CODEN:LUTEDX/(TEIE-5194)/1-71/(2005)

Industrial Electrical Engineering and Automation

Batteries or supercapacitors as energy storage in HEVs?

Christian Tallner

Simon Lannetoft

Dept. of Industrial Electrical Engineering and Automation
Lund University

Abstract

In this thesis different energy storage systems in the drive train of a hybrid electric vehicle, HEV, are investigated. The primary aim of the investigation is to determine installation cost and lifetime for the energy storage system. Comparison between altered systems such as nickel metal hydride and lithium ion batteries and super capacitors is done. Different control strategies in the HEV are also considered. Those are plugin HEV, PHEV, and mild hybrid, MHEV. In PHEV high energy batteries are assumed and in MHEV high power batteries or super capacitor are supposed. In order to compare these things, models on the energy storage are built. Different models are made regarding what energy storage that are used. The simulation software used is Matlab/Simulink.

Unfortunately no validation against measurements has been done because of the lack of available data. However, simulations show that there is a promising future in the PHEV market due to the fact that they would be very cost effective and environmentally friendly. Concerning the MHEV one can clearly see that super capacitor would be a great complement to batteries, or even a challenger, if the price of it were reduced and its energy density enhanced.

Keywords: Energy storage, Nickel Metal Hydride, Lithium Ion, Super capacitor, High energy, High power, Hybrid Electric Vehicle.

Sammanfattning

I detta arbete har en utredning angående olika energilager till elhybridbilar, HEV, gjorts. Det huvudsakliga målet av utredningen är att uppskatta installationskostnader och livstid för energilagret. De olika energilager som jämförts är nickel metal hydrid och lithium jon batterier respektive så kallade superkondensatorer. De olika kontrollstrategier av HEV som är betraktade är plugin HEV, PHEV, och mild hybrid, MHEV. I PHEV strategin används batterier med stort energiinnehåll och i en MHEV används mestadels högeffekt batterier eller superkondensatorer. För att kunna jämföra dessa olika energilager har olika simuleringsmodeller till respektive energilager byggts. Simuleringsprogrammet som använts är Matlab/Simulink.

Tyvärr har man inte kunnat bekräfta teorin på grund av brist på mätdata. Men simuleringarna visar ändå att PHEV skulle kunna ha en mycket lovande framtid på grund av att de skulle kunna vara mycket kosteffektiva och miljövänliga.
Angående MHEV framgår det tydligt att superkondensatorer skulle kunna vara ett utmärkt komplement, eller till och med en utmanare, till batterier. Men detta kräver att dess pris reduceras och att energidensiteten förbättras.

Acknowledgement

This thesis wouldn’t be possible to realize without assistance from experienced people.

When modeling the batteries SAFT America gave us invaluable information on how one can model a lithium ion cell and how it works. In the end of the thesis we also had contact with a PhD student from KTH named Shelley Brown. Her knowledge on batteries helped us a lot in order to straighten out some important questions.

A very helpful man when modeling the super capacitor was Peter Kim from Nesscap. He provided us with data and information on the capacitor such that this model became rather accurate.

When having problem with the Simulink car model a PhD student at IEA named Jonas Ottosson provided us with great help.

Last but not least Mats Alaküla at IEA, our main supervisor, acted as an excellent guide through this thesis. With him we discussed almost every part of the project.

During this project almost everybody at IEA provided us with some kind of help, so in order to not forget anyone we want to express gratitude to everyone who has helped us through this time.

1 Introduction

There are many reasons to install an electric drive system combined with a combustion engine. A central reason is that the electrical engine can provide the combustion engine with additional torque in order to make it operate an extended time on operating points with good efficiency. The difference between ICE power and tractive power charge the battery. There is also an ability to store energy at regenerative braking. Another reason is that it is possible to drive pure electrically in e.g. emission free zones, like parking garage and in city centers. Or why not a commuting car that is able to drive 50-100 km on pure electrical propulsion.
The increasing energy requirement, produced of electric equipments, leads us to the need of a bigger generator and energy storage.

1.1 Background

The secondary energy storage is a vital component in hybrid electrical vehicles. As electric energy storage the lead acid battery is traditionally used, in particular as 12 and 24 V system battery in vehicles. However, in the last years the nickel metal hydride battery has become used in several vehicles, and today the lithium technology is also of interest. A widespread experience with battery technology in vehicles is that the cost relate to lifetime is a limitation. Without this limitation it would be possible to install a sufficient amount of battery so that a passenger car easily can be driven most of the everyday mileage pure electrically. This would result in a considerable reduction of apparent fuel consumption.

An important alternative is the super capacitors that are assumed to have almost unlimited lifetime. The drawback with this is its low energy density. This limits the possibility to drive a long mileage on pure electric power. However consider the possibility, in a hybrid electric vehicle, not to have the need of changing worn-out batteries.

1.2 Thesis outline

In chapter 1 an introduction to the work is written. Here a brief explanation on the powerassist and a plugin vehicle is made and also the objective of the thesis is presented here.

Chapter two presents what kind of model that is used in this project and it also explains the basic components of a battery.

The three subsequent chapters, e.g. 3, 4 and 5, explain how the Li-ion and nickel metal hydrid batteries and the super capacitor work. Here is also a brief historic resume on these energy storages. Chapter six discusses some practical issues on those energy storages. Big parts of these chapters originates from references [5], [10] and [A].

The modeling of batteries and the super capacitor is described in chapter 7 and 8 and in chapter 9 the implementation in Matlab/Simulink and temperature modeling is expounded.

Chapter 10 and 11 describes the lifetime model and the cost model. In chapter 11 there is also a description of the driving cycles and a specification of the vehicles used in the simulation.

The twelfth chapter presents the how the simulations proceeded and the results of them. This chapter contains mostly plots and tables.

Finally, in chapter 13, alternative solutions are discussed. Following this chapter is the references and the appendixes.

1.3 Plugin and powerassist

Hybrid electric vehicles, HEVs, encompass a wide range of different designs with a combustion engine either in parallel, in series or a combination of them both, with a electric drive.

In this thesis there are two complete different hybrid vehicle variants with slightly different control strategies for HEVs considered. One is called *plugin HEV* or PHEV and is intended to be a commuting car that is able to drive 50-100 km on pure electrical propulsion. They are also referred to as the zero emission vehicles, ZEV. The PHEV utilize a large battery pack, which have a large energy density but not so high power density, which can be charged from the power grid when depleted. An option, or complement, to this strategy is to change mode into HEV if the battery runs down during driving. In that case the electric drive is used as power assist for acceleration and to put the combustion engine to a better level of efficiency. This will eventually charge the battery due to its ability to store energy at regenerative braking.

The idea behind this vehicle is that the average person only uses the car for commuting between their home and their place of work. Normally this distance is not more than 10-15 km one way trip, which would yield approximately a medium of 35 km per person per day with shopping, picking up kids etc. included. This number was validated by Statistics Sweden [1] who made an investigation on this in the year of 2002. This investigation says that the average person drives 13150 km per year. With these numbers it would be much likely to develop a car that would have zero emissions at commuting distances, a so called ZEV. Of course this would be very attractive on the market due to the fact that electric energy is more cost-effective than gasoline, e.g. the electric motor reaches much higher efficiency than the combustion engine. To ad is that no emission occurs, which means a more environmental friendly vehicle.

At the moment there is no such vehicle on the market, but some different prototypes have been made. For example the UCDavis (University of California, Davis) have a number of prototypes with different control strategies.

The other hybrid vehicle variant in this thesis is the *mild hybrid* (MHEV). In this configuration the electrical engine is meant to provide the combustion engine with necessary power in order to make the ICE operate on a better point of efficiency.
The car also gets better acceleration due to the fact that an electrical engine provide torque at low speed, when the ICE is relatively weak, and the combination of ICE and electric drive thus provide an significant general improvement in torque, in particular in the lower speed region.
Since the battery pack in a MHEV is not meant for pure electric operation, it is selected with focus on power density rather than energy density. The higher power density is needed to alleviate the ICE power relative to the tractive power, without sacrificing vehicle weight.
The charging of the batteries in the MHEV is done via regenerative braking or when the combustion engine is providing more torque than needed. The residual power is then used to charge the battery.

If the vehicle is designed to be able to be driven pure electrically, the battery may be able to provide an all-electric range of up to maybe 3 km. However, this is not the main aspect of the MHEV topology.

On the market today there are a couple of different MHEVs available; the most common is the Toyota Prius. This car has become popular because of its environmental image and specified low fuel consumption, less than 0.5 litres per 10 km.

1.4 Objective of the thesis

The purpose of this thesis is to examine different energy storage technologies in hybrid cars. Energy storage systems to be evaluated are Li-ion batteries, NiMH batteries and super capacitors. Comparisons are to be made on following points:

- Cost of installation
- Cost of operation during an energy storage lifetime and an assumed drive cycle.

The choice of energy storage should be made for the two different configurations discussed in the previous section, PHEV and MHEV.
The original vehicle in this thesis is the SAAB MHD with somewhat changed specifications in agreement with SAAB Automobile.

To evaluate the different energy storages, state of charge (SOC, percent of energy available in the energy storage) models of the energy storages, lifetime models and estimated cost models are required.

1.5 Limitations

The model of the car is only considering the state of charge of the battery. It doesn’t consider the power available. This thesis is limited to only building the models for the energy storages; but not to deal with vehicle control strategies related to available power.

The batteries and super capacitors are only modeled in series connection. To model parallel cells of the energy storage the model would be much more complex and that it is out of the scope of this project.

Sometimes combinations of different energy storages are desired. For example super capacitors and NiMH could be very good complements to each other due to their differences in performance. This would probably be quite complex to realize and therefore it isn’t even considered in this thesis.

The cost model is limited in that way that the price information from the manufacturer is very vague. This is of course due to the fact that the cost is mostly dependent on the amount of units to be fabricated.

2 Modelling of a cell

When modelling a cell one must first decide which kind of model to work with. In this thesis a model based on an equivalent circuit is considered. In order to build a good model it is necessary to know how the cell in matter works. Therefore a brief historic resume and an insight in the technologies will be given in the following chapters.

2.1 Basic components of a secondary electrochemical cell

The cell basically consists of two electrodes, anode and cathode, and one electrolyte (see Fig 2.1). The anode is the place where the oxidation takes place and electrons are fed out of the cell into the load circuit. The cathode is the electrode where reduction takes place and the electrons from the external load returns to the cell. The electrolyte serves as a path for completing the electrical circuit inside of the cell via transport of ions from one electrode to the other.
When a secondary cell is on charge the negative electrode becomes the cathode and the positive electrode becomes the anode. This change of roles in a secondary cell can make one a bit confused; therefore the electrodes are hereby referred to as either positive or negative electrode [A].

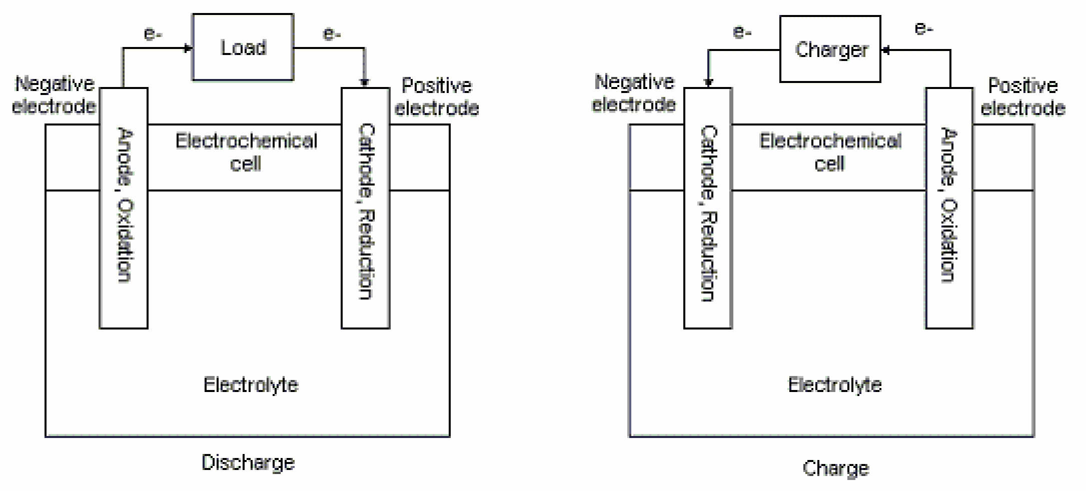


Figure 2.1. A simplified picture of a secondary cell.

Beneath some normally occurring electrochemical terms are stated.

C-Rate - Discharge or charge current, in amperes, expressed in multiples of the rated capacity. For example, C/10 discharge current for a battery rated at 1.5 Ah is 1.5/10 = 150 mA. A cell's capacity is not the same at all discharge rates and usually increases with decreasing rate.

Electrolysis - During the application of the high-charge current, some oxygen is generated due to electrolysis of the electrolyte. The generated oxygen gas accumulates as "bubbles" attached to the cell plates, reducing the effective surface area and raising the internal impedance. This increased impedance reduces charge efficiency and causes heating during rapid charging.
The fact that the electrolyte reduces also enhances the resistance.
This is valid for the NiMH batteries due to its aqueous electrolyte.

Polarization - The lowering of the potential of a cell or electrode from its equilibrium value caused by the passage of an electric current.
Different polarizations are:

- **Ohmic –** this polarization occurs due to the internal impedance of the cell. During charge this impedance contributes to a voltage added to the overall voltage and during discharge it, of course, reduces the overall voltage. This voltage is proportional to the rate of the current flowing through the cell due to Ohm's law. So if a fully charged cell is exposed to a large discharge current the cell voltage can easily drop below 1V (NiMH) and 3V (Li-ion), even though it is almost fully charged. This must be considered when modeling the cell.
- **Concentration –** Concentration polarization is proportional to the surface area of the anode and cathode of the battery. Bigger area of these active plates yields greater reduction in the polarization. This is determined during the development of the battery and cannot be influenced after manufacturing.
- **Activation –** activation polarization refers to the amount of energy that is spent to cause the chemical reaction. At a molecular level temperature has a great effect on the amount of energy it takes to make a reaction emerge.

Diffusion - The movement of chemical species (ions or molecules) under the influence of concentration difference. The species will move from the high concentration area to the low concentration area till the concentration is uniform in the whole phase. Diffusion in solutions is the most important phenomenon in electrochemistry, but diffusion will occur also in gases and solids. The rate of diffusion (diffusional flux) is proportional to the gradient of the concentration in the solution, with the proportionality constant called the "diffusion coefficient".

Further reading on this can be done in reference [2], [3] and [4].

3 The nickel metal hydride cell

Research on the NiMH system started in the 1970s as a means of storing hydrogen for the nickel hydrogen battery. Today, nickel hydrogen is used mainly for satellite applications. Nickel hydrogen batteries are bulky, require high-pressure steel canisters and cost thousands of dollars per cell.

In the early experimental days of NiMH, the metal hydride alloys were unstable in the cell environment and the desired performance characteristics could not be achieved. As a result, the development of NiMH slowed down. New hydride alloys were developed in the 1980s that were stable enough for use in a cell. Since then, nickel-metal hydride has steadily improved.

The success of nickel-metal hydride has been driven by high energy density and the use of environmentally friendly metals. The modern NiMH offers up to 40% higher energy density compared to the standard nickel cadmium. There is potential for yet higher capacities, but not without some negative side effects.

NiMH is less durable than nickel cadmium. Cycling under heavy load and storage at high temperature reduces the service life. NiMH suffers from high self-discharge, which is higher than that of nickel cadmium.

NiMH has been replacing nickel cadmium in markets such as wireless communications and mobile computing. Experts agree that NiMH has greatly improved over the years, but limitations remain. Most shortcomings are native to the nickel based technology and are shared with nickel cadmium. It is widely accepted that NiMH is an interim step to lithium based battery technology.

Here is a summary of the advantages and limitations of NiMH batteries.

Advantages

- 30-40% higher capacity than standard nickel-cadmium. Nickel-metal-hydride has potential for yet higher energy densities.
- Less prone to memory than nickel-cadmium - fewer exercise cycles are required.
- Simple storage and transportation - transport is not subject to regulatory control.
- Environmentally friendly - contains only mild toxins; profitable for recycling.

Limitations

- Limited service life - the performance starts to deteriorate after 200-300 cycles if repeatedly deeply cycled.
- Relatively short storage of three years. Cool temperature and a partial charge slows aging down.
- Limited discharge current - although nickel-metal-hydride is capable of delivering high discharge currents, heavy load reduces the battery's cycle life.
- More complex charge algorithm needed - nickel-metal-hydride generates more heat during charge and requires slightly longer charge times than nickel-

cadmium. Trickle charge settings are critical because the battery cannot absorb overcharge.
- High self-discharge - typically 50% higher than nickel-cadmium.
- Performance degrades if stored at elevated temperatures - nickel-metal-hydride should be stored in a cool place at 40% state-of-charge.
- High maintenance - nickel-metal hydride requires regular full discharge to prevent crystalline formation. nickel-cadmium should be exercised once a month, nickel-metal-hydride once in every 3 months [5].

3.1 Basic operation of NiMH

The basics of the NiMH cell are based on its ability to absorb, release and transfer hydrogen between the electrodes.
The success of NiMH technology comes from their rare earth metal alloys used in the negative electrode, which contributes to larger volume available for the positive electrode. This is the primary reason for higher capacity and longer service life over competing technologies.

NiMH battery is an alkaline battery and it has an aqueous electrolyte (potassium hydroxide, KOH). Rechargeable alkaline batteries are dominant in the market for several technical reasons, such as high electrolyte conductivity (good for high power applications), operation over a wide range of temperature and higher energy density, which results in lower cost per watt-hour.

The electrolyte has a very high conductivity, due to its aqueous solution, and it doesn’t take part in the process to any significant extent. The concentration of the electrolyte remains rather constant over the charge and discharge process. Due to this the resistance of the cell also remains almost constant over the SOC range. This leads to a battery with high power performance and long cycle life.

The NiMH cells active materials are made of metal alloys or metallic oxides that are good conductors in a charged state. The nickel oxide hydroxide electrode exchanges a proton only in the charge-discharge process and the electron transfer is very quick. This corresponds to a high power capacity. The small change in size of the electrode during charge and discharge also results in greater mechanical stability and therefore longer cycle life.

3.2 Charge and discharge reaction

The first thing that happens in the charging reaction is that the positive electrode releases hydrogen into the electrolyte (see Fig 3.1). The hydrogen is then absorbed and stored in the negative electrode. The reaction begins when the nickel hydroxide ($Ni(OH)_2$) in the positive electrode and hydroxide (OH^-) from the electrolyte combine. This produces nickel oxyhydroxide (NiOOH) within the positive electrode, water (H_2O) from the electrolyte and one free electron (e^-). At the negative electrode the metal alloy (M) in the negative electrode, water (H_2O) from the electrolyte and an electron (e^-) reacts to produce metal hydride (MH) in the negative electrode and hydroxide (OH^-) in the electrolyte.

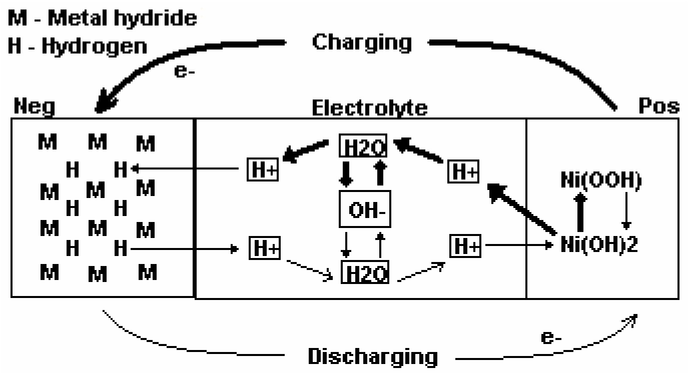


Figure 3.1. Principle drawing of the charge/discharge reaction of a NiMH cell.

The discharge reaction is the opposite of the charge reaction. Hydrogen stored in the metal alloy of the negative electrode is released into the electrolyte to produce water. This water then releases a hydrogen ion that is absorbed into the positive electrode to form nickel hydroxide.
The process of moving hydrogen from the negative to the positive electrode absorbs heat and is therefore endothermic. Heat continues to be absorbed until the cell reaches a state of overdischarge, where a secondary reaction occurs within the cell resulting in a rise of temperature.

3.3 Electrodes

The active material in the negative electrode is hydrogen, the same as in NiH batteries, except that the protons (hydrogen ions) are stored in the metal hydride structure that also serves as the electrode. The metal hydride is very efficient as hydrogen storage, resulting in better volumetric efficiency than liquid hydrogen.
The reaction for the negative electrode can be written as:

$$M + H_2O + e^- \underset{discharge}{\overset{charge}{\rightleftarrows}} MH + OH^-$$

Where M is the metal hydride material.

Since the positive electrode in NiMH and NiCd is the same (nickel hydroxide) this is a very well developed material for electrodes. The fact that the NiMH cell is a nickel-based alkaline battery contributes to fabrication of very large surface areas, which in turn yields high capacities and current densities. This makes this technology very popular. The conductivity stays at a high level on trough the whole capacity of the battery because of that the electrolyte is not a part of the electrode reaction. In addition the active nickel material is unsolvable in the KOH electrolyte, leading to a longer life and better mistreatment acceptance. Only a proton is involved in the charge-discharge reaction leading to a very small change in density and improved mechanically stability of the electrode during cycling.
The simplified nickel electrode reaction for the cell is:

$$Ni(OH)_2 + OH^- \underset{discharge}{\overset{charge}{\rightleftarrows}} NiOOH + H_2O + e^-$$

3.4 Complete cell reaction

The combined cell reaction can be written as

$$M + Ni(OH)_2 \underset{discharge}{\overset{charge}{\rightleftarrows}} MH + NiOOH$$

In figure 3.2 one can see the overall chemical reaction of a NiMH cell.

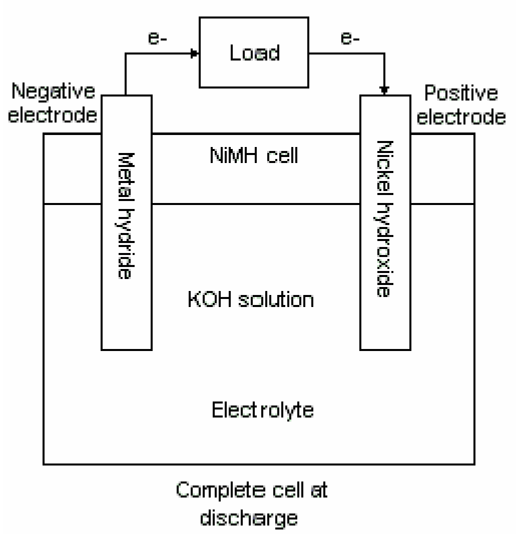


Figure 3.2. Overall chemical reaction.

3.5 Overcharge and overdischarge

The NiMH cell has an oxygen cycle for overcharge. Oxygen cycle means that there is oxygen produced when the battery is overcharged.

Oxygen cycle (overcharge):

$$\begin{array}{ll} positive\,electrode & 4 \cdot OH^- \Rightarrow 2 \cdot H_2O + O_2 + 4 \cdot e^- \\ negative\,electrode & 2 \cdot H_2O + O_2 + 4 \cdot e^- \Rightarrow 4 \cdot OH^- \end{array}$$

Overcharging occurs when the positive electrode no longer has any nickel hydroxide to react with the hydroxide from the electrolyte and when it begins to evolve oxygen. The oxygen diffuses through the separator where the negative electrode recombines the oxygen with stored hydrogen to form excess water in the electrolyte. If the oxygen-recombination occurs at a slower rate than the rate at which oxygen is evolved from the positive electrode, the result is a buildup of excess oxygen (gas), resulting in an increase in pressure inside the cell. Due to this NiMH cells are constructed with a negative electrode that has greater capacity (more active material) than the positive electrode.

The NiMH cell has a hydrogen cycle for overdischarge. Hydrogen cycle means that there is hydrogen produced when the cell is overdischarged.

Hydrogen cycle (overdischarge):

$$\begin{aligned} &\textit{positive electrode} \quad 2 \cdot H_2O + 2 \cdot e^- \Rightarrow H_2 + 2 \cdot OH^- \\ &\textit{negative electrode} \quad H_2 + 2 \cdot OH^- \Rightarrow 2 \cdot H_2O + 2 \cdot e^- \end{aligned}$$

There are two stages when overdischarging a NiMH cell. The first stage involves the active material of the positive electrode becoming fully depleted and the generation of hydrogen gas begins. Since the negative electrode has more active material (MH), it has the ability to absorb some of the hydrogen gas evolved by the positive electrode. Any hydrogen not absorbed by the negative electrode begins to build up a pressure in the cell. The second stage begins when the entire negative electrode is fully depleted of active material. Once both electrodes are fully depleted the negative electrode absorbs oxygen contributing to the loss if useable capacity.

Extreme overdischarge of a NiMH cell results in excessive gassing of the electrodes resulting in permanent damage in two forms. First, the negative electrode is reduced in storage capacity when oxygen permanently occupies a hydrogen storage site, and second, excess hydrogen is released through the safety vent reducing the amount of hydrogen inside the cell. To protect against damaging effects of overdischarging, proper end of discharge terminations must be used.

In these two cycles (overcharge and overdischarge) heat and gas is produced. This contributes to increasing pressure inside the cell. If the pressure becomes too high inside the cell then the gas need to be let out in some way. This is done via a safety vent that opens when the pressure is too high.

3.6 Self discharge

A factor in the short-term self-discharge is the energy used by the oxygen cycle at high SOC. This causal is normally insignificant at SOC below 70%. The long-term self-discharge is caused by the ion flow which continuously discharge the cell over a long period. The flow rate depends on the temperature of the cell, higher temperature yields higher self-discharge rate.
The long-term self-discharge at storage can be seen in figure 3.3 below.

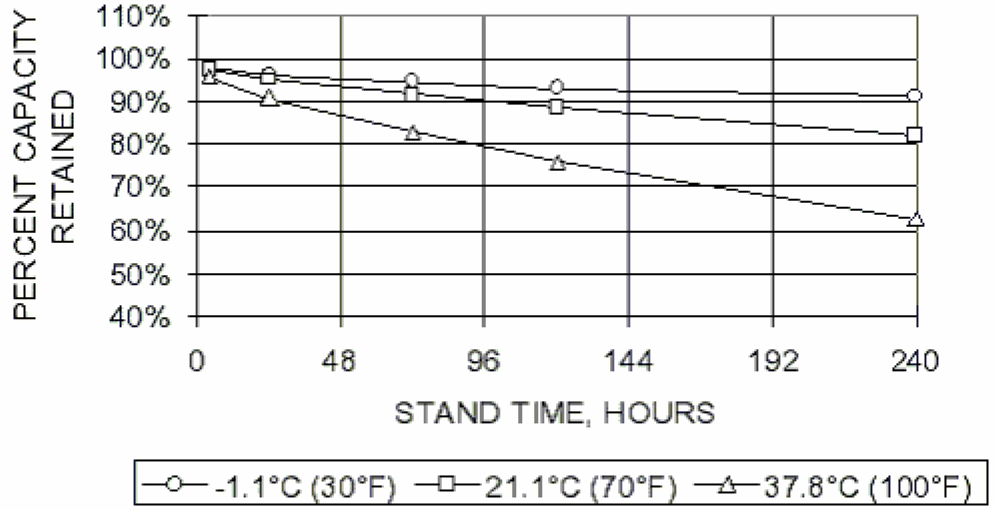


Figure 3.3. The discharge rate of NiMH cells at different temperatures.

4 The lithium ion cell

Pioneer work with the lithium battery began in 1912 under G.N. Lewis but it was not until the early 1970s when the first non-rechargeable lithium batteries became commercially available. Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the largest energy density for weight.

Attempts to develop rechargeable lithium batteries failed due to safety problems. Because of the inherent instability of lithium metal, especially during charging, research shifted to a non-metallic lithium battery using Li-ions. Although slightly lower in energy density than lithium metal, lithium-ion is safe, provided certain precautions are met when charging and discharging. In 1991, the Sony Corporation commercialized the first lithium-ion battery. Other manufacturers followed suit.

The energy density of lithium-ion is typically twice that of the standard nickel-cadmium. There is potential for higher energy densities. The load characteristics are reasonably good and behave similarly to nickel-cadmium in terms of discharge. The high cell voltage of 3.6 volts allows battery pack designs with only one third of the required amount with a nickel-based (1.2 volts per cell).

Lithium-ion is a low maintenance battery, an advantage that most other chemistries cannot claim. There is no memory and no scheduled cycling is required to prolong the battery's life. In addition, the self-discharge is less than half compared to nickel-cadmium, making lithium-ion well suited for modern fuel gauge applications. Lithium-ion cells cause little harm when disposed.

Despite its overall advantages, lithium-ion has its drawbacks. It is fragile and requires a protection circuit to maintain safe operation. Built into each pack, the protection circuit limits the peak voltage of each cell during charge and prevents the cell voltage from dropping too low on discharge. In addition, the cell temperature is monitored to prevent temperature extremes.

Aging is a concern with most lithium-ion batteries and many manufacturers remain silent about this issue. Some capacity deterioration is noticeable after one year, whether the battery is in use or not. It should be noted that other chemistries also have age-related degenerative effects. This is especially true for nickel-metal-hydride if exposed to high ambient temperatures.
Manufacturers are constantly improving lithium-ion. New and enhanced chemical combinations are introduced every six months or so. With such rapid progress, it is difficult to assess how well the revised battery will age.

Storage in a cool place slows the aging process of lithium-ion (and other chemistries). Manufacturers recommend storage temperatures of 15°C. In addition, the battery should be partially charged during storage. The manufacturer recommends a 40% charge.

Advantages

- High energy density - potential for yet higher capacities.
- High coulombic and energy efficiency.

- No memory effect.
- Relatively low self-discharge - self-discharge is less than half that of nickel-based batteries.
- Low Maintenance - no periodic discharge is needed; there is no memory.

Limitations

- Requires protection circuit to maintain voltage and current within safe limits.
- Subject to aging at high temperatures, even if not in use - storing the battery in a cool place and at 40% charge reduces the aging effect.
- Transportation restrictions - shipment of larger quantities may be subject to regulatory control. This restriction does not apply to personal carry-on batteries.
- Expensive to manufacture - about 40 percent higher in cost than nickel-cadmium.
- Not fully mature - metals and chemicals are changing on a continuing basis [5].

4.1 Basic operation of the Li-ion cell

The discovery that lithium forms intercalation compounds with certain types of graphite was decisive for the development of rechargeable batteries with lithium electrodes.

The main feature of Li-ion cells is that current is carried by lithium ions, from the positive electrode to the negative electrode during charging, and from negative to positive during discharging. The ions are small and reside within the crystal structure of the electrode materials.

The cell uses something called intercalation and de-intercalation to store the ions in its layered grid while electrons are being absorbed and released at the same time. Concisely this intercalation is the ability of the carbon to absorb and emit ions and electrons. This method is also called the “rocking chair” method, due to that the ions moves from the positive electrode to the negative electrode and back again in the charge-discharge cycle.

The ion is formally discharged, but no defined chemical combining occurs.

Lithium is the alkaline metal with the smallest molecular weight and is found at the negative end of the electrochemical voltage scale with a standard potential equilibrium of -3.045V. For that reason lithium as a material for negative electrodes allows for a particularly high storage capacity. The disadvantages are:

- that lithium cannot be combined with aqueous electrolytes. High-impedance organic electrolytes or molten salts must be used instead,
- that the lithium-ions formed during the electron reaction are highly soluble.

Thus, an electrode of lithium metal is completely dissolved during discharge. As a result the electrode structure is lost and the initial structure cannot be re-established when the electrode is recharged. Furthermore, lithium dendrites can grow during charging and cause short circuits. Both effects reduce the cycle stability dramatically.

For this reason, lithium is used as a metallic electrode predominantly in primary (e.g. not rechargeable batteries) batteries with organic electrolytes.

In secondary cells (rechargeable ones) metallic lithium is not used to prevent this growth of dendrites that reduces the cell life due to internal short circuit. Instead a highly crystallized carbon is used. In addition chemical stability of this carbon node even when the cell is fully charged is higher than for metallic lithium.

4.2 Charge and discharge reaction

During charge lithium in the positive electrode is ionized (Li^+) and moves through the organic solution electrolyte to the negative electrode (see Fig 4.1). This ion is then intercalated into the highly crystallized carbon (graphite or coke). In this process there is also an electron (e^-) released from the positive electrode that is transferred to the negative side via the load. When these chemical species are intercalated into the carbon the negative electrode looks like this, Li_xC_6.

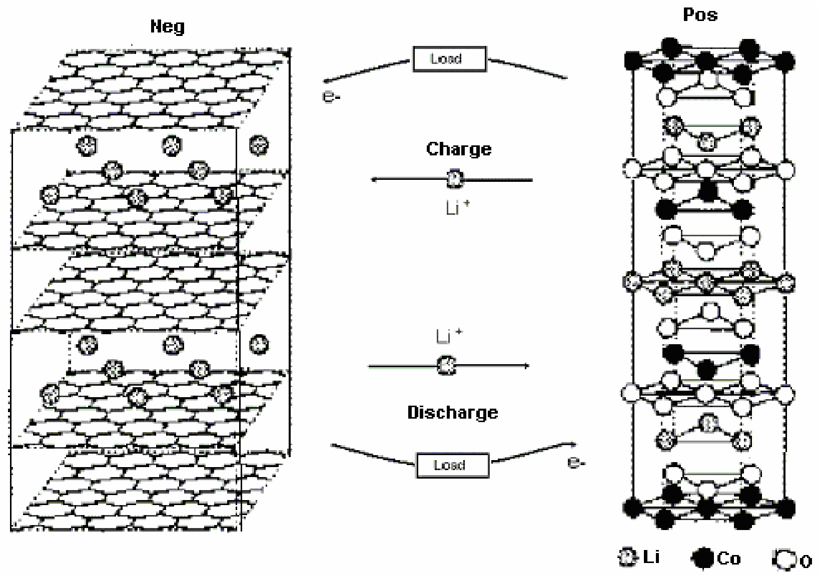


Figure 4.1. Principle drawing of the charge/discharge reaction of a Li-ion cell.

The discharge reaction is the opposite of the charge reaction (see Fig 4.1). The intercalated lithium ion in the negative electrode and the electron, which transfers via the load, returns to the positive electrode. The process when the carbon releases the ion is called de-intercalation.

The fact that there is no real chemical reaction occurring in the cell results in no essential change in the anode or cathode.

4.3 Electrodes and electrolyte

As said before the negative electrode is made of carbon in order to achieve higher energy density and safety. This carbon material must be able to have a large lithium storage capability. Such material is a highly crystallized carbon such as graphite or an unstructured carbon like coke. The biggest difference between coke and graphite is their charge and discharge characteristics (see Fig 4.2).

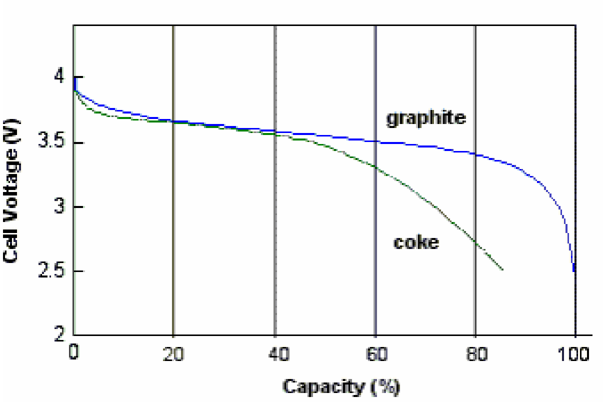


Figure 4.2. Difference between different materials in the negative electrode.

Absorption and release of the lithium-ions (Li^+) corresponds to the reaction:

$$\text{Negative electrode} \quad x \cdot Li^{+} + x \cdot e^{-} + C_{6} \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_{x}C_{6}$$

which means that per six carbon atoms (C_6), x lithium-ions are absorbed, where x can reach values of around zero. Absorption of lithium means charging, and release of lithium-ion means discharging of this negative electrode. During these reactions the electrode potential remains fairly constant.

The materials used in the positive electrode in a Li-ion cell must be capable of de-intercalate lithium ions during charge and intercalate the ions during discharge. Materials that are known to be capable of doing this are lithium oxide in alloy either with cobalt, manganese or nickel. Lithium cobaltite ($LiCoO_2$) is mainly used in the open market.
The charge/discharge equation of the positive electrode composed with manganese is:

$$\text{Positive electrode} \quad LiMn_{2}O_{4} \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_{1-x}Mn_{2}O_{4} + x \cdot e^{-} + x \cdot Li^{+}.$$

One can also use lithium cobaltite ($LiCoO_2$) in the positive electrode, and then the equation would look like this:

$$\text{Positive electrode} \quad LiCoO_{2} \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_{1-x}CoO_{2} + x \cdot e^{-} + x \cdot Li^{+}.$$

Here absorption of lithium ions means discharging of the active mass, while lithium-ions are released during charging.

The electrolyte is the part of the cell that enables the flow of lithium ions. In the NiMH cell an aqueous solution was used, but in the Li-ion cell the voltages are higher, usually above 4V. This would cause electrolysis of the water in the solution. Therefore Li-ion uses an electrolyte made of high-impedance organics or molten salts. The solvent is required to satisfy the following characteristics:

- High conductivity of Li-ion
- Electrochemical stability over 4V
- Chemical and thermal stability
- Wide temperature range.

Because of the high voltages only a few types of solvents are appropriate.

4.4 Complete cell reaction

The complete cell reaction can be written as

$$LiCoO_2 + C_6 \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_{1-x}CoO_2 + C_6Li_x$$

In figure 4.3 one can see the overall chemical reaction of a Li-ion cell.

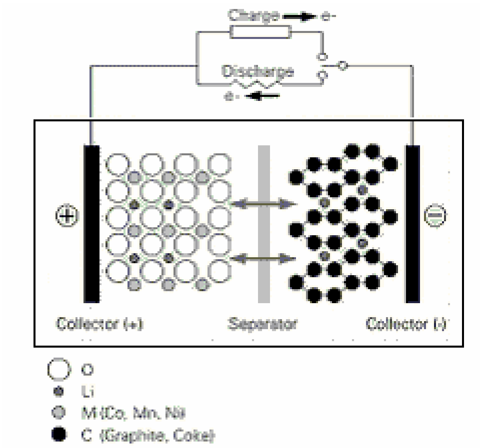


Figure 4.3. The complete cell reaction of a Li-ion cell.

4.5 Overcharge and overdischarge

As said before there is no real chemical reaction in the charge-discharge cycle as in the NiMH cell. The ions are only transferred back and forth. This yields an, almost, 100% charge-discharge efficiency of the Li-ion cell. This is not only a good thing; because of this it is very easy to overcharge and overdischarge the cell if the control circuit isn't properly developed. If the Li-ion cell is discharged below 2V it will degrade and it may vent when overcharged, as they don't have a chemical mechanism to manage overcharge unlike aqueous cell chemistries.

4.6 Self discharge

The self-discharge rate in a Li-ion cell is, as you can see in figure 4.4, very low compared to a NiMH cell. Self-discharge is a natural phenomenon of a chemical system. Similar to a spring under tension, a battery wants to return to a state of rest or revert to the lowest form of energy. Self-discharge is not a manufacturing fault per se, although poor manufacturing practices and improper use can accelerate this phenomenon.

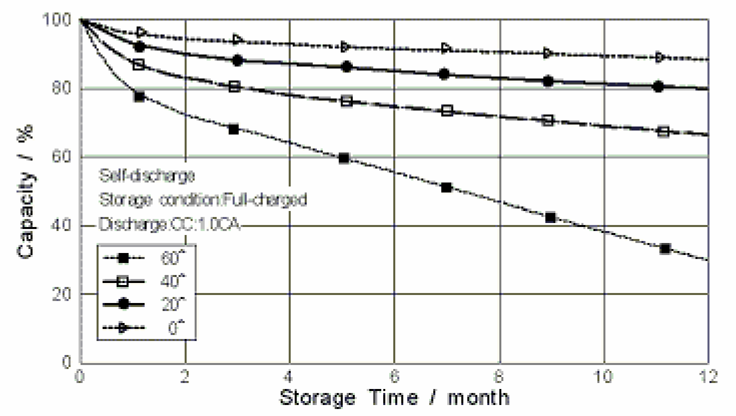


Figure 4.4. The discharge rate of Li-ion cells at different temperatures.

If both electrodes are combined in a cell during charging and discharging only the lithium-ions are absorbed and released and migrate between the electrodes. The host grids of carbon and manganese oxide essentially remain unaltered (when the lithium-ions are absorbed, there is a small increase in volume). Thus the above-mentioned difficulties related to the solubility of lithium compounds no longer apply, and the system can perform a great number of cycles. A further advantage is the comparatively high cell voltage of approx. 3.6 V. Consequently, one cell of this system can be used instead of three cells of the nickel-cadmium or the nickel-hydride system.

The lithium-ion battery is a powerful system that reaches 120 Wh/kg and 270 Wh/l and has the advantage that it operates at room temperature. At present, use of this battery system in the form of small cylindrical cells is fast increasing, due to its high energy content at a low weight. Its main applications are cellular phones, computer and camcorders. Large cells for electric vehicle applications with capacities up to 60 Ah have been developed and are being built as prototypes, for example, in the Varta R&D Center at Kelkheim. Field trials in vehicles will commence shortly [6].

5 Energy density capacitors

Although the theory behind the EC capacitor has been known for over 100 years, it was not until the 1960s that SOHIO developed a functional energy storage device. NEC developed the first successful product for the memory back-up market in the late 1970s. In the 1990s the technology scaled up and commercialized targeting pulse power applications, engine starting applications, and specialty energy storage applications.

Super capacitors have an excellent power density, sometimes up to 100 times more than some batteries. Load characteristics are also very good with an efficiency of almost 100% compared with some batteries that only have 50-60%. The fact that they have pretty low energy density, up to 300 times less than some batteries, limits their use in HEVs to instant power assist.

Aging is not an issue for the super capacitor. Provided that it is not subjected to overvoltages, too large currents and too high temperatures its lifetime can be up to almost 80 years. It is also possible to deep cycle it more than 500000 times.
When storing the super capacitor it is recommended to keep it in a cold place due to its high self discharge rate.

Advantages

- Virtually unlimited cycle life - can be cycled millions of times.
- Low impedance - enhances load handling when put in paralleled with a battery.
- Rapid charging - super capacitors charge in seconds.
- Simple charge methods - no full-charge detection is needed; no danger of overcharge except lifetime deterioration.

Limitations

- Linear discharge voltage prevents use of the full energy spectrum.
- Low energy density - typically holds one-fifth to one-tenth the energy of an electrochemical battery.
- Unable to use its entire energy spectrum.
- Cells have low voltages - serial connections are needed to obtain higher voltages. Voltage balancing is required if more than three capacitors are connected in series.
- High self-discharge - the rate is considerably higher than that of an electrochemical battery. [5]

In HEV applications, a super capacitor unit will have a voltage of 200-400 V, this resulting in many cells in series and parallel. Therefore it is important that there are not too big variations between the cells. Otherwise the maximum voltage of the unit must be significantly reduced to prevent over voltage of individual cells due to their lower capacitance or higher resistance. This results in energy losses due to equation 5.1. Therefore quality control in the fabrication of super capacitors is extremely important [G]. It's possible to solve this problem if we are using a so-called active balancing circuit [H], but this result in a heavy capacity pack.

5.1 Basic operation of the super capacitor

Capacitors store energy by charge separation. This energy is given by

$$E = \frac{C * V^2}{2} \tag{5.1}$$

Where C is its capacitance (Farads) and V is the voltage between the terminal plates. The breakdown characteristics of the dielectric material determine the maximum voltage of the capacitor. CV gives the charge Q (coulombs) stored in the capacitor. The capacitance of the dielectric capacitor depends on the dielectric constant (*K)* and the thickness (th) of the dielectric material and its geometric area (*A).*

$$C = \frac{K * A}{th} \tag{5.2}$$

A super capacitor, sometimes referred as an electrochemical capacitor, is an electrical energy storage device that is constructed much like a battery. They utilize two electrodes immersed in an electrolyte with a separator between the electrodes. The electrodes are fabricated from high surface area, porous material having pores of diameter in the nanometer (nm) range. The surface area of the electrode materials (BET surface area) used in super capacitors, 500–2000 m^2/g, is much greater than that used in battery electrodes being below 50 m^2/g. Charge is stored in the micro pores at or near the interface between the solid electrode material and the electrolyte. Calculation of the super capacitors capacitance is much more difficult as it depends on complex phenomena occurring in the micro pores of the electrode. There are many sorts of super capacitor technologies; some examples are carbon double-layer capacitors, utilizing pseudo-capacitance capacitors, metal oxide capacitors, conducting polymer capacitors and hybrid capacitors.
In figure 5.1 one can see a schematic of a double layer super capacitor.

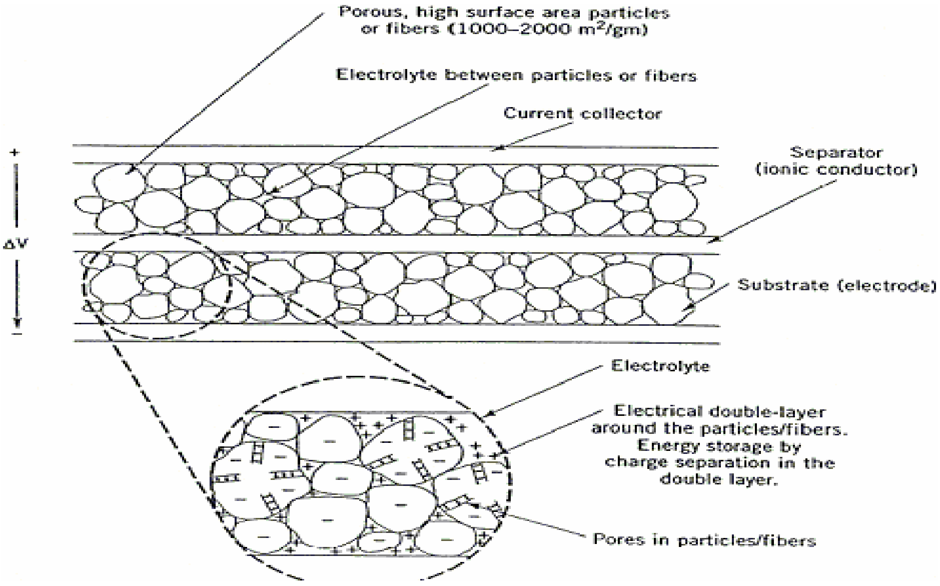


Figure 5.1. Schematic of a double-layer super capacitor.

5.2 Charge and discharge reaction

During charging the electrolyte anions and cations are drawn to electrodes of opposite polarity (see Fig 5.2) where they accumulate into layers inside the activated carbon pores with a distribution governed by pore size. When charging, the electrolyte becomes depleted of ions.

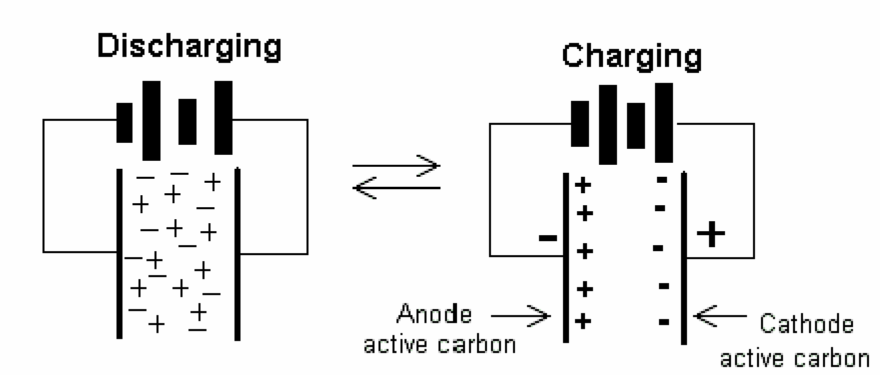


Figure 5.2. Distribution of cations and anions in the capacitor.

5.3 Electrodes and electrolyte

Various materials are proposed as electrodes and electrolytes. To increase the surface area of the electrodes and thus the energy density of the capacitor, the electrodes are made from materials such as activated carbon. In the sulphuric acid electrolyte system, activated carbon is used for the electrode material. In the organic electrolyte system, activated carbon or activated carbon fibre is used for the electrode material. Organic electrolyte systems are favourable because of keeping its decomposition voltage high.

DLC's with organic electrolytes have voltage ratings of <3.0 V per cell whereas with aqueous electrolytes the voltage rating drops to <1.23 V per cell, typically 0.9 V. In all DLC's the terminal capacitance consists of the series combination of an anode DLC and the cathode DLC, so the net rated voltage is twice the value of the electrolyte decomposition voltage. Organic electrolyte DLC's have higher decomposition voltages and higher specific energy but higher resistance than aqueous types. The low conductivity of the organic electrolyte DLC results in higher ESR.

5.4 Overcharge and overdischarge

The super capacitor cannot be overdischarge by reason of that it can operate linearly in its entire voltage range, but when it comes to overcharging it must be protected. If it is charged with a voltage level above its maximum rated voltage it is damaged and its lifetime shortens dramatically. Besides that the lifetime is reduced gas can be generated by the electrochemical reactions inside the capacitor and this may cause it to leak or rupture.

5.5 Self discharge

The self-discharge rate of a super capacitor is, as you can see in figure 5.3, quite high compared to electrochemical batteries.

Super capacitors with an organic electrolyte are affected the most. In 30 to 40 days, the capacity decreases from full charge to 50 percent.

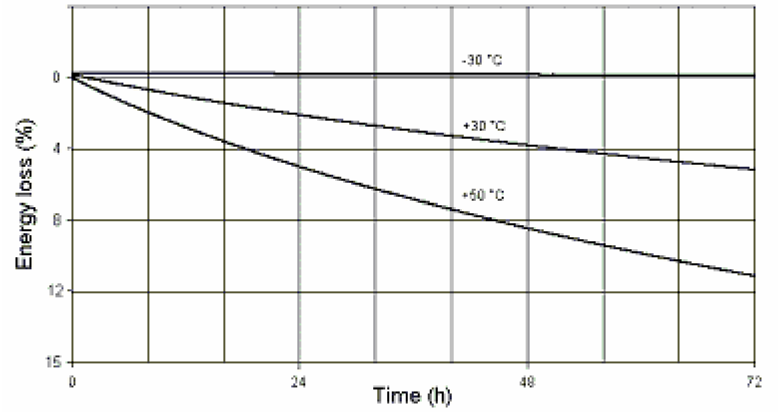


Figure 5.3. The self discharge rate of super capacitors at different temperatures.

The data in figure 5.3 is from a double layer capacitor with symmetric carbon electrodes and with an organic electrolyte rated at 3600F.

The reason why super capacitors have a higher self discharge rate than batteries is because of the fact that the super capacitors larger BET surface area favours oxidation of the electrolyte. This means that there is a larger leakage current in the super capacitor than in batteries [B].

6 Practical issues

When utilizing an energy storage, in any application, one must consider some practical issues in order to not to shorten the lifetime of the cell or damage it. Because of the physical differences there are diverse things to consider for batteries and super capacitors.

6.1 Batteries

If the cell is overcharged or over discharged it can suffer from severe damage. Also the temperature must stay in certain regions, normally between –40 to 60 °C, therefore it is not applicable to discharge or charge it with to high currents (during a long time) and there must be an excellent cooling system.

The voltage of the cell also has to be observed. If the voltage across the cell during charge respectively discharge is too high respectively too low it is most likely damaged and thus its lifetime is shortened. The maximum and minimum voltages for Li-ion and NiMH are normally around 3 respectively 4 volts and 0.8 respectively 1.6 volts

When charging the batteries there are some different strategies to follow such as pulse discharge and the constant current/constant voltage method. These methods are designed in order not to exceed the maximum voltage of the cell, but there is no room for further explanation on these methods in this thesis. In stead the reader are referred to the manufacturer who can provide the best information on how their batteries are to be charged for best performance.

In a MHEV the SOC of a cell is best suited beneath 80%. After this limit the voltage tends to overshoot due to the steepness of the cell voltage vs. SOC curve, and the consequences can be a damaged battery. The lower limit of the SOC is a little bit more vague for the MHEV. Beneath 20% SOC is not to consider by reason of the same fact as for the upper limit, but in a MHEV you normally don’t want to cycle the battery this far. This would only cause a lower lifetime of the battery and nothing else, in stead it is more suitable to decide how much the battery should be cycled, let’s say 20% as an example. This yields a maximum reference value of 65-70% SOC.

6.2 Super capacitors

The capacitor may not be charged with voltages above its rated maximum voltage, normally 2.5V. However it can’t be either over discharged or overcharged due to the fact that it may operate in its entire range of voltage without being damaged. Normally it isn’t applicable to operate it below half the maximum voltage. This is because of that the energy of the capacitor is then reduced to a fourth of its capacity, and the voltage of the system might be to low for the electric parts in the drive system of the MHEV to operate properly.

As for the batteries one need a cooling system in order not to exceed the temperature limit, which normally is about the same as for batteries.

Due to the fact that the super capacitor has quite low energy density and very high power density it is only considered in the MHEV. As said before the state of charge can be practically operated between 25% and 100% SOC. The fact that super capacitors almost have 100% efficiency yields a normally used reference value at 60% SOC.

7 Thevenin battery model

A commonly used battery model is the Thevenin equivalent circuit [C]. As one can see in figure 7.1 it consists of an ideal no-load voltage (Eo), internal resistance (R), an overvoltage resistance Ro and Co. Co represents the capacitance of the parallel plates. Ro represents the non-linear resistance contributed by the contact resistance of plate to electrolyte.

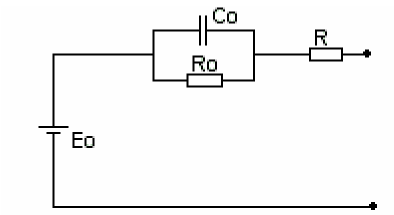


Figure 7.1. The Thevenin battery model.

The main disadvantage of this model is that all values are assumed to be constants, but in real life they vary with many things such as SOC and temperature.

7.1 Extended Thevenin models

It is possible to extend the Thevenin battery model to a more complex model, which represents other phenomena to. In the figure below some different models are illustrated. The first one could be e good model of a Li-ion cell, while the ones with Rp is more valid for NiMH. Complete explanations of the components are stated beneath figure 7.2.

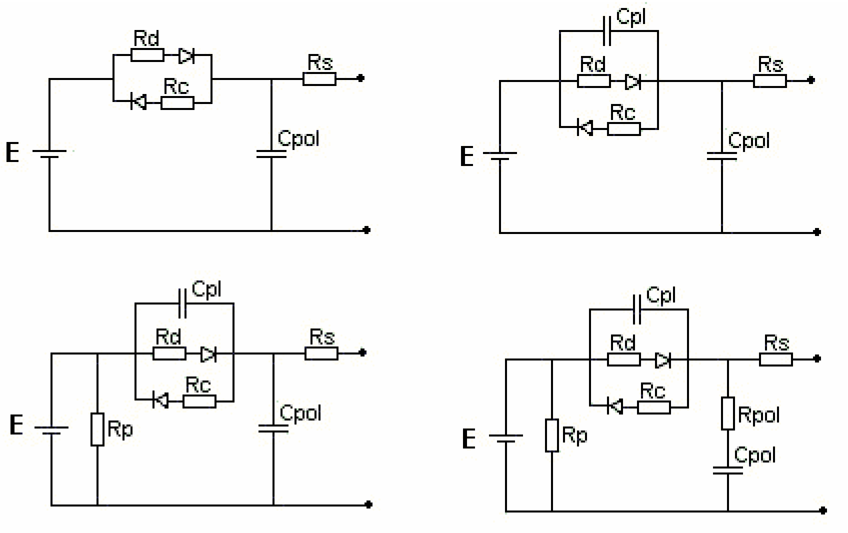


Figure 7.2. Different extended Thevenin models.

- Cpl represents the capacitance of the parallel plates (necessary at high rates)
- Rd represents the series resistance when discharging the cell
- Rc represents the series resistance when charging the cell
- Rs represents the overcharge/discharge resistance
- E represents the open source voltage (Voc) of the cell
- Rp represents the selfdischarging resistance of the cell
- Cpol represents the polarization capacitance of the cell (due to diffusion)
- Rpol represents the polarization resistance of the cell

Rp takes into account the resistance of the electrolysis of the aqueous liquid in the electrolyte at high voltages. It also represents the small leakage across the cell terminal at low voltages.

Rd and **Rc** are associated with electrolyte resistance, plates resistance and fluid resistance, those can differ in charge and discharge mode.

Rs will change significantly due to the electrolyte diffusion in overcharge or over discharge. Varies in charge and discharge mode [C].

7.2 Battery model

The model in this thesis is decided to be similar for both Li-ion and for NiMH but with different values of the components. This is possible due to that this model models the most relevant features of the batteries such as diffusion and polarization. It is also assumed that the state of charge should be held between 20% and 80% where these batteries are quite linear.
Figure 7.3 illustrates the equivalent circuit of the model.

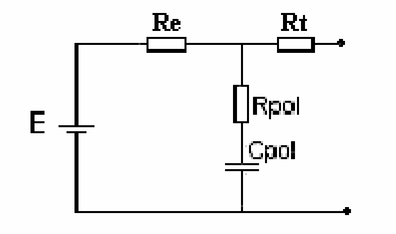


Figure 7.3. Battery model.

This model is implemented with blocks in Matlab/Simlink. It could also be done with an s-function in order to make it more flexible e.g. make it easier to change the equivalent circuit to a different one and to have multiple input/output ports.
The drawback with this model is that it doesn't take into account all the specific electrochemical features of the batteries but only the most common ones. For example it doesn't models the hysterisis effects of the batteries. This is more essential in the NiMH technology, but also noticeable in Li-ion, especially at low temperatures. The hysterisis effect of the batteries is shown in figure 7.4.

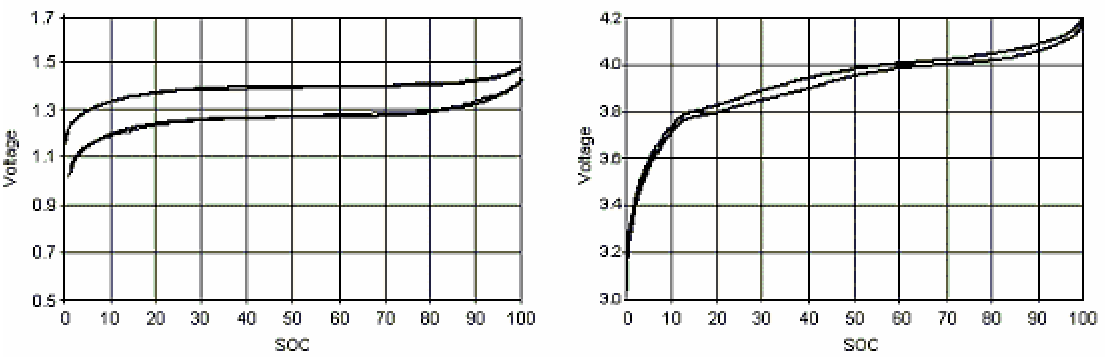


Figure 7.4. Charge and discharge curves for NiMH (to the left) and Li-ion (to the right).

This effect shouldn't be very hard to implement in the model, it is only to use one resistor for charge and another for discharge. The problem is to find the values of the

components. Fitting a curve by the “cut-and-try” principle could do it. However this isn't very accurate for different conditions. It is much better with values that are tested and measured at different SOC and temperatures.
This is a big problem when modelling a chemical cell because all suppliers are very cautious with whom they are sharing their information. This is probably because of that the battery market is in a research era right now. Therefore it is very seldom that they supply any other than their customer with data of the battery (and sometimes not even them). To find out which values to use it is therefore suitable to find a research paper or a publication in which a similar model is used. Saft developed a model for PSpice, which are similar to the model presented in this thesis. This model was converted into a state space model in order to implement it into a vehicle simulation program called Advisor.

7.2.1 High power and high energy battery

Of course there is physical differences between high power batteries, HP, and high energy batteries, HE. These differences must be considered when modelling the cell.

In a HP the size of the electrodes is smaller, e.g. thinner, which results in higher currents and less voltage drop due to its smaller internal resistance. There will also be less diffusion than in the HE e.g. smaller distances to travel in the battery means smaller concentration gradients.

In HE one wants higher energy and this yields smaller currents for a longer period of time, and therefore the size of the electrodes is increased. This results in higher internal resistance and a larger voltage drop during load. The species in the cell have to travel further in the electrolyte to utilize the entire battery electrode and therefore one will have more problems with diffusion in HE.

These differences in HP and HE will result in different charge/discharge curves. The difference in the output voltage during a pulse discharge for a Li-ion cell is illustrated in figure 7.5.

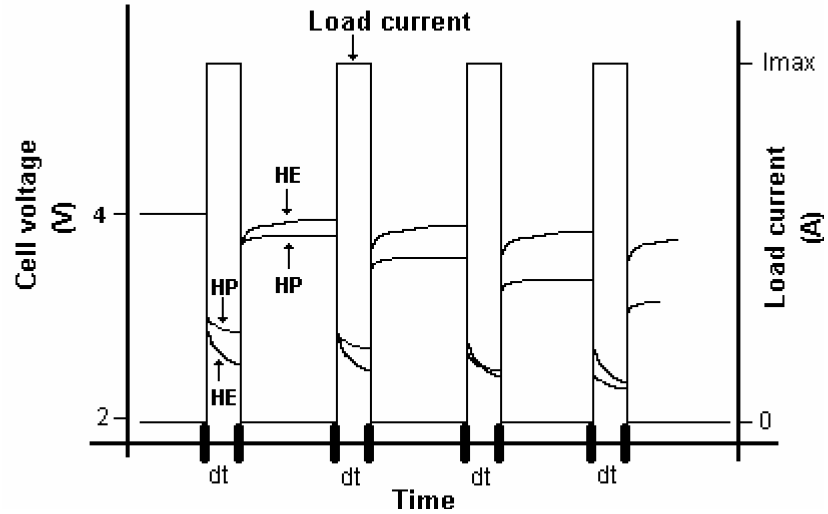


Figure 7.5. Difference in voltage between HE and HP Li-ion cell.

7.3 Battery model parameters

The first parameters were taken from the Advisor battery rc-models. Those were values generated for the high power cells, and weren't applicable for the high energy cells. Therefore a different way to determine the coefficients was desired.
A way of doing it is the following. A pulse discharge current applied to the terminals of the cell generates, off course, an output voltage in pulse format (see Fig 7.6).

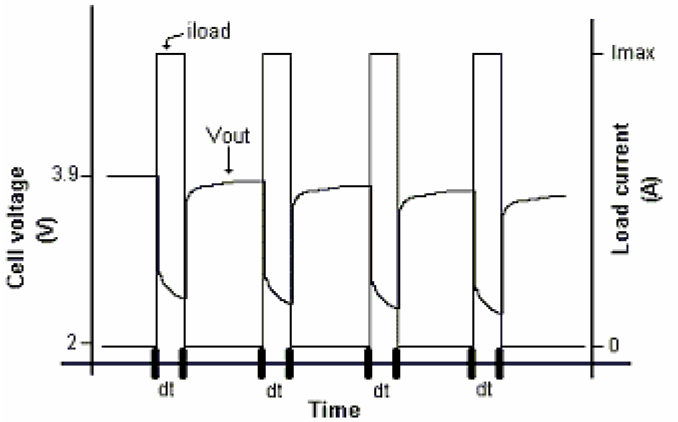


Figure 7.6. Pulse discharge of a chemical cell.

From this discharge curve it is possible to determine the bulk resistance of the cell. The next problem is to split up this resistance into the three resistances in our model. In order to do this a relation between the coefficients in the original Pspice model was considered. Trying to find a relation in the Advisor models yielded the same relative between the resistances as in the Pspice model. Due to this the same relation is used for the model in this thesis.
Finding the time constant, tau, for the RC circuit in non-load mode (see Fig 7.7), derives the capacitor Cpol.

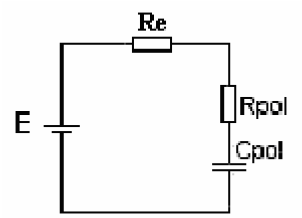


Figure 7.7. The battery model in non-load mode.

These calculations can be found in Appendix C.

8 Super capacitor model

The equivalent circuit used for conventional capacitors can also be applied to super capacitors. The original form of the equivalent circuit, in the Simulink model, is a first order model (see Fig 8.1). It’s comprised of four ideal circuit elements, the internal capacitance C, a series resistor Rs (ESR), the parallel resistance Rp and L. ESR contributes to energy loss during capacitor charging and discharging. Rp simulates the energy loss due to capacitor self discharge. The last component, a small inductor L results primarily from the physical construction of the super capacitor.

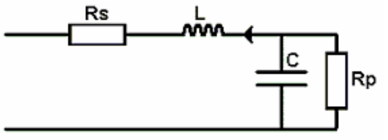


Figure 8.1. A first order model for capacitors.

It’s possible to neglect the resistor Rp because of that the times that the simulations are run is quite small compared to the self discharge time. The car application is only in use of dc from the super capacitor, thus currents charging and discharging the super capacitor are only dc, which makes it possible to neglect the inductor L. This results in the equivalent circuit in figure 8.2.

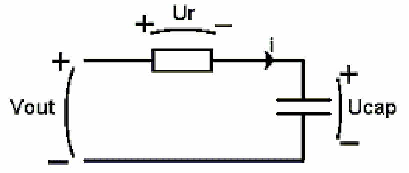


Figure 8.2. A first order model there Rp and L are neglected.

9 Implementation in Matlab/Simulink

To implement the energy storages in Simulink, it's possible to use Simulinks state-space block, but there is no possibility to have more than one output in this block. Instead the models are implemented in Matlab/Simulink as s-functions. This way was chosen due to its capability to cope with several input/outputs, which can change with time. This way also makes it easier to follow the calculations and it is also easy to ad additional inputs and outputs if desired. For example quantities as energy, power, power losses etc. can be added in the same block (see Fig 9.1). This calculations is done with help of the input quantities of the packages current, resistance, capacitance and the max voltage

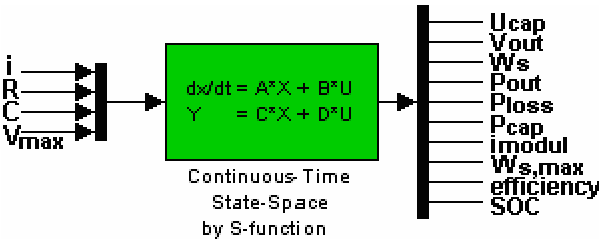


Figure 9.1. State-space of the super capacitor in a S-function block with variable input and output.

The car model calculates the desired power from the energy storage. This power contains auxiliary loads and the power request from the engine, which can be both positive and negative. As an output from the energy storage the car model needs only the state of charge. To calculate the state of charge it is usually needed to know the currents and the voltages as well. Therefore it is easy to add, for instance, the available power and the output voltage from the energy storage as outputs.
The implementation of the batteries and the super capacitor is presented in the following two sections.

9.1 Battery model

The state of charge is the remaining amount of energy in the battery. It is calculated like this

$$SOC = \frac{W_{used}}{W_{batt}} \cdot 100 \tag{9.1}$$

where

$$W_{used} = \int P_{charge} dt \, . \tag{9.2}$$

W_{batt} is the maximum amount of energy in the battery and P_{charge} is the power that either is charging or discharging the battery.

$$P_{charge} = P_t - P_{loss} \tag{9.3}$$

Where P_{loss} is power that is turned into heat in the battery and P_t is the power requested from the traction drive system. The heat generated in the battery is equal to the power generated in the resistances in the equivalent circuit (see Fig 9.2):

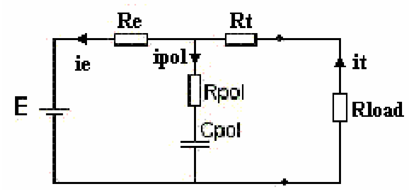


Figure 9.2. The currents in the equivalent circuit.

The power that is transferred into heat equals

$$P_{loss} = i_e^2 \cdot R_e + i_{pol}^2 \cdot R_{pol} + i_t^2 \cdot R_t \,. \tag{9.4}$$

This is further discussed in the next section.

In order to calculate the currents i_c and i_e one needs to know the terminal current (load current) i_t. The load current is found by dividing the load power, P_t, with the output voltage V_{out}:

$$i_t = \frac{P_t}{V_{out}} \,. \tag{9.5}$$

V_{out} is found by superposition, and when doing this, the load is seen as a current source and the capacitor as a voltage source, see figure 9.3.

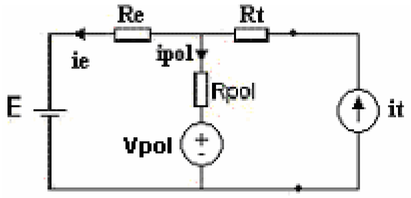


Figure 9.3. The load is seen as a current source in superposition.

In superposition voltage sources are seen as short circuits and current sources as interrupts. In this equivalent circuit there are three sources, one current (the load) and two voltage sources (the capacitor and E).

To start with the current source is interrupted and V_{pol} is short circuited (see Fig 9.4).

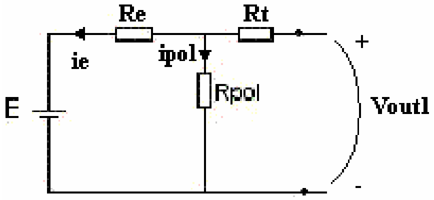


Figure 9.4. Current source is interrupted and V_{pol} is short circuited.

From figure 9.4 it is easy to derive V_{out1}:

$$V_{out1} = E \cdot \frac{R_{pol}}{R_e + R_{pol}} \,. \tag{9.6}$$

The procedure is the same for the other sources in the circuit and their contribution to the output voltage becomes

$$V_{out2} = V_{pol} \cdot \frac{R_e}{R_e + R_{pol}} \tag{9.7}$$

and

$$V_{out3} = i_t \cdot (R_t + \frac{R_e \cdot R_c}{R_e + R_c}) \,. \tag{9.8}$$

Summarising these three voltages results in the output voltage

$$V_{out} = V_{out1} + V_{out2} + V_{out3} = E \cdot \frac{R_{pol}}{R_e + R_{pol}} + V_{pol} \cdot \frac{R_e}{R_e + R_{pol}} + i_t \cdot (R_t + \frac{R_e \cdot R_c}{R_e + R_c}) \,. \tag{9.9}$$

The open source voltage (E) and the resistances (Re, Rc, Rt) are determined via look-up tables were the SOC and temperature are inputs and the voltage and the resistances are outputs. These values are then forwarded into the s-function.

V_{pol} is determined using a state space representation of the capacitor C_{pol}. The state space equation is derived by letting a current i_e passing through R_e and a current i_{pol} passing through C_{pol}. (see Fig 9.2).

V_{pol} is considered as the only state of the state space equation and this relation is used to find it:

$$\begin{aligned} i_e &= i_t - i_{pol} \\ i_{pol} &= \frac{dq_{pol}}{dt} \end{aligned} \tag{9.10}$$

The fact that the voltage drop across R_e and E is equal to the voltage drop across R_{pol} and C_{pol} is used to set up the state space equation:

$$\begin{aligned} & R_e * i_e + E = R_{pol} * i_{pol} + \frac{1}{C_{pol}} \int i_{pol} dt \\ & R_e * i_t - R_e * i_{pol} + E - R_{pol} * i_{pol} - \frac{1}{C_{pol}} \int i_{pol} dt = 0 \\ & R_e * i_t - R_e * \frac{dq_{pol}}{dt} + E - R_{pol} * \frac{dq_{pol}}{dt} - \frac{1}{C_{pol}} * q_{pol} = 0 \end{aligned} \tag{9.11}$$

As said before the state in the state space equation is the voltage across the capacitor:

$$x = \frac{q_{pol}}{C_{pol}} \tag{9.12}$$

The state space equation for the voltage V_{cc} becomes:

$$\begin{aligned} & R_e * i_t - C_{pol} * (R_{pol} + R_e) * \dot{x} + E - x = 0 \\ & \dot{x} = -\frac{1}{C_{pol}(R_e + R_{pol})} * x + \frac{1}{C_{pol}(R_e + R_{pol})} * E - \frac{R_e}{C_{pol}(R_e + R_{pol})} * i_t \end{aligned} \tag{9.13}$$

From this it is easy calculate the current i_{pol}:

$$i_{pol} = \frac{dV_{pol}}{dt} * C_{pol} = \dot{x} * C_{pol} \qquad (9.14)$$

Now all the necessary currents and voltages are determined in order to find the power that charges and discharges the battery, and thus SOC can be found.
In the next section the temperature of a chemical cell is discussed.

9.1.1 Temperature model

The temperature of the cell can be found with the following expression

$$q = -I \cdot T \cdot \frac{dE}{dT} + I \cdot (E - V) \qquad (9.15)$$

where

q = heat generation rate [W]
I = current through the cell [A]
T = temp [K]
dE/dT = temperature coefficient [V/K]
E = equilibrium voltage (open source voltage, [V])
V = cell voltage [V].

The first term of the expression, $-I \cdot T \cdot \frac{dE}{dT}$, correspond to the electrochemical reactions in the cell. This is very small in these large batteries for HEVs and EVs and therefore this term is negligible.
The other term corresponds to the power generated in the internal resistances of the cell. This term is calculated in the previous section known as P_{loss} [D].

Knowing the specific heat capacitance, cp [J/(kg*K)] (can be found for Li-ion in [F]), and the weight of the cell it is rather easy to find the temperature. The temperature, T, is calculated like this:

$$T = \int \frac{P_{loss}}{mcp} dt \qquad (9.16)$$

where
mcp = weight*cp [kg*J/(kg*K)]. (9.17)

Proof:

$$T = \int \frac{P_{loss}}{mcp} dt = \int \frac{[W]}{\left[\frac{J}{kg \cdot K}\right] \cdot [kg]} dt = \int [W] \cdot \frac{[K]}{[J]} dt = \qquad (9.18)$$

$$= \int \frac{[J]}{[s]} \cdot \frac{[K]}{[J]} dt = \int \left[\frac{K}{s}\right] dt = [K] = T$$

So as an example assume that the initial temperature of the cell is 25 degrees Celsius and the last coefficient of the expression above, Kelvin per seconds [K/s], equals 275[K/s]. Converting this coefficient into Celsius per second yields 2[°C/s] meaning that the temperature of the cell would increase with 2 °C per second. So in 10 seconds the temperature would become 25+10*2 = 45°C.

The specific heat capacitance of the cell can probably be obtained from the manufacturer or from an experimental setup if you know the internal bulk resistance.

9.2 Super capacitor model

To implement the super capacitor model, that was introduced in chapter 8, in Simulink a state space equation used. Using Kirchoff's voltage law for the equivalent circuit yields:

$$V_{out} - U_r - U_{cap} = 0 \Leftrightarrow V_{out} - R * i - \frac{1}{C}\int i dt = 0 \qquad (9.19)$$

From this it is rather easy to derive the state space equation for the voltage across the capacitor U_{cap}. In equation 9.20 the only state of the state space is calculated.

$$\frac{dU_{cap}}{dt} = \frac{1}{C} * i \qquad (9.20)$$

The actual super capacitor internal resistance (R) and capacity (C) vary with quantities as current, voltage and temperature. So if the super capacitor model should fit to the real super capacitor the variables C and R should vary in the state space equation. This is done with value from the manufactures data sheet and implemented in the Simulink model as Look-Up Tables. The variations for Maxwells PC2500 capacitor is seen in figure 9.6.

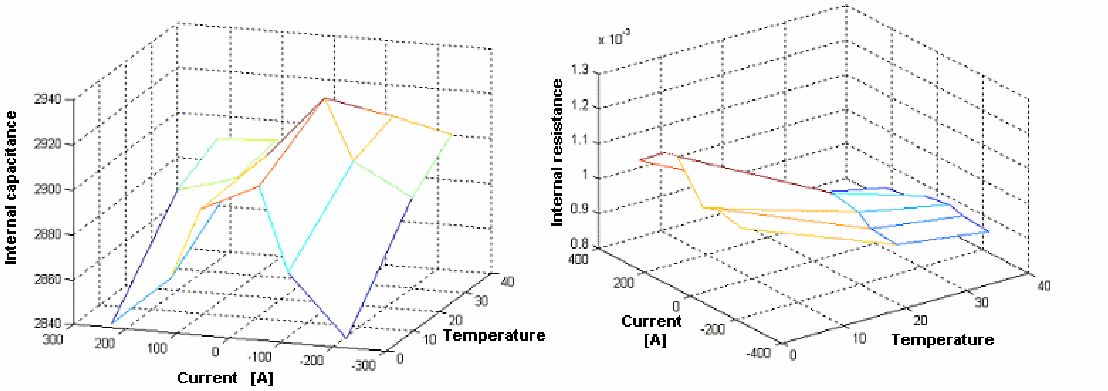


Figure 9.6. To the left the internal capacitance and to the right the internal resistance and they vary with quantities as current and temperature.

The definition of the SOC in the super capacitor model is the energy in the super capacitor divided with the total energy when it is fully charged.

$$SOC = \frac{E_{cap}}{E_{\max}} = \frac{\dfrac{U_{cap}^2 * C}{2}}{\dfrac{U_{cap,\max}^2 * C}{2}} = \frac{U_{cap}^2}{U_{cap,\max}^2} \qquad (9.21)$$

Because of the variation in the capacitance the total energy vary with current too. U_{cap} is found as a state in the state space function and $U_{cap,max}$ is the max voltage that the capacitor can deal with. This voltage is normally to be found in the datasheet of the super capacitor.

The temperature model of the super capacitor is modeled in the same way as for the batteries. The only thing to change is the specific heat capacitance and the weight.

10 Lifetime model

There is a lifetime for every part of the HEV and so for the energy storage. For that reason we need a kind of estimation of the lifetime for the energy storage. This lifetime is dependent of how many years old the energy storage is and how big the cycle variations, in SOC and temperature, have been.

A simple lifetime model is suggested in this context. It is based on the following assumptions:

- It is the deviation in state of charge that affects the lifetime of the battery. This deviation affects the lifetime in a non linear way, that is assumed to be square.
- The reference level, from which the SOC deviates, may vary if it varies slowly, i.e. a battery may vary its SOC around 70% as well as around 60 %, affecting the lifetime similarly. A slow transition from e.g. 70 % to 60 % SOC in reference level must be allowed

The equation that is used (see Eq 10.1) result in that the lifetime is more punished when there is a long and fast charge or discharge than if it is short and slow.

$$Degeneration(t) = k\int_0^t (SOC(t) - SOC_{mean}(t))^2\,dt \qquad (10.1)$$

The SOC mean value (SOCmean) is calculated with a moving average filter from the SOC curve. The SOC and the SOCmean, from a certain simulation, is plotted in figure 10.1.

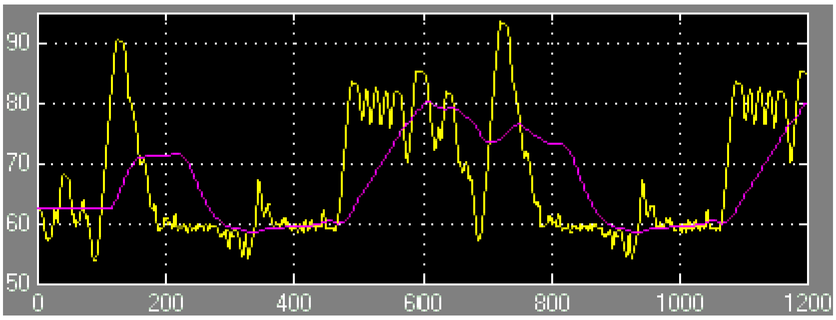


Figure 10.1. SOC and SOCmean from a 1200 sec us06 cycle simulation with a Li-ion battery.

The energy storage gets punished or degenerated more if the SOC curve differ much from SOCmean curve.
If SOC and SOCmean were constant all the time the energy storage would be degenerated if there were a constant error between them. This is not occurring because of the fact that a mean value filter is used.
There are different SOCmean values between the powerassist model and plugin model. This is considered in correspondingly chapter.
How much the energy storage gets punished is simulated with the part of equation 10.1 that is shown in equation 10.2.

$$(SOC(t) - SOC_{mean}(t))^2 \qquad (10.2)$$

The result of equation 10.2, if the SOCmean=60, is shown in figure 10.2.

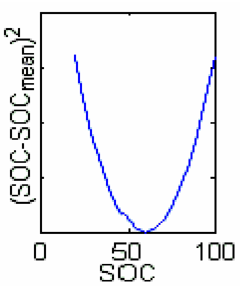


Figure 10.2. Result of equation 10.1 when SOCmean=60.

An integration of equation 10.2 makes it possible to get the total degeneration of the energy storage during a simulation. There is also a need of a constant (k) to make this work for different energy storages (see Eq 10.1).

10.1 Degeneration with powerassist

To get the right value on the constant *k* there must be some definitions made on the energy storages. The cycle definition for the Li-ion HP and NiMH HP batteries is presented in figure 10.3. It starts from SOCmean value and charges to SOCmean+5% in one second and then its constant in one second before it's discharged to SOCmean again.

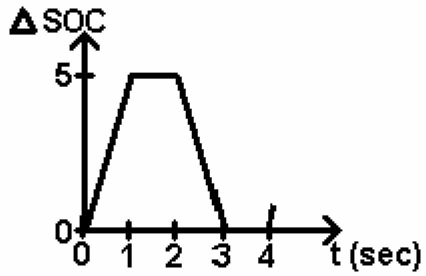


Figure 10.3. Definition of one 5% cycle
for the SOC model for the batteries.

The cycle definition for the super capacitors is showed in figure 10.4. It starts at SOC=25% and charges to SOC=100% in 20 seconds and then its constant in 10 second before it's discharged to SOC=25 again. In this cycle is SOCmean=62.5%

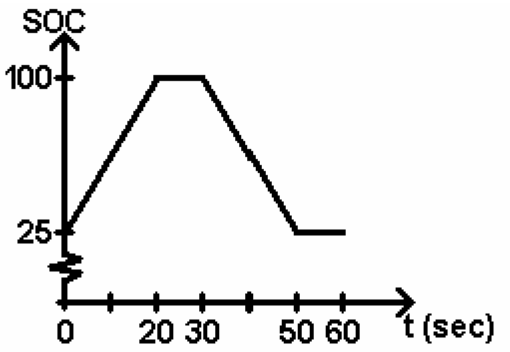


Figure 10.4. Definition of one cycle for the SOC model for the super capacitor.

The Li-ion is able to cycle about 200000 times with this 5%-cycel before it is considered as worn-out. With the same 5%-cycle is it likely for the NiMH to deal with about 2/3*200000 cycles. The super capacitors are able to cycle 500000 times with the cycle in figure 10.4. With this data is it possible to calculate the constant k for the different energy storages.

Li-ion:

$$Degeneration(t) = 100\% = Cycle\_life * k\int_0^t (SOC(t) - SOC_{mean}(t))^2\,dt \Rightarrow$$

$$\Rightarrow k = \frac{100}{Cycle\_life * \int_0^4 (SOC(t) - SOC_{mean}(t))^2\,dt} = \frac{100}{200000 * \frac{125}{3}} = \frac{3}{250000} \qquad (10.3)$$

NiMH:

$$k = \frac{100}{200000 * \frac{2}{3} * \frac{125}{3}} = \frac{9}{500000} \qquad (10.4)$$

Super capacitor:

$$k = \frac{100}{500000 * 46875} = \frac{1}{234375000} \qquad (10.5)$$

10.2 Degeneration with plugin

A plugin-cycle for a Li-ion HE battery starts at SOC=100% and discharges to SOC=20% and then charged up to 100 % SOC again. With this cycle the battery is able to cope with 1500 cycles before it’s used up. An us06 simulation, with 100 kg Li-ion HE, shows that the vehicle can drive 55 km on pure electric power before it is discharged to 20% (see Chapter 13).

To get SOCmean there is a need of a filter constant (Time_filter). First the number of km, that the vehicle is able to drive pure electrically *(X(km))*, is noted. This number is multiplied with the number of cycles that it is possible to cycle the energy storage before it is worn-out. This yields the total distance *(Y(km))* before the battery is worn out (see Eq 10.6).

$$Y(km) = X(km) * C(Number\ of\ cycles) \qquad (10.6)$$

Then iteratively change the Time_filter constant and simulate the model, until the number of kilometers that the energy storage are capable to survive, are the same as *Y(km)* in equation 1.3. The time filter constant was found to be 85.

11 Cost models

The system cost is an important part of the choice of which energy storage technology that should be used. In the total cost the installation cost, petrol and net charging cost (for the plugin) is included.

The cost/10km, for a certain energy storage technology, is dependent on either how many years old the energy storage is capable to become or how many km a vehicle has been driven with the energy storage.

11.1 Kilometre cost for the energy storage

As mentioned before people are typically driving 13150 km per year. If an energy storage lifetime is 10 years the vehicle is capable to go 10*13150 km before it is necessary to replace it. If the driver has been driven less than 10*13150 km the 10km cost (installation cost/10km) will become calculated with the 10*13150 km distance. If the vehicle is driven more than 10*13150 km in these 10 years, the 10km cost will become calculated with this distance instead

The gasoline cost per 10km is calculated with the number of liter, that the vehicle has consumed, divided by the number of 10 km that is driven. However there is a difference between the calculations for the powerassist and the plug in.

11.1.1 Cost for the powerassist

When the car has been in use, the SOC of the energy storage may end up on a different level than it started at. This result in that next time the car is used the SOC is starting at this new level. To have a fair compare, by the different energy storages in the powerassist, the difference in SOC must be leveled out (see Fig 11.1).

First the difference in SOC is converting into energy with equation 11.1.

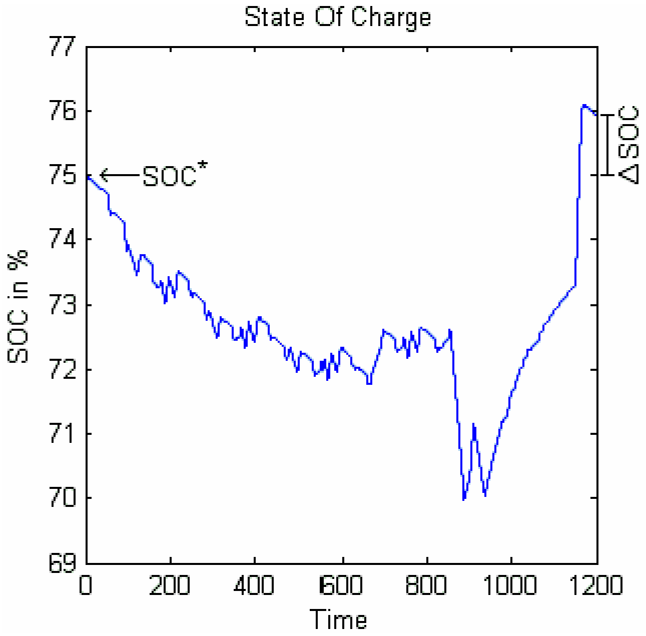
$$\Delta E = \frac{SOC^* - SOC}{100} E_{storage\_\max} \qquad (11.1)$$

Then how many liters of petrol that corresponds to ΔE is calculated in equation 11.2.

$$l_{Energy\_petrol} = \frac{\Delta E}{E_{petrol} * \eta} \qquad (11.2)$$

E_{petrol} is the energy (Ws) in one liter petrol and η is the mean efficiency, for the ICE, in the powerassist.

This amount of petrol (l_{Energy_petrol}) is added to the total petrol consumption.



Figur 11.1. At the end of the SOC the delta SOC must be compensated.

11.1.2 Cost for the plugin

So as for the powerassist there probably is a difference between the starting SOC and the ending SOC after using the plugin vehicle. In the plugin the difference between those SOC levels, in the energy storage, is charge by the net. To calculate the price per 10km the cost of the energy charged by the net must be included (see equ.11.3).

$$Cost = \frac{\int P}{3600 * 1000} * \frac{price}{kWh} \tag{11.3}$$

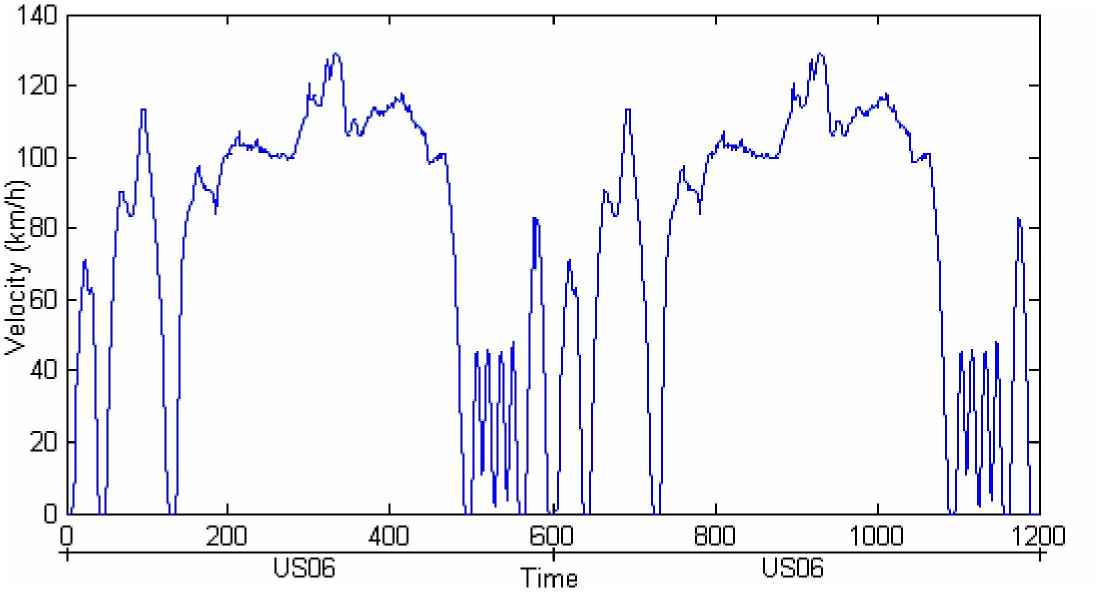
This cost is then added to the total cost.

11.2 Specifications of drivingcycles

11.2.1 US06

On October 22, 1996, the final rule on Motor Vehicle Emissions Federal Test Procedure Revisions was published in the Federal Register. This rule revises the tailpipe emissions portion of the Federal Test Procedure (FTP) for light–duty vehicles and light–duty trucks. The primary new element of the rulemaking is a Supplemental Federal Test Procedure designed to address shortcomings with the current FTP in the representation of aggressive (high speed and/or high acceleration) driving behavior, rapid speed fluctuations, driving behavior following startup. The name of this cycle is called us06.

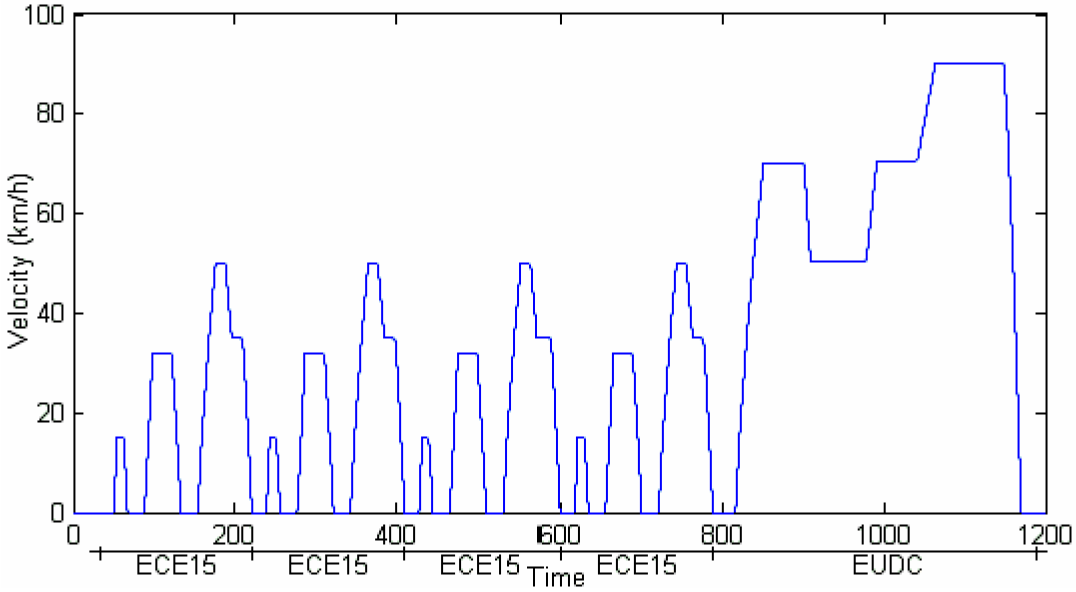
The simulink model is using two standard US06 cycles in compound as the US06 driving cycle. This new US06 cycle represents a 25.8km trip with an average speed of 77.4 km/h, maximum speed 129.2 km/h, and duration of 1200 seconds (see Fig 11.2).



Figur 11.2. Simulink model driving cycle is represent by two us06 cycles.

11.2.2 ECE15

The driving cycle called ECE15 in the simulink model isn't really an ECE15 cycle. Actually it consists of two parts, one ECE15 and one EUDC, that correspond to urban and highway (extra-urban) driving conditions in that order. ECE15 test cycle simulates a 4.052 km urban trip at an average speed of 18.23 km/h and a maximum speed of 50 km/h. Its duration is 800 seconds (see Fig 11.3). The same part of the ECE15 driving cycle is repeated four times to obtain an adequate driving distance and to put the ICE on a proper temperature. The EUDC (for low-powered vehicles) cycle instead illustrates the aggressive, high speed driving at a maximum speed of 90 km/h. Its duration is 400 seconds and 6.59 km at an average speed of 59.3 km/h.



Figur 11.3. Simulink model driving cycle is represented by four ECE15 cycles and one EUDC cycle.

Further reading on these cycles can be made in reference [7], [8] and [9].

11.3 Vehicle characteristics

In the next two sections the characteristics of the simulated car is presented. The following characteristics is used for the car:

Weight: 1836 kg
FAS power: 7 kW
BAX power: 36 kW
ICE power: 128 kW
Total power: 171 kW

11.3.1 Plugin

As discussed in chapter 1.3 a PHEV is a hybrid vehicle that can operate pure electrically on commuting distances. Since the car model doesn't contain a PHEV mode this had to be developed.

The strategy used is that the PHEV operates pure electrically until the state of charge is approaching 20%, which is its cut off limit. If the distance to be driven exceeds the distance that the PHEV is able to operate in electric mode, this limit is reached. When this limit is reached the ICE is started and the energy storage doesn't provide any power until it is charged to the upper limit of SOC, which is chosen to be 90%.

The energy storage is charged either when the car is braking, i.e. at regenerative braking, or when there is too much torque produced from the ICE. For example if the driver desires a certain amount of torque then the ICE produces either this amount of torque or more. The reason why the ICE sometimes is producing too much torque is that the ICE desires to operate at the best possible efficiency.

11.3.2 Powerassist

The control strategy that the SAAB MHD is using is basically to put the ICE on a better point of the efficiency map. This is done by providing the ICE with necessary power from the electrical engines, FAS and BAX.

Another vital property of this car is the stop and go function. This means that the ICE is turned of when the car is at stand still, for example at a red light. When the driver of the car is about to go and he puts his foot on the accelerator the car starts in a couple of hundredths of seconds because of the high torque produced by the FAS.

12 Simulations and results

As mentioned in the introduction a vital part in this thesis is to compare the different energy storages. The comparisons are made between HE NiMH and HE Li-ion and between supercapacitor, HP Li-ion and HP NiMH.

12.1 Powerassist

In the MHEV supercapacitor, Li-ion HP and NiMH HP batteries are of interest. A first thought may be to compare the energy storages regarding how much power that's installed. However there's a difficulty to do a fair comparison between the energy storages in this way. For example the super capacitors is best at produce high power during 2 seconds while the NiMH HP has its best performance at high power in 18 seconds. Another way may be to compare the energy storages regarding to energy. Because of that the MHEV is mostly depending on power this is not a good alternative. An important thing is the volume and weight of the energy storage in the car and therefore this is an all right choice to make when comparing them.

A good way to start when simulating the battery pack is to sweep across the considered range of amount of cells. From this one gets varied data, at different number of cells, of the energy storage. Plotting these data yields the size of the optimal energy storage pack

12.1.1 Decision of pack size

The choice of how large energy storage pack to use is selected with help of different units as voltage, power, energy, weight and volume. To not limit the simulation sweep too much a good idea is to start with mostly looking at the weight. Then limit the size of the energy storage pack due to voltage, energy and power. The chosen input data for the NiMH HP sweep are printed in the table (see Table 12.1). The data for the energy storages Li-ion HP, super capacitors PC2500 and 3500/2.7V are printed in Appendix A.

Table 12.1 The input data for the NiMH sweep.

	Modern	Further (year 2015)
Gas price (sKr)	10	20
Price to buy (sKr/kWh)	2000	700
Price to buy (sKr/kW)	--	--
Life time (year)	15	
SOC reference value	75	
Quantity (cells)	20 to 250	
Quantity (kg)	20.8 to 260	

From this sweep one can plot price per 10km vs. the weight of the pack (see Fig 12.1). In order to decide how big the optimal pack should be, regarding to price, plainly allocate the minimum of the curve and from this one can decide the amount of kg to use on the x-axis.

The price is calculated with help of price/liter, litre/10km and the installation cost (see Eq 12.1). When the package gets bigger the litre/10km cost goes down (see Fig 12.2) but the installation cost goes up.

$$kr/10km = ((litre/10km)*(kr/litre)) + (installation\ cost/10km) \qquad (12.1)$$

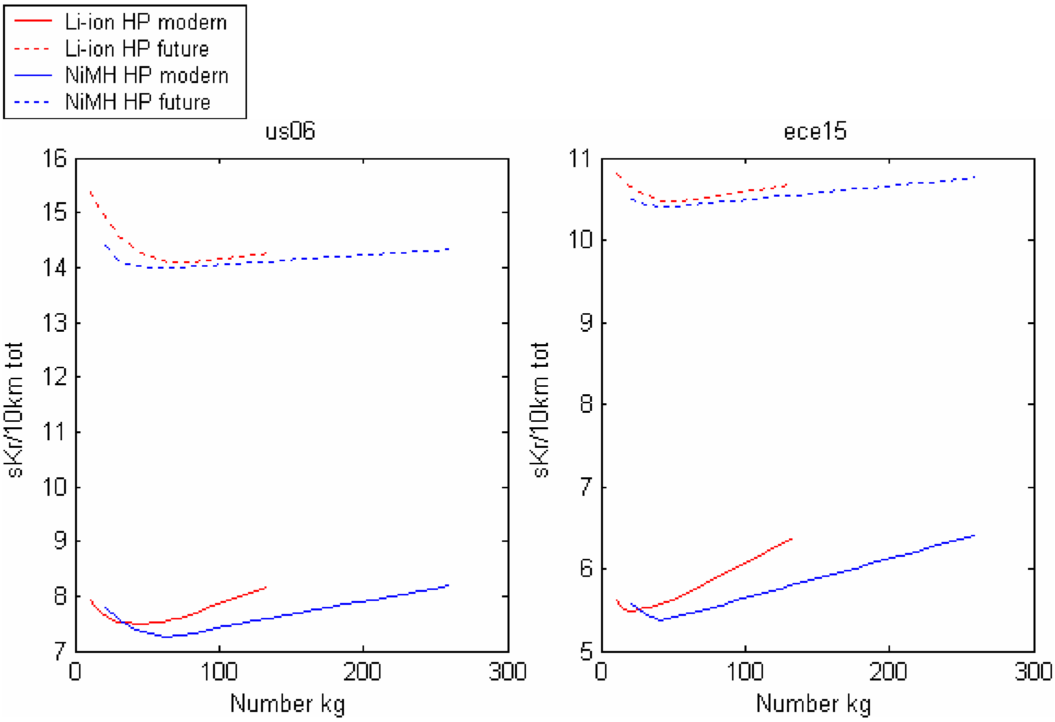


Figure 12.1. NiMH vs. Li-ion. Filled lines are for modern time and the dotted lines are for the future. Gas price and installation cost are printed in table 1

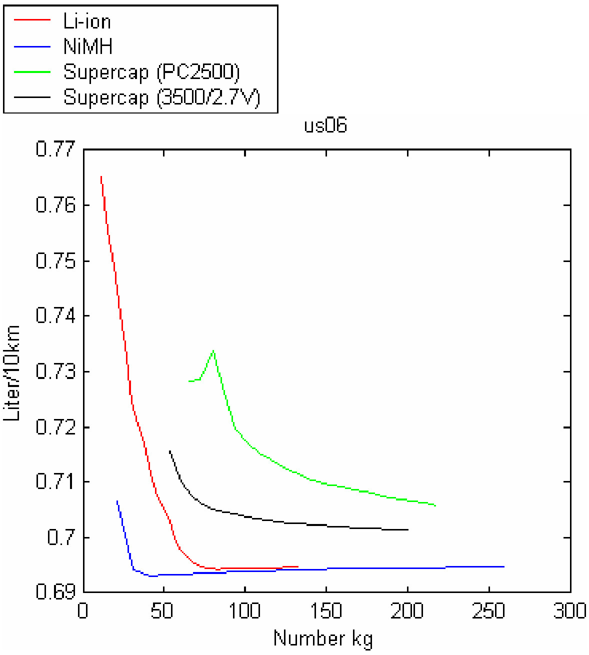


Figure 12.2. A plot of the energy storage with litre/10km vs. kilograms.

By looking at figure 12.1 and 12.2 one can see that the optimal weight for the NiMH HP is about 60 kg. After the same procedure with the Li-ion battery the optimal weight is decided to be around 40 kg.

A big difference between the energy storages is the lifetime; here measured in how many 10km sections it lasts before it's worn-out. The super capacitor have outstanding lifetime compared to Li-ion and NiMH (see Fig 12.3). From these curves it's possible to decide how long a certain size of an energy storage pack will last.

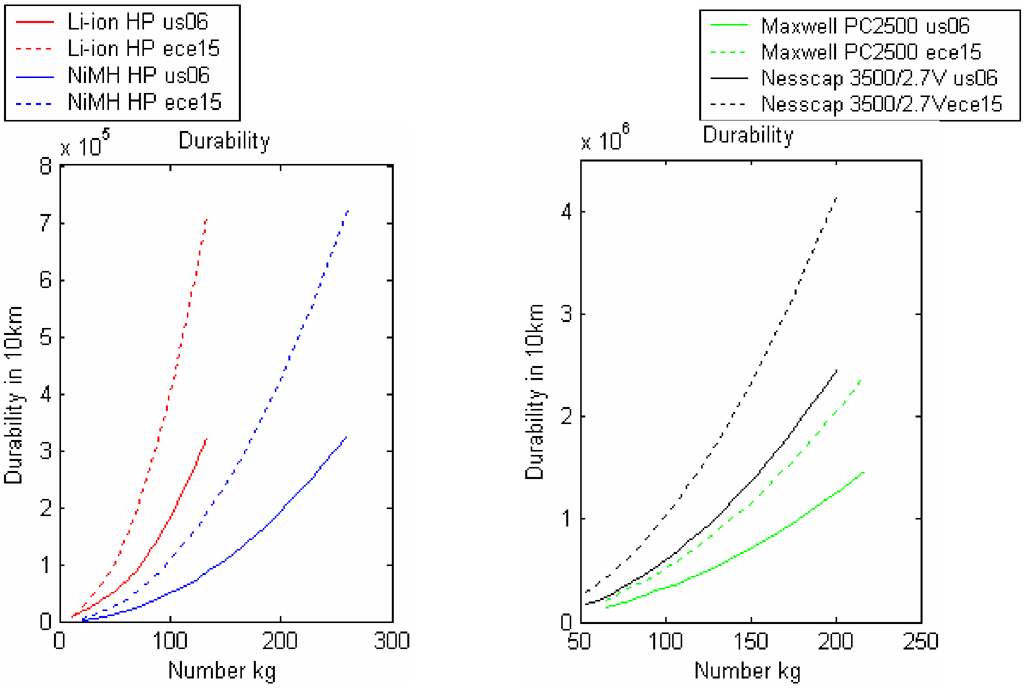


Figure 12.3. Lifetime of the energy storage. Notice the exponent on the y-axis.

It is not a good idea to use less than a certain number of kg because of the power, voltage and energy that the car demands. Not either more because of the volume and weight the pack would contribute with. If there is any interest of the other plots of the energy storages refer to Appendix A.

12.1.2 Optimal weight comparison

To examine the energy storage a little bit closer at the so-called optimal weight, look at the following tables. After each table a plot follows with the SOC Vs time for the current energy storage.

The optimal weight of the Li-ion battery is 40kg and NiMH 60kg. To make a fair comparison 50kg of each is chosen. It is not possible to have such small quantity of super capacitor in the US06 and ece15 drive cycles. This is because of that the voltage and the SOC drops too much.
To start with a Li-ion cost optimized simulation for us06 is presented in table 12.2.

Table 12.2. Cost optimal for Li-ion modern time (50kg).

US06	**Li-ion**	**NiMH**	**Super capacitors**	
			Nesscaps 3500/2.7V	**Maxwells PC2500**
Number of cells	132	48	75	69
Max Volt	514	432	202.5	172.5
sKr/10km batt/cap (today/future)	0.45/0.13	0.38/0.13	--	--
sKr/10km gas (today/future)	7.05/14.1	6.93/13.86	--	--
sKr/10km powergrid (today/future)	--/--	--/--	--	--
Tot sKr/10km (today/future)	7.5/14.23	7.32/13.99	--	--
Liter/10km	0.70	0.69	--	--
Lifetime (10km*1000)	52	12	--	--
Installation cost sKr*1000 (today/future)	9/2.6	5/1.75	--	--

Below the SOC curves for Li-ion and NiMH battery packs are plotted. It is clearly seen in the graph below that Li-ion batteries doesn't vary as much as NiMH batteries and this is due to the fact that they have much higher energy density than NiMH. Because of this 40kg of NiMH last less than 40kg of Li-ion.

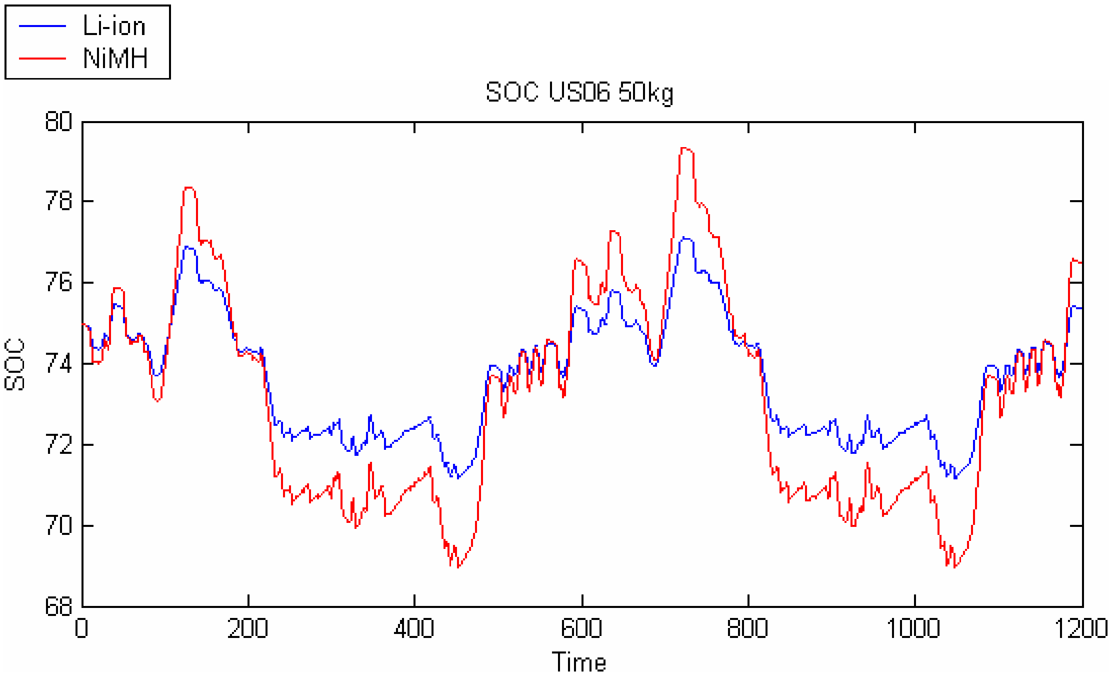


Figure 12.4. Li-ion and NiMH, SOC Vs time, at 40kg on an Us06.

Next comparison to be made is the cost optimal for Li-ion simulated in an ece15 cycle. The values of this comparison can be seen in table 12.3.

Table 12.3. Cost optimal for Li-ion modern time (50kg).

Ece15	Li-ion	NiMH	Super capacitors	
			Nesscap 3500/2.7V	Maxwell PC2500
Number of cells	132	48	75	69
Max Volt	514	432	202.5	172.5
sKr/10km batt/cap (today/future)	0.45/0.13	0.24/0.084	--	--
sKr/10km gas (today/future)	5.16/10.32	5.16/10.32	--	--
sKr/10km powergrid (today/future)	--/--	--/--	--	--
Tot sKr/10km (today/future)	5.62/10.45	5.40/10.44	--	--
Liter/10km	0.52	0.52	--	--
Lifetime (10km*1000)	102	26	--	--
Installation cost sKr*1000 (today/future)	9/2.6	5/1.75	--	--

As one can see in the table above there is still no values in the super capacitor column. This is due to the fact that 50kg of super capacitors wouldn't produce enough energy, and therefore their SOC would drop to zero almost instantly.
In figure 12.5 below the SOC varies more with NiMH than Li-ion and as mentioned before this is due to that Li-ion contains higher energy density. Ece15 doesn't require as much power as the us06 cycle, therefore this SOC curve is more flat.

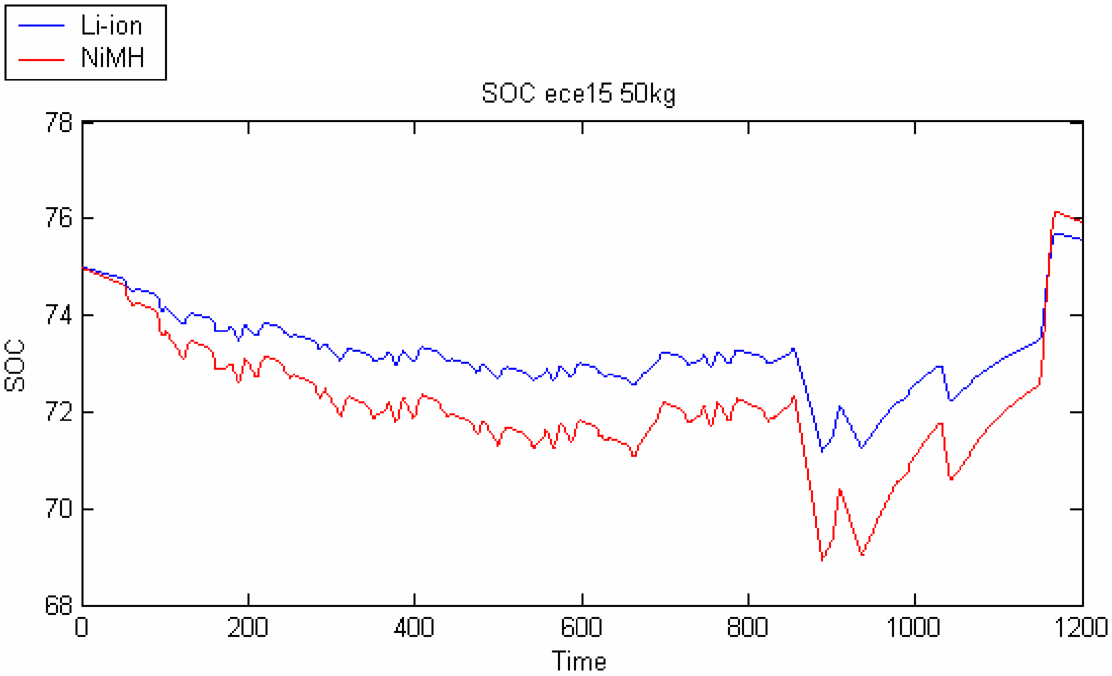


Figure 12.5. Li-ion and NiMH, SOC Vs time, at 40kg on a ece15.

The super capacitors litre/10km starts to be flat at 100kg, but it doesn't reach a minimum in reasonable weights (see Fig 12.2). Therefore an optimum for the super capacitors is decided to be at 100kg, and as a result of this the next comparison to be made is at 100kg for all the energy storages in the us06 cycle (see Table 12.4).

Table 12.4. Compare the energy storage at 100kg.

US06	Li-ion	NiMH	Super capacitors	
			Nesscap 3500/2.7V	Maxwell PC2500
Number of cells	263	96	149	138
Max Volt	1026	864	402	345
sKr/10km batt/cap (today/future)	0.91/0.26	0.48/0.16	8.26/1.65	2.16/0.43
sKr/10km gas (today/future)	6.94/13.88	6.94/13.88	7.04/14.08	7.17/14.34
sKr/10km powergrid (today/future)	--/--	--/--	--/--	--/--
Tot sKr/10km (today/future)	7.85/14.14	7.41/14.04	15.29/15.73	9.33/14.77
Liter/10km	0.69	0.69	0.70	0.72
Lifetime (10km*1000)	182	48	598	335
Installation cost sKr*1000 (today/future)	18/5.25	9.5/3.32	270/54	71/14.2

In the figure below one can see that the SOC varies a lot more with super capacitors than with batteries. This is of course because of that batteries contain higher energy density. Instead the capacitors have much higher power density and they can provide more power at a faster response.

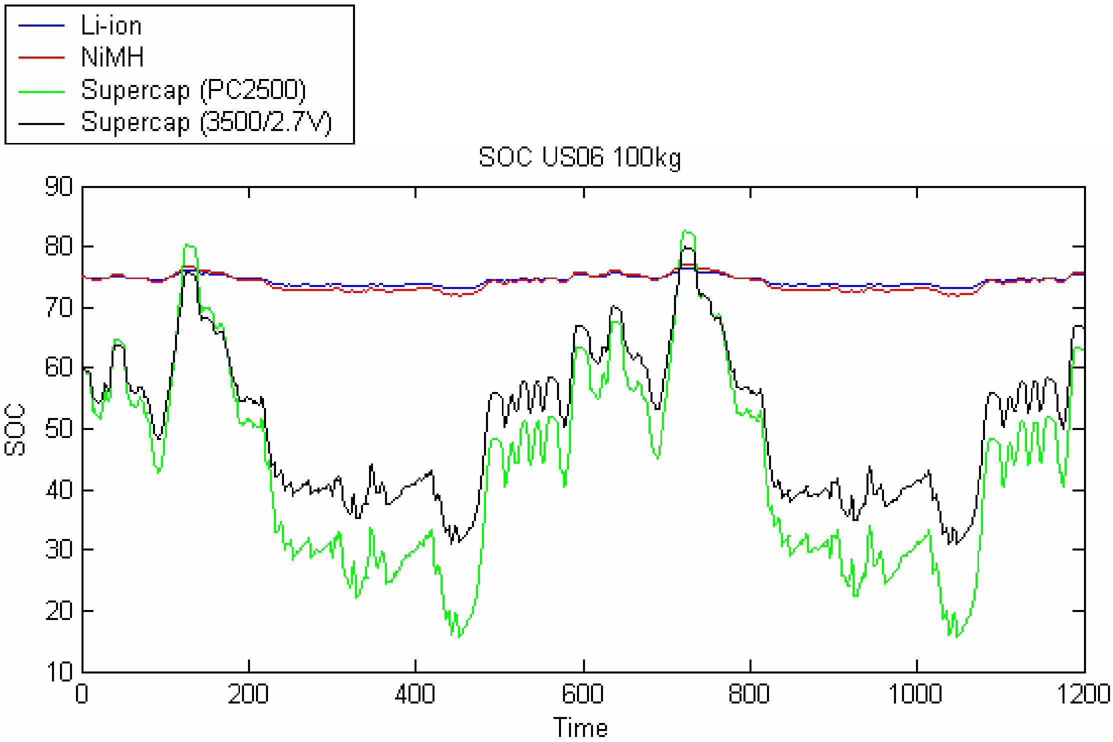


Figure 12.6. Li-ion, NiMH and the super capacitors, SOC Vs time, at 100kg on an Us06.

In table 12.5 the same comparison is to be made, but instead the ece15 is simulated. It’s clearly seen in this table that the lifetime of the super capacitors is superior the batteries lifetime. However as said before the cost is a main drawback of this technology, here the installation cost is more than 10 times that of Li-ion.

Table 12.5. Compare the energy storage at 100kg.

Ece15	Li-ion	NiMH	Super capacitors	
			Nesscap 3500/2.7V	Maxwell PC2500
Number of cells	263	96	149	138
Max Volt	1026	864	402	345
sKr/10km batt/cap (today/future)	0.91/0.26	0.48/0.16	8.26/1.65	2.16/0.43
sKr/10km gas (today/future)	5.16/10.32	5.16/10.32	5.17/10.34	5.23/10.46
sKr/10km powergrid (today/future)	--/--	--/--	--/--	--/--
Tot sKr/10km (today/future)	6.07/10.58	5.64/10.48	13.42/12	7.39/10.89
Liter/10km	0.52	0.52	0.52	0.52
Lifetime (10km*1000)	402	106	1017	520
Installation cost sKr*1000 (today/future)	18/5.25	9.5/3.32	270/54	71/14.2

As said before the capacitors doesn’t produce as much energy as the batteries and therefore it varies more in the SOC (see Fig 12.7). If one would cycle a battery this hard its lifetime would be much less than that stated in the tables above. This ability to cycle a capacitor this much that often without damage it is one of the greatest benefits of super capacitors.

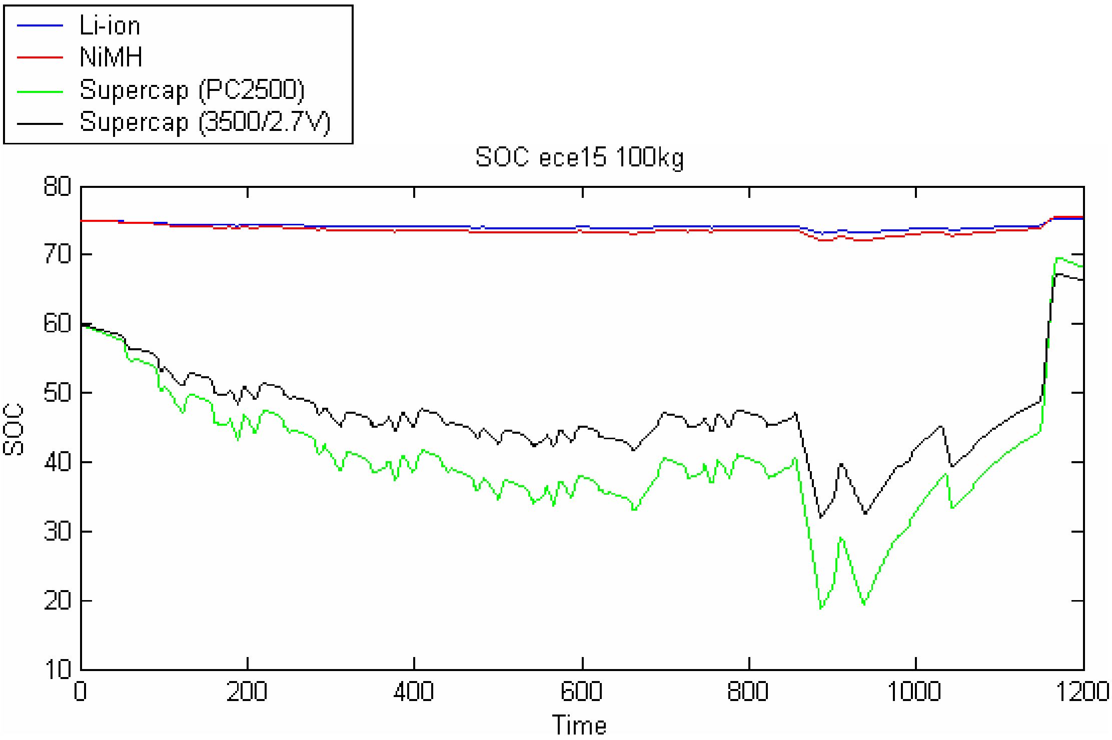


Figure 12.7. Li-ion, NiMH and the super capacitors, SOC Vs time, at 100kg on an ece15.

12.2 Plugin

In the PHEV Li-ion HE and NiMH HE are batteries of interest. A natural choice to compare this energy storage is regarding how much energy that is installed. Why? Because of that the PHEV wants to operate pure electrically as long as possible, and therefore the most important unit is energy.
As for the powerassist the battery pack for the plugin is swept over a range of sizes of the pack in order to achieve different kind of interesting data, which are used to decide the optimal size of the pack.

12.2.1 Decision of pack size

The sweep for the plugin is made in a similar way as for the powerassist. The car must be able to operate pure electrically all the time during simulation. So in order to simulate interesting sizes of the battery pack it can’t be smaller than 150kg. To not overdo the sweep it stops at 350-400 kg of installed battery.
The chosen input data for the NiMH HE sweep are showed in table 12.6, and data for the Li-ion HE are to be found in Appendix B.

Table 12.6. The input data for the NiMH sweep.

	Modern	Further (year 2015)
Grid price/kWh (sKr)	0.7	0.7
Price to buy (sKr/kWh)	2000	700
Price to buy (sKr/kW)	--	--
Life time (year)	15	
SOC start/stop value	90/20	
Quantity (cells)	200 to 500	
Quantity (kg)	166 to 416	

In the same way as for the powerassist the size of the pack is chosen by plotting price vs. kWh for the energy storages (see Fig 12.8). The price is calculated with help of kWh/10km and the installation cost (see Eq 12.2). When the package gets bigger the kWh/10km cost goes down and the installation cost goes up.

$$kr/10km = ((kWh/10km)*(kr/kWh)) + (installation\ cost/10km) \qquad (12.2)$$

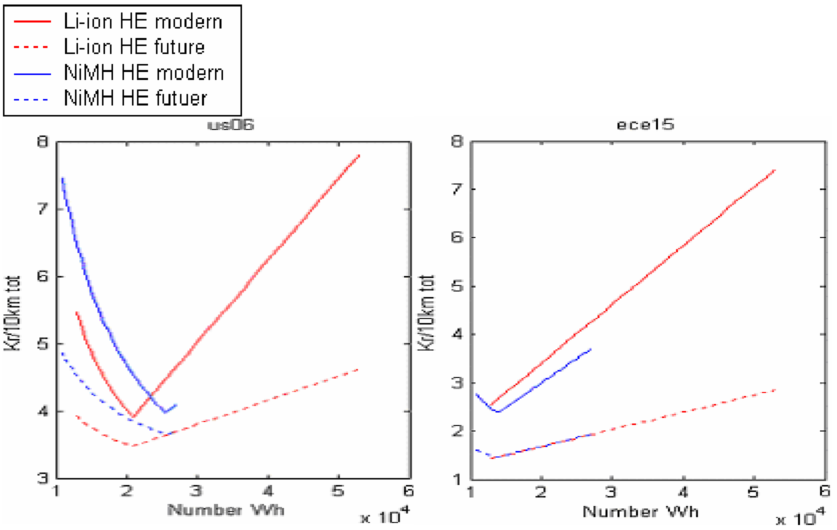


Figure 12.8. NiMH vs. Li-ion. Modern time and the dotted line are further. Grid price/kWh and installation cost are printed in table 12.6.

In this way can we se that the optimal size for the NiMH HP is about 20kWh (15-25 kWh) this correspondence to 300kg. After the same procedure with the Li-ion battery the optimal weight is decided to be 100 kg.

There are differences in lifetime between the energy storage, as one can see in figure 12.9, and here it is also possible to decide how many 10km sections the energy storage will run before it's used up.

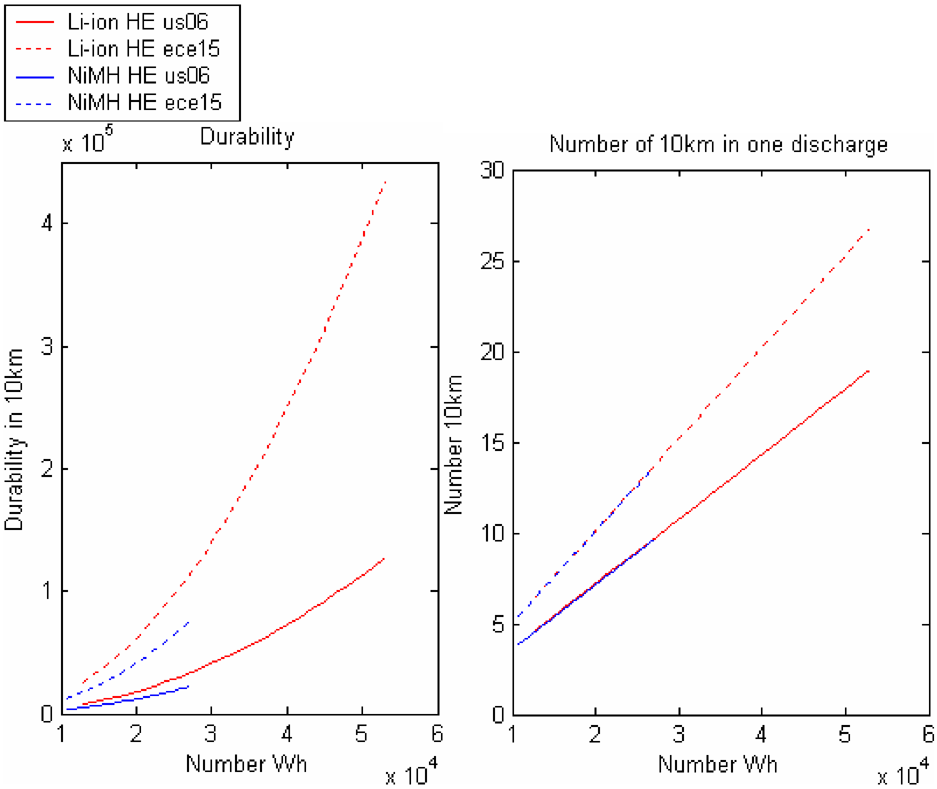


Figure 12.9. Left: Lifetime of the energy storage. Right: Number of 10km that it is possible to drive in one charge.

It is not a good idea to use less than a certain number of kg because of the power, voltage and energy that the car demands. Not either more because of the volume and weight. If there is any interest of the other plots on the energy storages refer to Appendix B.

12.2.2 Optimal weight comparison

In the following tables a little bit more detailed comparison of the different batteries, at their optimal weights, is done. After each table follows a plot a with the SOC Vs time for the current energy storage.

The optimal weight on Li-ion battery is 100kg. Because of this an interesting comparison to be made is 100kg Li-ion with 100kg of NiMH.

Table 12.7. Cost optimal for Li-ion modern time (100kg).

US06	Li-ion	NiMH
Number of cells	93	120
Max Volt	372	192
sKr/10km batt (today/future)	3.52/1.03	9.91/3.47
sKr/10km gas (today/future)	--/--	1.84/3.68
sKr/10km powergrid	1.36	1.15
Tot sKr/10km (today/future)	4.89/2.39	12.90/8.3
Nr km on pure electric	53.7	22.7
Lifetime (10km*1000)	10	1.3
Installation cost sKr*1000 (today/future)	35.8/10.44	13/4.55

Below, in figure 12.10, the SOC curves are plotted. The lower curve is the NiMH plot and in this one can see that 100kg of NiMH is not enough in the plugin vehicle. It reaches 20% SOC after approx. 1000 seconds and then the ICE is started.

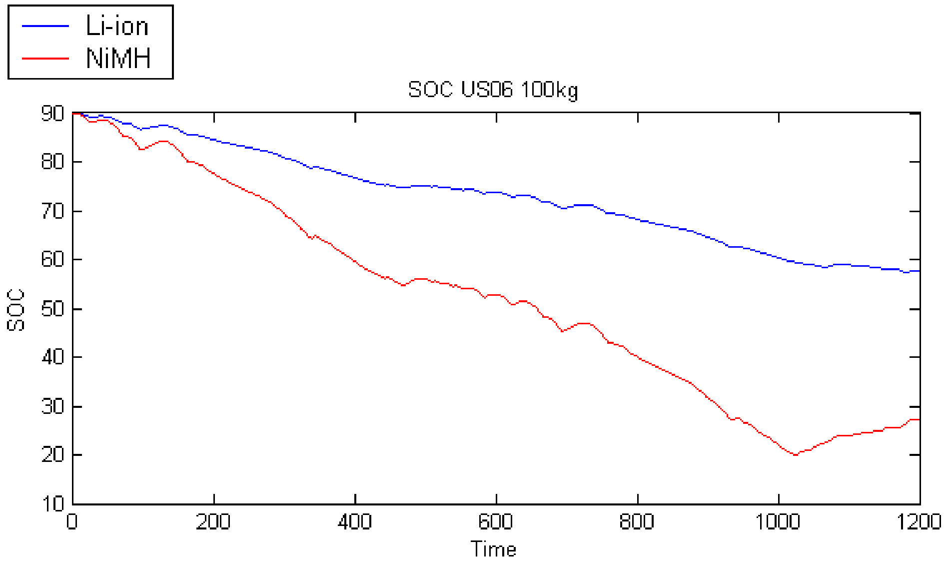


Figure 12.10. Li-ion and NiMH, SOC Vs time, at 100kg on an Us06.

Table 12.8 contains Li-ion cost optimal data for the ece15 simulation at present time.

Table 12.8. Cost optimal for Li-ion modern time (100kg).

Ece15	Li-ion	NiMH
Number of cells	93	120
Max Volt	372	192
sKr/10km batt (today/future)	1.82/0.53	2.98/1.04
sKr/10km gas (today/future)	--/--	--/--
sKr/10km powergrid	0.97	0.97
Tot sKr/10km (today/future)	2.79/1.5	3.95/2.01
Nr km on pure electric	75.5	32.9
Lifetime (10km*1000)	34.5	4.36
Installation cost sKr*1000 (today/future)	35.8/10.44	13/4.55

In figure 12.11 it is clearly that 100kg of NiMH or Li-ion easily managed to operate pure electrically during the whole drive cycle. Both of these technologies would cope with several ece15 cycles on one charge when using 100kg of them.

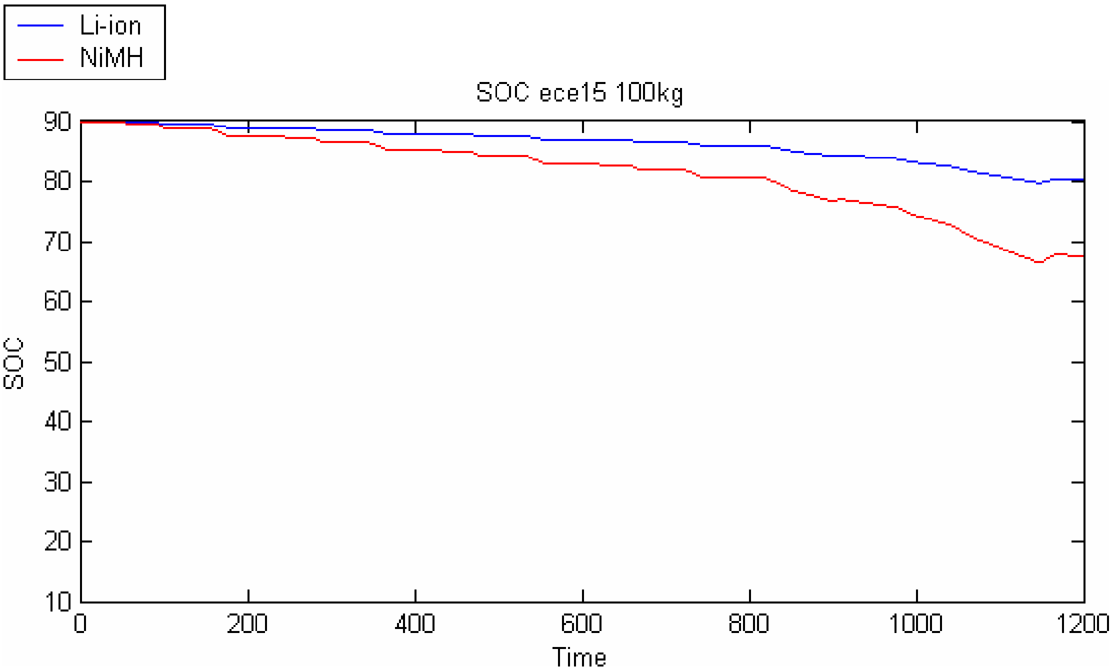


Figure 12.11. Li-ion and NiMH, SOC Vs time, at 100kg on an ece15.

The optimal weight for the NiMH battery was decided to be about 300kg in the previous section. So in table 12.9 a comparison of 300kg NiMH and 300kg of Li-ion is made.

Table 12.9. Cost optimal for NiMH modern time (300kg).

US06	**Li-ion**	**NiMH**
Number of cells	280	360
Max Volt	1120	576
sKr/10km batt (today/future)	5.47/1.59	3.40/1.19
sKr/10km gas (today/future)	--/--	--/--
sKr/10km powergrid	1.37	1.37
Tot sKr/10km (today/future)	6.84/2.96	4.77/2.56
Nr km on pure electric	161.1	69.8
Lifetime (10km*1000)	91.5	11.5
Installation cost sKr*1000 (today/future)	107.9/31.46	39/13.65

In figure 12.12 one can see that the SOC doesn’t fall beneath 65% for any of the batteries although this is a very demanding driving cycle. Even the NiMH would cope with almost 3 such cycles before charging is needed. As one can see in the table above this amount of battery would manage almost 70 km pure electrically with NiMH.

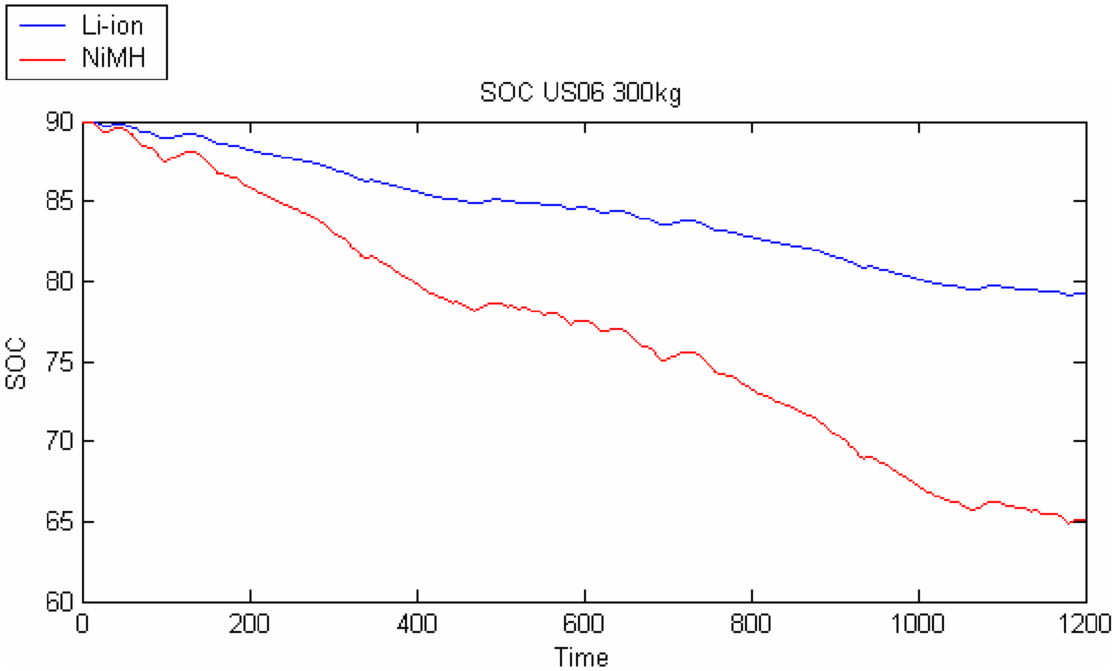


Figure 12.12. SOC for 300 kg of Li-ion and NiMH on a Us06.

The ece15 cycle is not that demanding and with 300kg of batteries the NiMH battery would cope with almost 100km on pure electric propulsion (see Table 12.10). Li-ion contains even more energy and can manage to drive electrically in almost 230km according to the simulations.

Table 12.10. Cost optimal for NiMH modern time (300kg).

Ece15	Li-ion	NiMH
Number of cells	280	360
Max Volt	1120	576
sKr/10km batt (today/future)	5.47/1.59	1.98/0.69
sKr/10km gas (today/future)	--/--	--/--
sKr/10km powergrid	0.97	0.97
Tot sKr/10km (today/future)	6.44/2.56	2.95/1.66
Nr km on pure electric	227.3	98.5
Lifetime (10km*1000)	313	39.2
Installation cost sKr*1000 (today/future)	107.9/31.46	39/13.65

Not even 10% of the state of charge is depleted after one ece15 cycle. So according to this simulation on could easily drive at least five such urban cycles without charging the batteries (see Fig 12.13). Unfortunately this is not validated with virtual testing but the numbers that the simulations produces is very interesting.

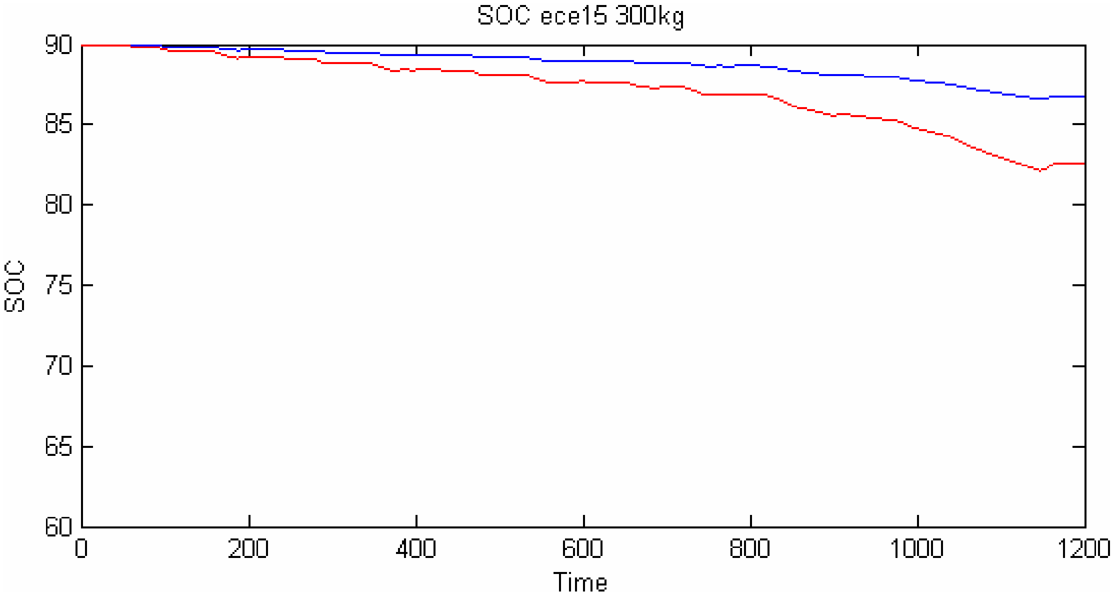


Figure 12.13. Li-ion, NiMH and the super capacitors, SOC Vs time, at 300kg on an ece15.

13 Discussion

In an early stage of this thesis it was decided to model the energy storages as equivalent circuits. This way was chosen due to its simplicity to implement, and therefore not very high computer performance is required. Of course there is a lot of alternative when building these models. The most accurate models probably are the electrochemical models, which describe every chemical reaction inside the energy storage. The drawback with these is that they demand a very high computer performance when simulating. Those can take days to simulate and therefore it isn't a very good alternative.
Other ways of doing it is neural networks, impedance spectroscopy among others. In reference [E] several methods are presented and discussed.

The implementation in Matlab/Simulink is done with s-functions in this project. An alternative would be to implement it with already existing blocks in Simulink.
This way was neglected because of that it is very hard to follow the calculations and it also prolongs the simulation time.

Batteries and super capacitors are not the only options for energy storage. Fuel cells are an alternative, but with limited dynamic range in power. Therefore a hybrid between batteries or super capacitors and fuel cells may be an alternative.
Another energy storage is the so-called flywheel. The flywheel stores energy by spinning a wheel and thus kinetic energy is produced. Those energy storages are quite big and volume consuming, therefore they aren't considered as an energy storage for HEV.

Currently the lifetime model used is the same for capacitors, NiMH and Li-ion. The only thing that is separating them at the moment is some constants. A better alternative would be to build a specific lifetime model for each technology due to the fact that all of them have different properties.

The control strategy for the powerassist is supposed to be the same as the one used in a real hybrid vehicle. Therefore no alternatives are considered because of that this is out of the scope in this thesis.
When receiving the simulation model there was no configuration for plugin mode, and therefore this had to be built. As mentioned before the strategy used in the simulations basically is that the car runs pure electrically until SOC is 20%. At that point the ICE starts and the battery is charged when generative braking occurs or when to much torque from the ICE is produced. An alternative would be to change mode into an MHEV when the 20% limit is reached. This may be a better alternative because that this would result in that ICE would run on a better point of efficiency than in the first alternative.

14 References

[1] www.scb.se, 2004

[2] www.rahq.com/chrginfo.htm, 2004

[3] www.high-techproductions.com/glossary1.htm#sectP, 2004

[4] www.corrosion-doctors.org, 2004

[5] www.batteryuniversity.com, 2004

[6] www.varta-automotive.com/eng/index2.php?p=4&s=3&content=knowhow/batterielexikon/entwicklung.html, 2004

[7] www.epa.gov/otaq/sftp.htm, 2004

[8] www.dieselnet.com/standards/cycles/ftp_us06.html, 2004

[9] herkules.oulu.fi/isbn9514269543/html/x787.html, 2004

[10] www.sanyo.com/batteries/pdfs/lionT_E.pdf

[A] John J.C. Kopera, “Inside the Nickel Metal Hydride Battery”, Texaco Ovonic Battery Systems, 2002

[B] Aurelien Du Pasquier, Irene Plitz, Serafin Menocal and Glenn Amatucci, “A comparative study of Li-ion battery, super capacitor and nonaqueous asymmetric hybrid devices for automotive applications”, Telcordia Technologies, 2002

[C] H.L. Chan, D.Sutanto, “A new battery model for use with battery energy storage systems and electric vehicles power systems”, IEEE 2000

[D] Pesaran A.A, Vlahinos A., Burch S.D., “Thermal performance of EV and HEV battery modules and packs”, Proceedings of the 14th International Electric Vehicle Symposium, Orlando, Florida, 1997)

[E] Sabine Piller, Marion Perrin, Andreas Jossen, “Methods for state-of-charge determination”, ZSW 2001

[F] Y. Saito, K. Kanari , K. Takano , T. Masuda, "A calorimetric study on a cylindrical type lithium secondary battery by using a twin-type heat conduction calorimeter”, Electrochemical laboratory Tsukuba Japan, 1996

[G] Andrew Burke, “Ultracapacitors: why, how, and where is the technology”, University of California, Davis, 2000

[H] NessCap Ultracapacitor, Technical Guide, Ver2 2003

Appendix

A. Powerassist

Table A.1. The input data for the NiMH sweep.

	Modern	Future (year 2015)
Gas price (sKr)	10	20
Price to buy (sKr/kWh)	2000	700
Price to buy (sKr/kW)	--	--
Life time (year)	15	
SOC reference value	75	
Quantity (cells)	20 to 250	
Quantity (kg)	20.8 to 260	

Table A.2. The input data for the Li-ion sweep.

	Modern	Future (year 2015)
Gas price (sKr)	10	20
Price to buy (sKr/kWh)	2400	700
Price to buy (sKr/kW)	--	--
Life time (year)	15	
SOC reference value	75	
Quantity (cells)	30 to 350	
Quantity (kg)	11.4 to 133	

Table A.3. The input data for the super capacitor PC2500 sweep.

	Modern	Future (year 2015)
Gas price (sKr)	10	20
Price to buy (sKr/kWh)	--	--
Price to buy (sKr/kW)	500	100
Life time (year)	25	
SOC reference value	60	
Quantity (cells)	90 to 300	
Quantity (kg)	65.25 to 217.5	

Table A.4. The input data for the super capacitor 3500/2.7V sweep.

	Modern	Future (year 2015)
Gas price (sKr)	10	20
Price to buy (sKr/kWh)	--	--
Price to buy (sKr/kW)	500	100
Life time (year)	25	
SOC reference value	60	
Quantity (cells)	80 to 300	
Quantity (kg)	53.6 to 201	

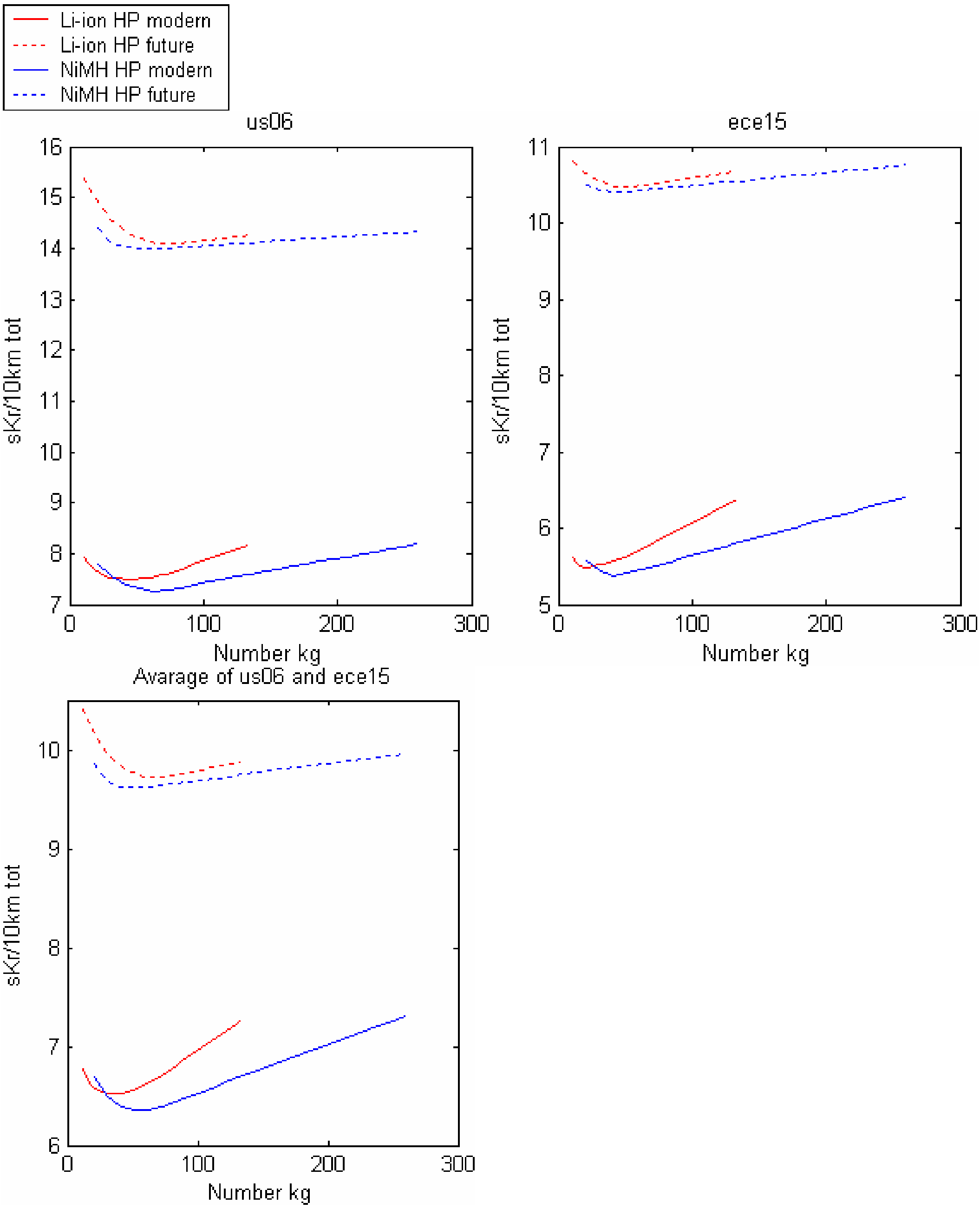


Figure A.1. NiMH vs. Li-ion. Modern time and the dotted line are future. Gas price and installation cost are printed in table A.1.

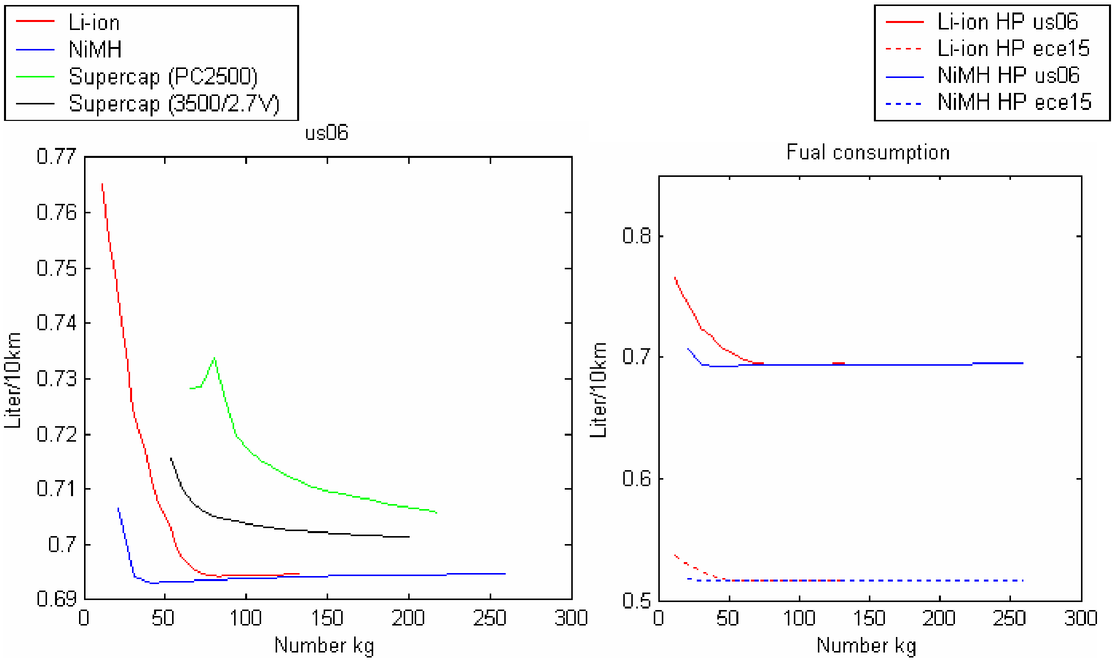


Figure A.2. Left figure: a plot of the energy storage with litre/10km Vs Kilo. Right figure: A plot of Li-ion and NiMHwith litre/10km vs. Kilo, (US06 and ece15).

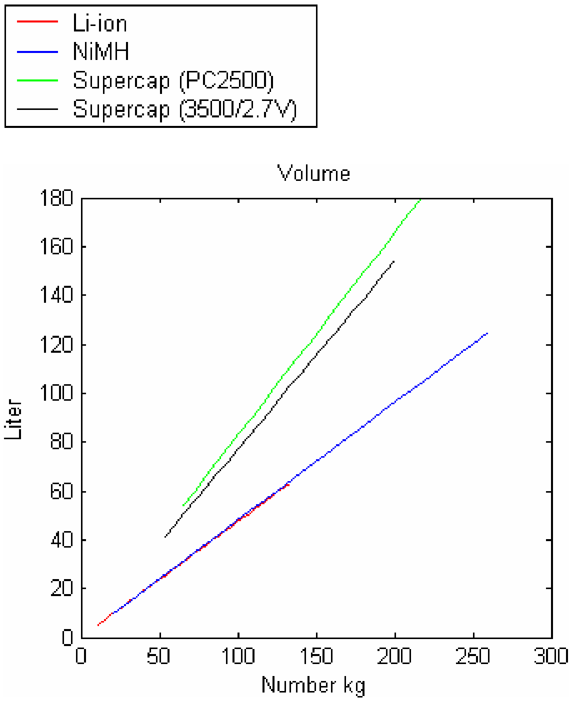


Figure A.3. Volume in litre Vs number of kg

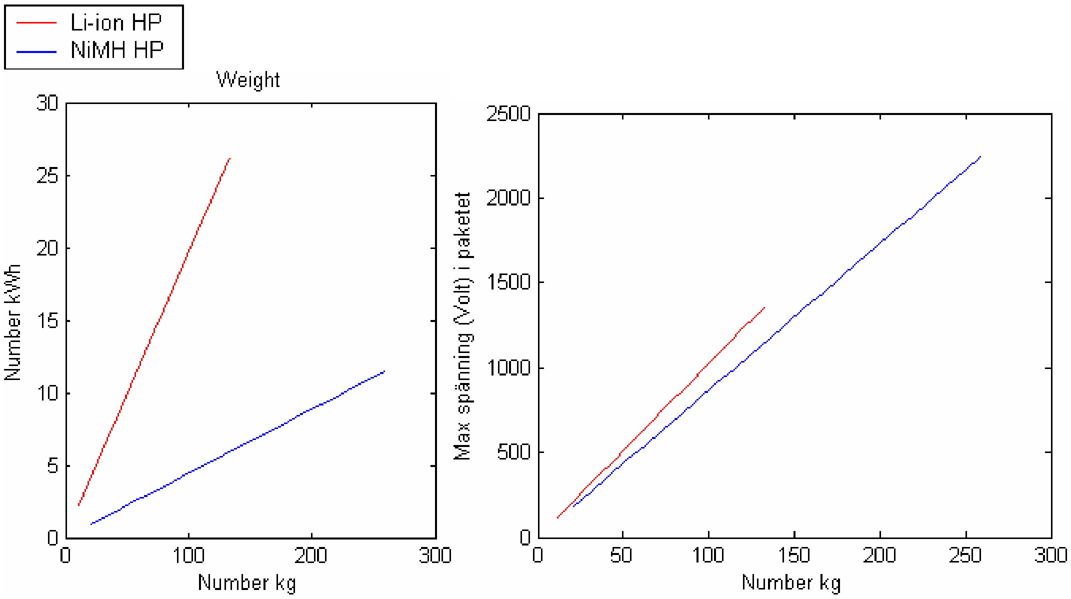


Figure A.4. Li-ion and NiMH. Left figure: Number of kWh Vs kilo. Right figure: Voltage Vs kilo

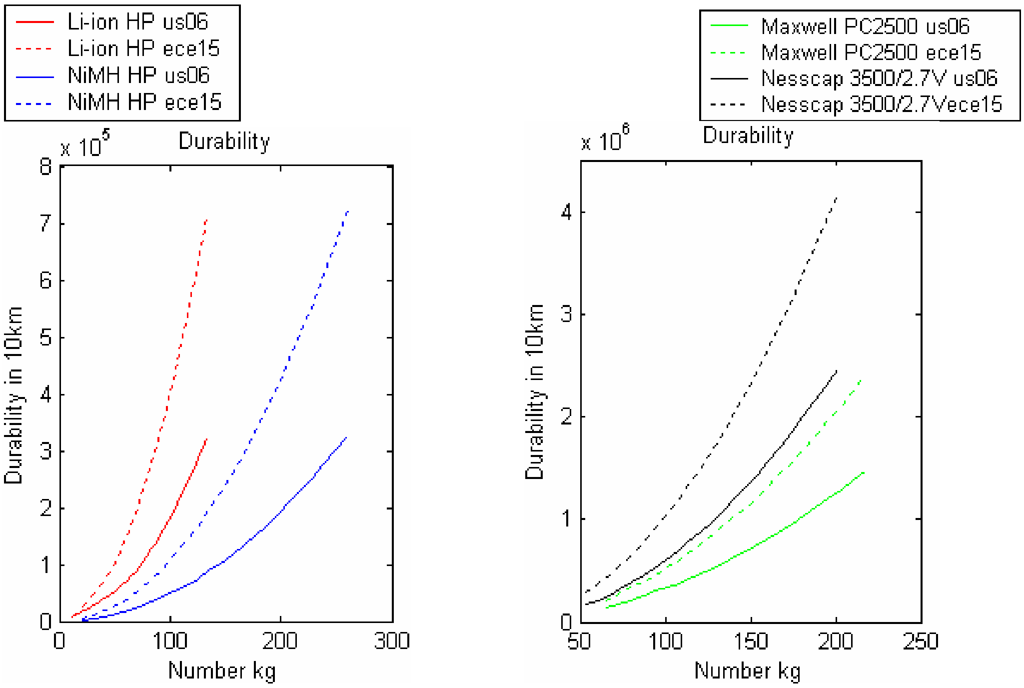


Figure A.5. Lifetime of the energy storage. Notice the exponent on the y-axis.

B. Plugin

Table B.1. The input data for the NiMH sweep.

	Modern	Future (year 2015)
Grid price/kWh (sKr)	0.7	0.7
Price to buy (sKr/kWh)	2000	700
Price to buy (sKr/kW)	--	--
Life time (year)	15	
SOC start/stop value	90/20	
Quantity (cells)	200 to 500	
Quantity (kg)	166 to 416	

Table B.2. The input data for the Li-ion sweep.

	Modern	Future (year 2015)
Grid price/kWh (sKr)	0.7	0.7
Price to buy (sKr/kWh)	2400	700
Price to buy (sKr/kW)	--	--
Life time (year)	15	
SOC start/stop value	90/20	
Quantity (cells)	80 to 330	
Quantity (kg)	85 to 353	

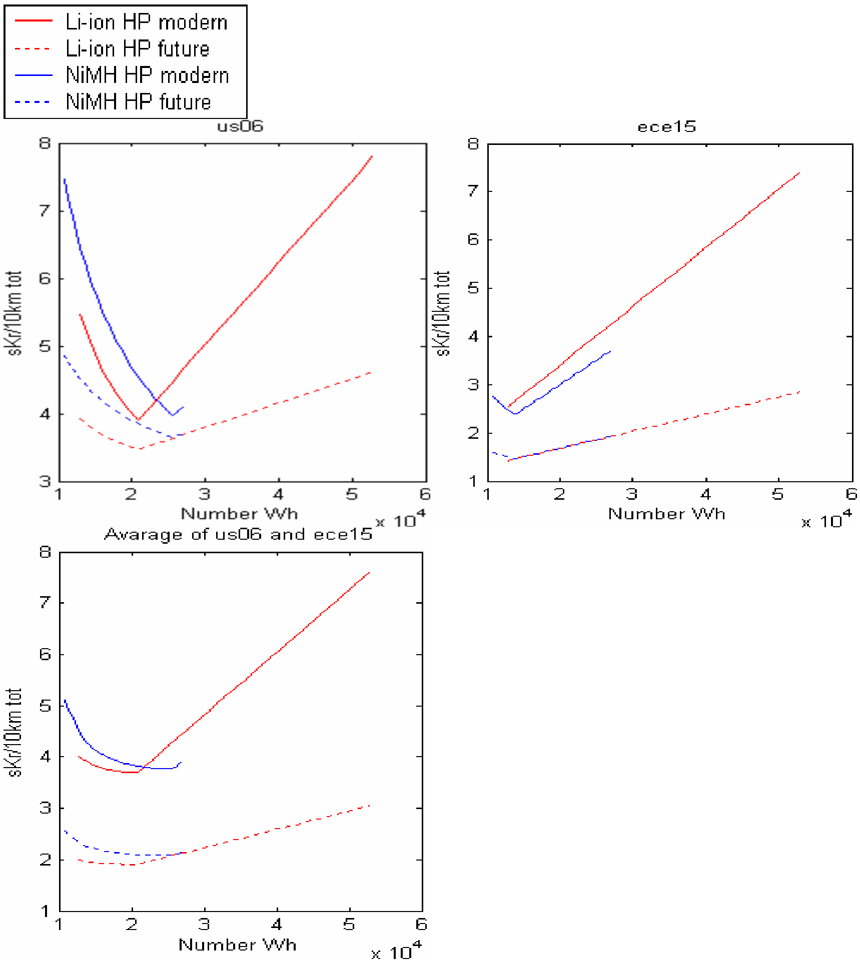


Figure B.1. NiMH vs. Li-ion. Modern time and the dotted line are future. kWh price and installation cost are printed in table B.1.

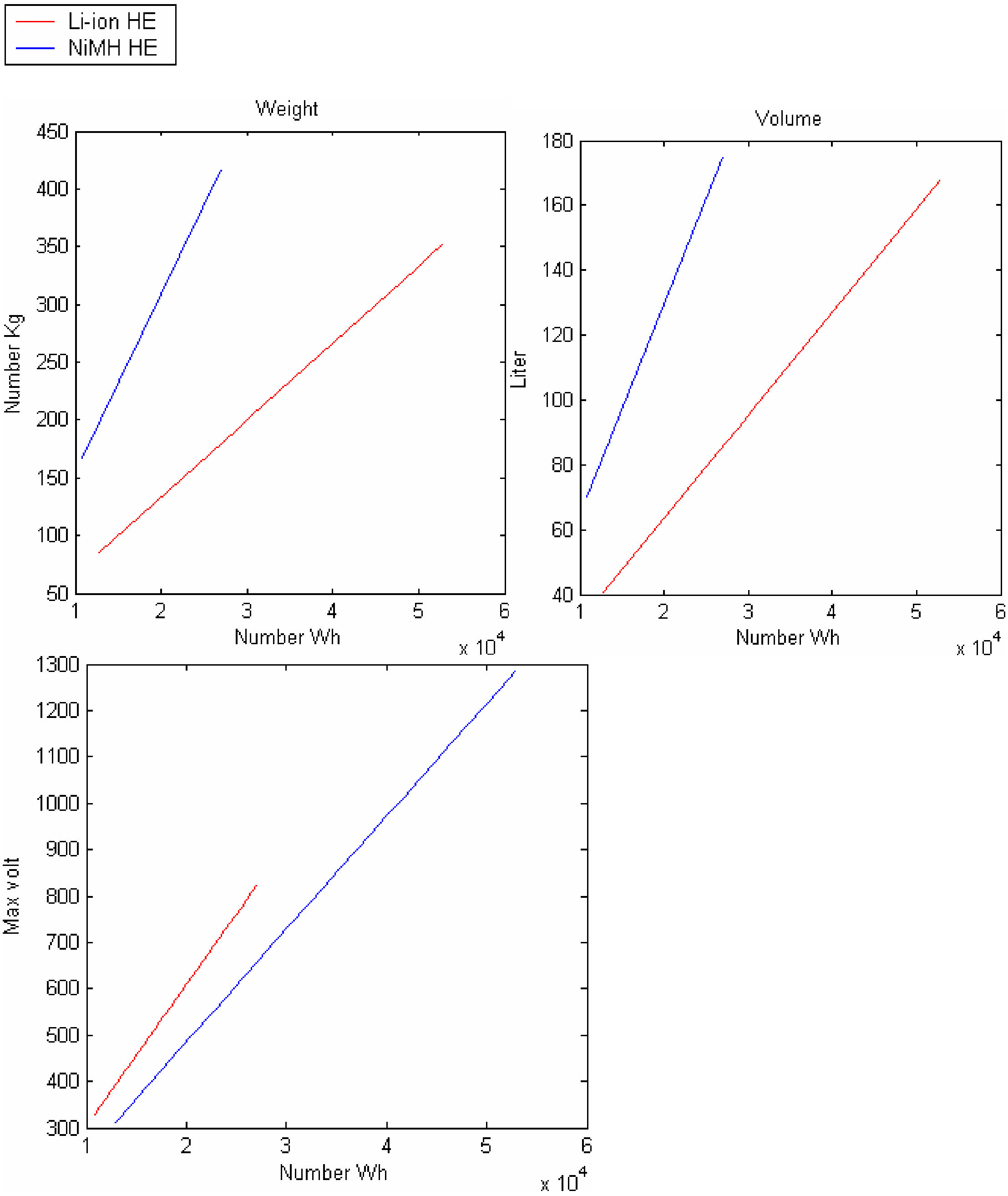


Figure B.2. Kilo, Volume in litre and voltage Vs number of kWh

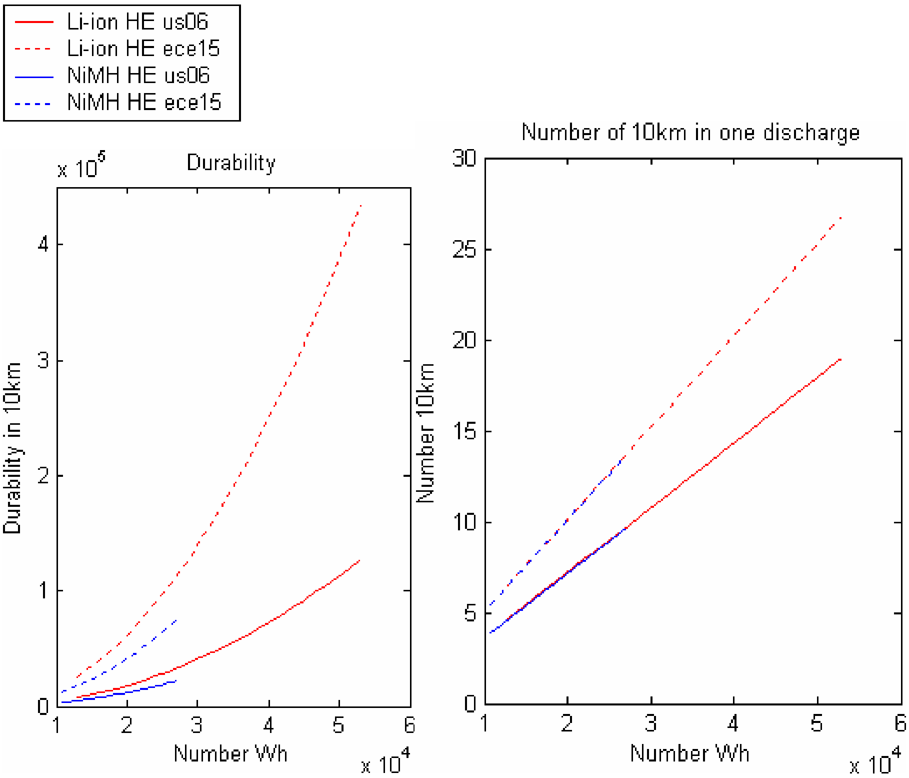


Figure B.3. Left: Lifetime of the energy storage. Right: Number of 10km that it's possible to drive in one charge.

C. Determination of battery parameters

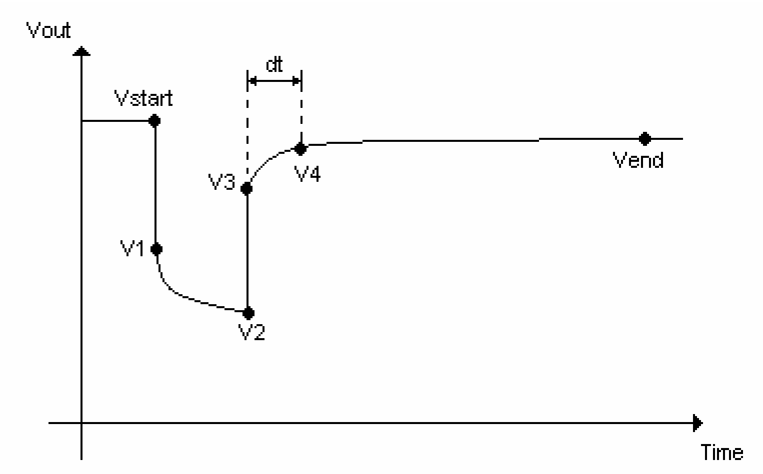


Figure C.1. Discharge of a cell with one current pulse.

Having the measurements marked in figure C.1 makes it possible to determine the parameters of the battery model in figure 7.3.
The bulk resistance of the circuit contributes to the instant voltage drop when discharging the cell:

$$R_b = (V_{start} - V_1) / I_{load} \tag{C.1}$$

In order to determine R_t and R_{pol} a relationship between them and R_b is supposed. The following relations are approximate values. From these one have to cut and try in order to get precise values for the cell in matters.

$$R_t \approx 1.25 * R_b \tag{C.2}$$

$$R_{pol} \approx R_t / 3 \tag{C.3}$$

R_b can be written like equation C.4:

$$R_b = R_t + \frac{R_e \cdot R_{pol}}{R_e + R_{pol}} \tag{C.4}$$

From this equation on can derive the resistance R_e, see equation C.5.

$$R_e = \frac{R_{pol}(R_t - R_b)}{R_b - R_t - R_{pol}} \tag{C.5}$$

Now all resistances are derived and the last component to evaluate is C_{pol}. V_{out} in figure C.1 follows the voltage across C_{pol} when the circuit has no load. The voltage across C_{pol} is then “charged” to the open source voltage (E), which is called V_{end} here. Equation C.6 shows the output voltage when the circuit in figure 7.3 is released from its load, e.g. from the point of time instantly following V_2 in figure C.1.

$$V_4(t) = V_3 + (V_{end} - V_3)(1 - e^{-t/\tau}) \tag{C.6}$$

In order to derive the value of C_{pol} one needs to know the time constant tau of the no-load circuit in figure 7.7. Tau is derived from equation C.6 and stated in equation C.7.

$$\tau = -\frac{dt}{\ln(1 - \frac{V_4 - V_2}{V_{end} - V_2})} \tag{C.7}$$

Tau is also equal to the capacitor times the resistance in the RC-circuit in figure 7.7:

$$\tau = C_{pol}(R_e + R_{pol}) \tag{C.8}$$

Putting equation C.7 and C.8 together yields the following equation for C$_{pol}$:

$$C_{pol} = -\frac{1}{R_e + R_{pol}} \cdot \frac{dt}{\ln(1 - \frac{V_4 - V_2}{V_{end} - V_2})} \tag{C.9}$$