	48,6	18	3,281	3,774	3,281	3,774			2,77	3,19	-	1385	90,0	50	1593	10		-40	70	-46	85	13,00	11,30
226	48,6	18	3,207	3,412	3,207	3,412			2,71	2,88	-	1353	90,0	50	1440	10		-40	70	-46	85	13,30	12,50
227	48,6	18	2,245	1,895	2,245	1,895			1,89	1,60	-	947	90,0	50	800	10		-40	70	-46	85	19,00	22,50
228	2,5	1	2,861	3,887	2,861	3,887	fail	fail	3,08	4,19	-	3081	90,0	50	4186		2,9	-25	60	-40	85	0,51	0,37
229	30,0	12	2,273	2,365	2,273	2,365	fail	fail	2,59	2,70	-	2593	90,0	50	2698		2,9	-25	60	5	35	7,23	6,95
230	30,0	12	7,254	7,127	7,254	7,127	1,674	1,645	2,65	2,60	-						16,3	-30	65			5,60	5,70
231	-	4	5,556	20,661	5,556	20,661	5,556	20,661	4,63	17,22		23148		100	86088			-40	150	-	-	18,00	4,84
232	2,5	1	3,200						65,00		24,0	624	10,0			10							
233	46,8	13							124,25	183,53	0,5	62		100	92			-25	50	-25	60	22,60	15,30
234	14,4	4	0,745	1,188	0,279	0,445			68,94	109,95	2,0	55		100	88			-25	50	-25	60	5,64	3,54
235	3,6	1	1,890	3,600					81,00	154,29	2,0	49	1,0	100	93			-25	50	-25	60	1,20	0,63
236	36,0	10	2,268	3,040					75,00	100,00	2,0	45	1,0	100	60			-25	50	-25	60	13,00	9,70
237	3,6	1							91,00	174,19	2,0	55	0,7	100	105			-25	50	-25	60	0,24	0,12
238	1,6	1	0,900	2,538					60,00	169,00	0,7	12	8,8	100	34			5	40	-30	50	0,05	0,02
239	1,7								55,00	100,00		28		100	50			-20	50				
240	13,0	8							55,71	101,60	0,3							-10	45	-20	25	2,80	1,54

#	System Voltage	Cells in System	Spec. Disch. 2s Pulse Power, Max. [kW/kg]	Disch. 2s Pulse Power dens. Max. [kW/l]	Spec. Reg. 2s Pulse Power, Max. [kW/kg]	Reg. 2s Pulse Power dens., Max. [kW/l]	Spec. Cold Crank. 2s Power @ -30°C, Max. [kW/kg]	Cold Crank. 2s Power dens. @ -30°C, Max. [kW/l]	Spec. Avail. Energy @3 kW [Wh/kg]	Avail. Energy Dens. @3 kW [Wh/l]	C-rate @any eta [1/h]	Spec. Cyc.Life @ 23°C, (80% capacity) [kWh/kg]	@ C-rate	@ % DOD	Cyc.Life Dens. (80% capacity) [kWh / l]	Calendar Life [Yrs]	Self Disch., 23°C [%/1st day]	Operating Temp. Range [°C]		Storage Temp. Range [°C]		System Weight [kg]	System Volume [Liters]
	max 48		**2,670**	**3,338**	**1,643**	**2,540**	**0,32**	**0,4**	**12**	**15**	**2,6**	**339,96**	**7**	**10,2**	**425**	**15**	**6,7**	**-30**	**52**	**-46**	**66**	**25**	**20**
241	42,0	21	0,400	0,818	0,200	0,409	0,250	0,511	25,00	51,15	0,3	18	0,5	100	36	6	0,5	-40	50			62,07	30,25
242	62,0	144	0,161	0,109			0,161	0,109	118,00	174,00						10		-40	50			125,00	184,55

Table B.2 dataset 2/2

Appendix C

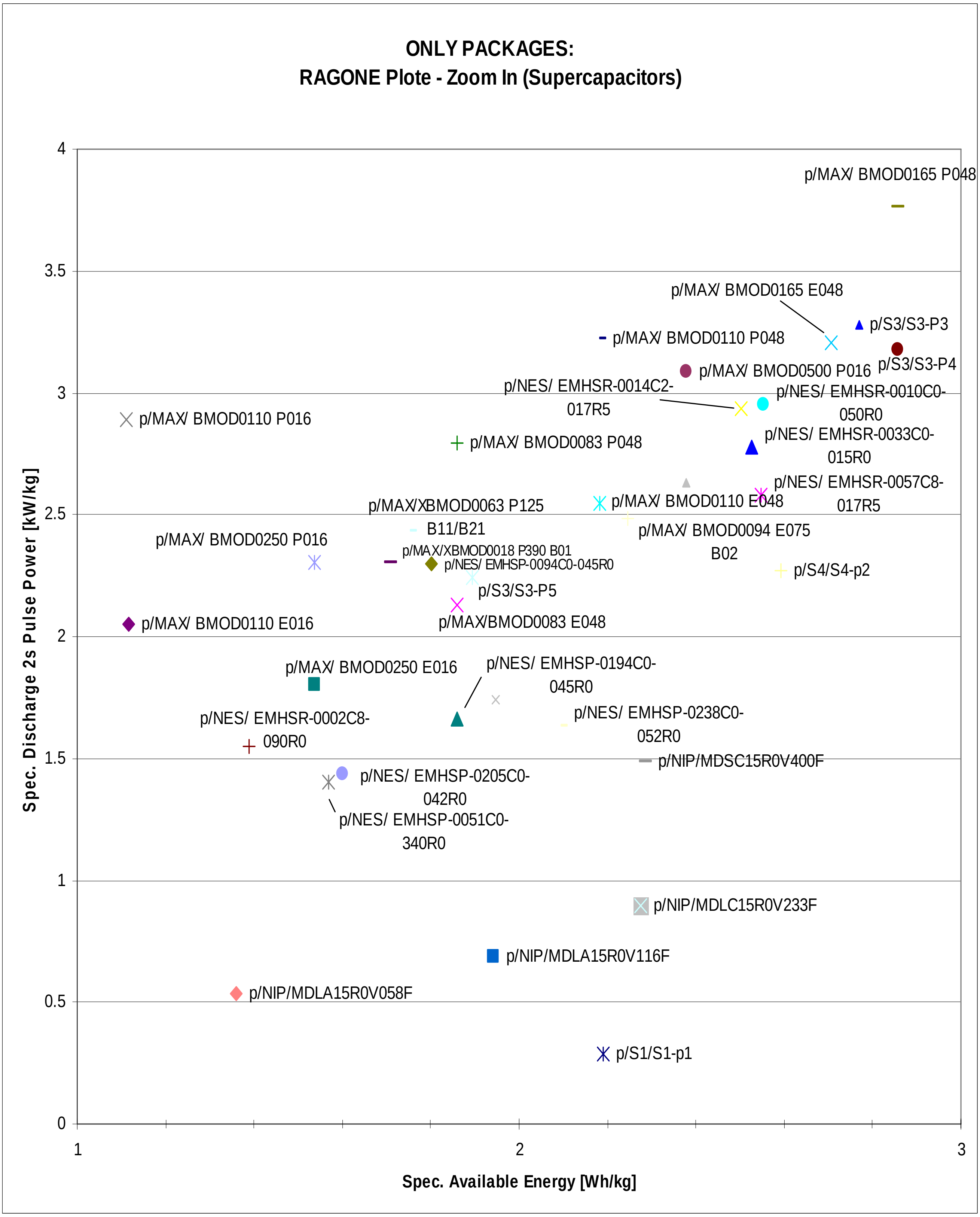


Figure C.1 Ragone Plot – zoom in Supercapacitors (only packages)

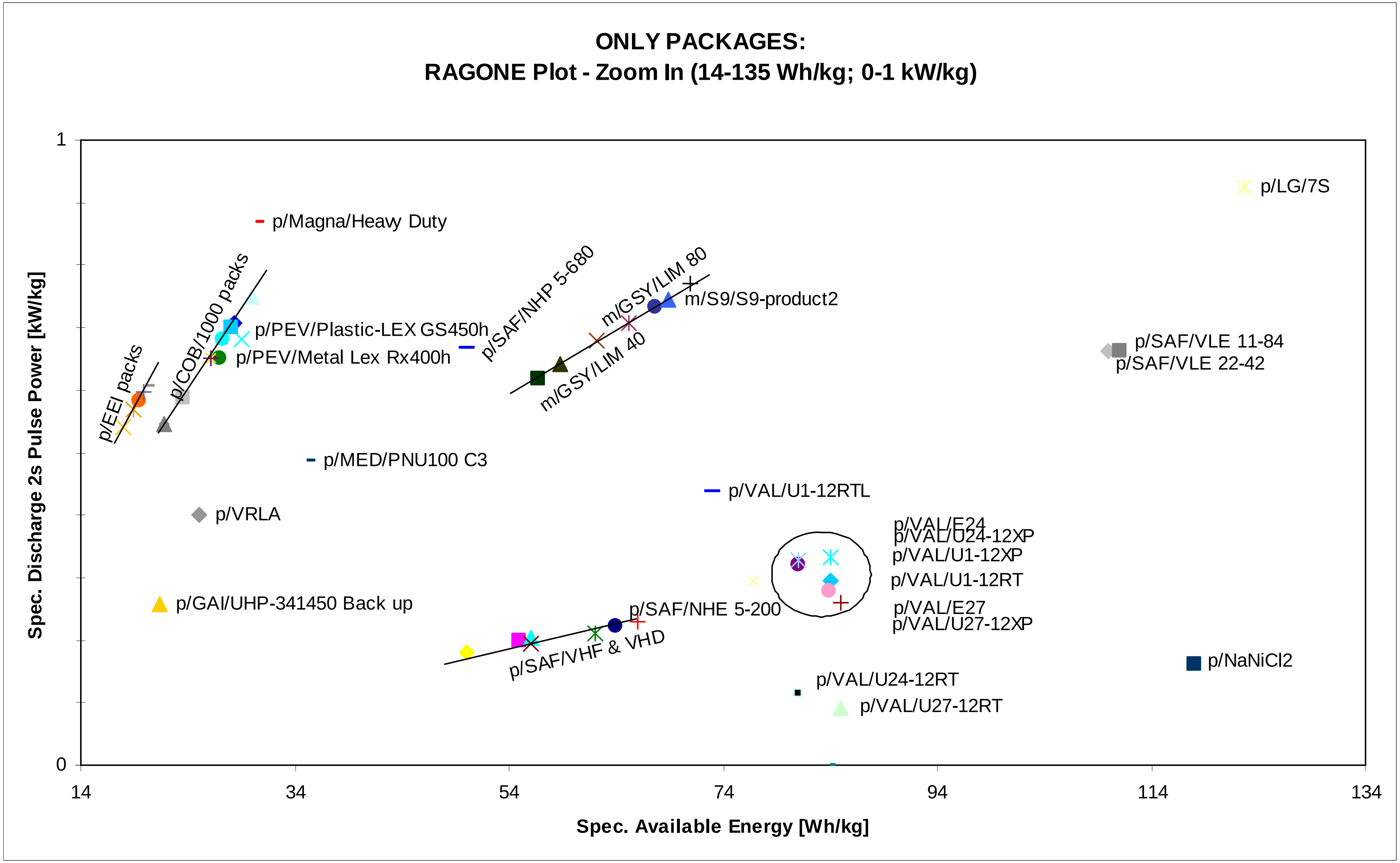


Figure C.2 Ragone Plot – Zoom in batteries (only packages)

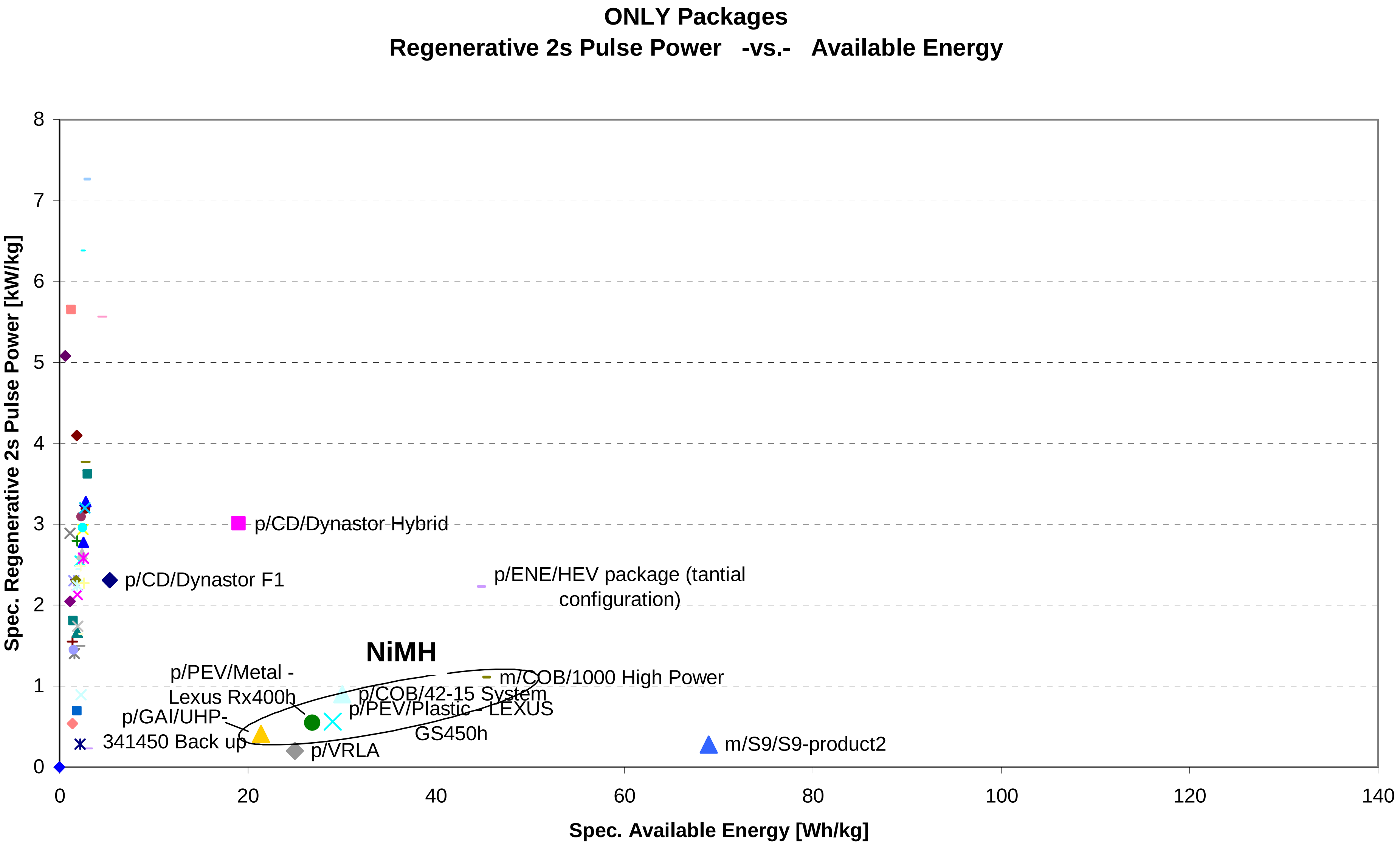


Figure C.3 Spec. regenerative pulse power (only packages)

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