Next Generation Battery System

Project within FFI Energi & Miljö

Theresa Granérus, Volvo Car Group

2015-04-30

Content

1. Executive summary

A prerequisite for a successful introduction of electrified vehicles such as hybrid, plug-in-hybrid and electrical cars are an increased competence and knowledge within the battery area. Today, we still see a rapid technology development especially regarding li ion battery cells. The battery system is a critical system for Volvo Car Group (VCG) ability to realize our strategic electrification plans, due to system complexity, cost, safety, life requirements.

The main objectives of this project (referred to as NGBS) was to enable high volume electrified vehicles, by introducing top down systems engineering approach, reduction of battery system life time cost and to develop specific knowledge for specification of VCG's next generation battery systems. An especially high set goal was to reduce the life-time cost, still with maintained properties, with 50% compared to Volvo Car Group first generation PHEV battery in 2012. This target was achieved with flying colors. The product cost ($/kWh) has decrease from V60 PHEV to next platform CMA PHEV with 60%.

Mastering the battery cell technology and understand how to use the battery in an optimal way and deliver range and performance is the number one challenge on the way to reliable performance and solid profitability for VCG's electrification strategy. The objectives of the project has been achieved and the strategically important battery knowledge obtained within all battery system areas have made Volvo Car Group a better specifier, developer and purchaser of battery systems. A commercial battery system with attributes meeting the customers' demands in turns of electrical range and vehicle performance will enable the implementation of Volvo Car Group's electrification program.

2. Background

Volvo Car Group vision is to be the world's most progressive and desired premium car brand. We will stand out from the crowd by delivering a distinct and sophisticated car experience built on our own, unique Scandinavian profile. We will challenge conventional thinking by delivering uncompromised mobility that supports a sustainable future. Desired by our customers. Respected within our industry. Moreover, inspired by a global society in continuous motion.

The core values within Volvo Car Group are safety, quality and environment. People's health, energy efficiency and resource efficiency drives our focus on the environment. We will continue to design our products to be a natural part in a sustainable future and to be a natural part of people's lives, as we strive towards uncompromised mobility. For example, the introduction of Drive-E powertrains means more power with less fuel consumption. Volvo Car Group is leading the CO2-reduction race by reducing fleet emissions by 12 grams, 8%, during 2013. This marks a 42% reduction since 1995. For Volvo Car Group, future mobility is the same as sustainable mobility. Volvo Car Group have 40 years of experience within efficiency and electrification and will continue to actively innovate so that sustainable mobility is achieved.

"We have a very strong portfolio of plug-in hybrid products right now. In fact we have the broadest offer of all car manufacturers. But we are not stopping there. We will introduce two new

Twin Engine variants every year in the coming years," said Dr. Peter Mertens, Senior Vice President Research & Development at Volvo Car Group April 2015.

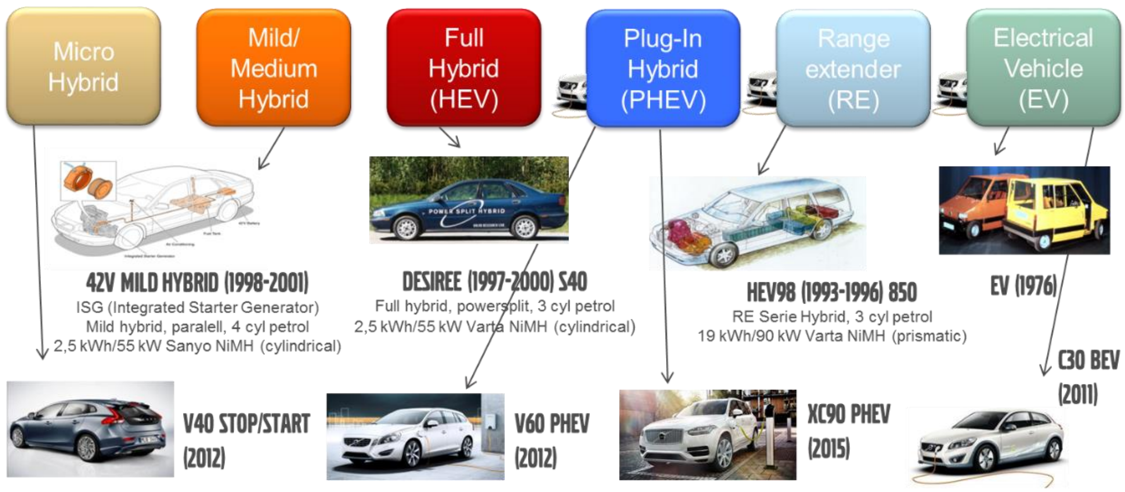

Figure 1. Example of projects within Volvo Car Group within the electrification area during the past years.

The battery area for automotive industry is a field that develops rapidly. The learning curve within the area has been steep during the past years. When Volvo Car Group developed the V60 plug-in hybrid and launched it in 2012, there were still very few electrified vehicles (such as hybrid, plug-in hybrid and pure electric vehicles) on the market. Today the number of electrical vehicles, especially the plug-in hybrid vehicles, increases steadily on the market. During the time of this project (the last four years) the general knowledge within the battery area both for battery and cell suppliers together with vehicle producers has increased very much. So also within Volvo Car Group, due to this project.

The battery development is moving very fast with new battery chemistries and technologies introduced on the market. This means that today there are no key answers to how long the battery will last and to what extent since batteries produced a decade ago were considerably different from today's batteries. In addition, most of them produced for the consumer electronics market with significantly different usage patterns and lifetime demands.

One strategic step taken of many companies within the automotive industry is by themselves develop and construct new knowledge of functions and steering algorithms to reach the desired needs of the customer such as performance, safety and life time. An optimization of battery properties and knowledge of how customer will use the battery in different applications are a prerequisite for obtaining a desired lifetime with a low lifetime-cost. Predicting the lifetime of these batteries in vehicles is today a strategic area and the automotive producers need to work in depth with these questions to make reliable methods.

The battery system is a critical system for Volvo Car Group's ability to realize VCG's strategic electrification plans, due to system complexity, cost, safety, life and the supplier chain inadequate knowledge within many areas. Volvo Car Group need to continue to build competence and strategically important knowledge to be able to develop in-house, strategically critical functionality and battery usage strategies. This is a prerequisite to minimize cost, weight and volume, deliver a premium car experience, and satisfy the customer's desire when it comes to electrical range and performance.

3. Objective

Main objectives of the project was to enable high volume electrified vehicles, by introducing top down systems engineering approach and gain strategic knowledge within the battery area. Benchmark of Volvo Car Group competitors together with thorough battery supplier evaluations have been performed.

Different methods within the different areas has been developed to optimize the battery usage, life, cost, HW/SW solutions, thermal system, safety, volume and weight, which were one of the objectives in the projects. Within the project we have develop specific knowledge for specification of VCG next generation battery systems, such as design guidelines for future battery systems.

Within the project, Volvo Car Group formulated very aggressive cost, weight and volume targets. The cost target was to reduce the battery system lifetime cost with 50% (with maintained properties) compared to VCG first generation PHEV battery from 2012. This has been accomplished. The product cost ($/kWh) has decrease from V60 PHEV to next platform CMA PHEV with approximately 60%. The weight and volume target, to decrease the weight and volume with 25% from the V60 PHEV, was almost accomplished. The system weight has decreased with approximately 17% and the volume with approximately 34% per kWh (energy content) from the V60 PHEV to next platform CMA PHEV.

The objectives of the project has been achieved and the strategically important battery knowledge obtained within all battery system areas have made VCG a better specifier, developer and purchaser of battery systems.

4. Project realization

Battery systems contains a number of different components and functionality that requires knowledge from different disciplines, such as, for example chemistry, mechanical and thermal knowledge.

For mastering the battery area, it requires a lot of different competence and within the project; we have set up ten work package that covers six different areas, system design & optimization, management functionality, models, usage & life, safety and thermal system.

Table 1. Work package and the corresponding battery area within the project.

	Work Package
1	Technology Watch
2	Optimize Battery System due to Life, Cost, Weight and Service

3	Battery Models
4	Battery Management System Functionality
5	Cell Balancing
6	Battery Usage
7	Life
8	Field Test Equipment in Hybrid Applications
9	Electro-chemical Safety
10	Energy Efficient Cooling System

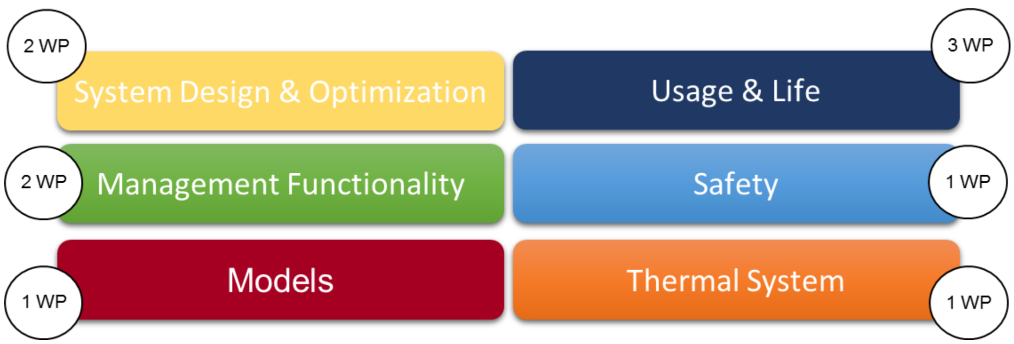

Figure 2. Battery areas where work have been performed within different work package.

4.1 WP 1 – Technology Watch

The enabling Li-Ion technology is juvenile and continuously undergoes rapid and frequent changes. Immature supplier base, especially with respect to battery packaging, battery usage in automotive and predictability of battery life length, have forced the competitors of Volvo Car Group to handle battery integration by themselves. VCG needs to build strategic knowledge and perform a thorough technology watch, including benchmark activities, battery supplier evaluation and cell performance evaluation.

During the past years, Volvo Car Group has also observed that the competitors are building up battery labs for in-house testing and cells, modules and battery systems. Included in the technology watch was also to understand what kind of in-house testing equipment VCG needs. The purpose with WP 1 was to gain competitive edge so VCG can offer latest technology at better cost, earlier in time.

Objectives & Achievements

The aim of the work package was to gain strategic knowledge within battery system and battery cells by conducting battery supplier evaluation and perform hybrid/plug-in hybrid/pure electrical vehicle competitor's benchmark. Gained knowledge of Volvo Car Group's needs of in-house testing of batteries has also been achieved and with this knowledge VCG has built a battery test facility. The objectives of the work package has been achieved.

Realization, Activities & Results

During the project time, an ongoing thorough technology watch has been conducted. The main activities has been to evaluate cell- and battery system suppliers by benchmarking activities according to Volvo Car Group developed methods. A number of suppliers and sub-suppliers techniques, strategies and concepts has been evaluated by meetings and on-sites visits. Tier 1 in both Europe, Asia and US have been visited or interview continuously during the project. Supplier visits reports and evaluation reports for different suppliers, for example the Chinese suppliers have been written. In the same way, continuously during the project, benchmark has been performed on competitors existing and future hybrid (HEV), plug-in-hybrid (PHEV) and electrical vehicles (EV). This has been performed by visiting automotive shows, general information gathering and teardown of competitor's vehicles, for example Opel Ampera.

An important part of the supplier evaluation is to evaluate the battery cells. This is done by evaluating the beginning-of-life (BOL) performance together with the performance over the battery life. The BOL performance is the energy or capacity content and the power capability of the cells.

The evaluation of the cell life performance over the years contains information how the degradation of the cell performance changes due to different cell usage. Knowledge within cell and battery usage for delivering required customer attributes, such as electrical range and power performance has been achieved within work package 6.

VCG specific test methods for evaluating suppliers different cells have also been developed. These test are named reference performance tests (RPT). Today there is a number of different international standardized test methods used. These have been evaluated within the project. A VCG specific RPT including capacity test and so called HPPC (Hybrid Pulse Power Characterization) test has been developed and used for evaluating different suppliers HEV and PHEV cells in VCG battery test facility.

The development of VCG specific test methods had not been possible without an in-house battery test facility. Due to the gain knowledge from this project, Volvo Car Group have built up an in-house battery test facility. In-house testing of batteries including cells, modules and systems are needed to have competitive edge within the battery area. The customer benefit by building strategic competence in-house also when it comes to testing batteries is that Volvo Car Group will understand how to use the battery system in an optimal way and thus being able to deliver the customer required range and performance. It is also important to avoid too aggressive usage as it may lead to premature battery end of life and high warranty costs together with discontent customers. Volvo Car Group need to secure the battery life by validating our life estimations. No standardized life estimation models are available today and VCG have developed a specific process to estimate the battery life dependent on the customer usage of the vehicle. The life estimation model use accelerated life test on cell level as input and today no standardized life tests are available. VCG have develop specific accelerated life test methods on cell, module or system level. In-house testing of batteries is necessary to acquire knowledge to secure the battery life.

Fewer test vehicles drives Volvo Car Group towards model-based development, which in turn is a prerequisite for shorter time to market and reduced development costs. Model based development is dependent on that we have validated cell/module/battery-models. In order to develop and validate, for example, the models for the control algorithms VCG must be able to characterize the cells and test them accordingly. Volvo Car Group does also needs to build competence in-house to be able to secure the right supplier choice by doing benchmark and test suppliers different cells.

A number of different conferences has been attended during the project to gain more battery knowledge. The achieved knowledge within Volvo Car Group has also been spread at different conferences and at different internal and external seminars and workshops. A number of presentations and conference contributions has been produced.

4.2 WP 2 – Optimize Battery System

The battery system is a critical system for Volvo Car Group 's ability to realize Volvo's strategic electrification plans, due to system complexity, cost, safety and life requirements. The purpose of this work package was to enable long-term cost reductions of batteries that would enable high volume of electrified vehicles in the future.

Objectives & Achievements

The aim were to develop a method to optimize cost, weight and safety of battery system and secured future integration of complete battery system with a scalable battery pack design. Within the work package Design Guidelines was developed with updated applicable system requirement specifications. A number of activities have been performed to develop Design Guidelines with refined system and functional requirement including battery usage and cell strategy for existing and coming projects. A commodity business plan (CBP) for system design, sourcing and manufacturing of battery system have also been developed. The objectives of the work package have been achieved.

Realization, Activities & Results

Within this project a commodity business plan (CBP) for the battery system was established. When this project started the current state of battery systems was characterized by the following primary cost drivers.

- The enabling Li-Ion technology was juvenile and continuously undergoes rapid and frequent changes.
- VCG have volume constraints due to lack of space together with unclear internal requirements on the battery system that drive costs.
- Low predicted product volumes of electrified vehicles prevent volume driven cost-down strategies.
- Immature supplier base, especially with respect to battery packaging and battery usage, forces the competitors to handle battery integration by themselves.

Within the work package the main activities have been to identify the key parameters for optimization of cost, HW/SW solutions, thermal system, safety, volume, weight, battery usage and life. The result is summaries in the Design Guidelines. The document contains guidelines to secure the future integration of battery systems with scalable battery design dependent on application. The purpose of the design guideline is to document the to-date knowledge level and internally share best practice and lessons learned within the battery area within Volvo Car Group. The document acts as support document within the construction area to avoid repeating problems, but also to avoid repeating problems arising in the interfaces with other related construction areas. The purpose is therefore to secure a successful and efficient battery system launch from a holistic car development point-of-view. The document also support component and system designers in the process of selecting or excluding technical solutions; either internally designed or offered by a supplier.

The document covers more than just solely construction related guidelines. Much work is put into development projects before the design and dimensioning starts. First attributes have to be assigned to the project which later need to be broken down into requirements, which in turn sets the boarders for the design, dimensioning and programming. Since all these phases contribute to the final quality of the product, both in terms of customer perceived quality of the final car, but also the quality and efficiency of the development process. Because of this, guidelines related to the whole development process is included in the document.

The product development process is covered with some central, general, guidelines aiming to support vital parts of the product development process. Quality feedback from the field is included. This is one of the most valuable feedback sources since these are problems that have slipped through the process and affected our customers. This input should be a vital part and natural feedback source to all design and redesign work. General guidelines concerning manufacturability and design for assembly is also covered. Important to remember is that anything designed, must be able to be produced to be able to reach the customers. The design of the product early determines the product cost and quality of the product, which has a direct relation to cost and customer satisfaction.

4.3 WP 3 – Battery Models

Model-based development is needed in the automotive industry due to very short developing times and low-cost requirements. By enabling model-based development Volvo Car Group will gain time to market. Model based development requires developed and validated battery models, which depends on the possibility to test cells, modules and battery systems in-house. Within the battery areas, different models can be used for different purposes. Evaluation of the needs for different battery models within Volvo Car Group has been performed. The electro-chemical processes that occur inside the cells often turn out to be too complex to model for practical application in electrical engineering. Instead, equivalent electric diagrams can be used to represent the behavior of batteries. These give an incomplete picture of the cell behavior but can be used if the model limitations are known and well understood. Besides electrical models, different VCG specific models, such as thermal, BMS controller, Electrochemical Impedance Spectroscopy (EIS), life, and cell crash models have been developed and validated. The life model has been developed within WP 7 and the cell crash model has been developed within WP 9.

Objectives & Achievements

The main objective was to develop and validate Volvo Car Group specific battery models, which has been achieved.

Realization, Activities & Results

One of the main activities has been to evaluate the need for different battery models within Volvo Car Group and document and share information about the existing battery models within VCG. Knowledge of different battery models have also been acquired by evaluation and mapping of different suppliers experience and knowledge of different models.

By performing complete vehicle drive train simulations, VCG estimate the fuel consumption using different vehicle control strategies. The battery model within this simulation model contain a plant model (including a thermal model) together with a controller model. The plant model is an electrical model, which is based on a cell model that can be scaled up to a battery depending on the number of cells/modules connected in parallel or in series. Different battery technologies can be simulated with this model by choosing an appropriate data file. The controller model contains estimation of the state-of-charge of the battery and limitations that are used by the PVC model (Propulsive Vehicle Control) to avoid abusive usage of the battery. All developed models needs to be validated. In addition, model validation is about quantifying how a combination of a model and a data file performs compared to measured data. Validation is always performed over a defined space represented by the internal states of the model, which is the range of validity for the model.

Within the battery management, system (BMS) in the vehicles a cell model is used in the control algorithms. An evaluation of the two different cell models developed by the battery supplier in the V60 PHEV and XC90 PHEV is performed. The evaluation states that it is extremely difficult to make a model that behaves exactly as the cell does, even within sensible voltages. This is because several internal processes have large impacts on the voltage response of the cell. These are inherently difficult to model, since they are sensitive to detailed chemical characteristics that differ from cell type to cell type and change over the life of the cell. The approach used in battery control algorithm implementations is therefore to rely on good algorithms to overcome the problems of the cell model.

An Electrochemical Impedance Spectroscopy (EIS) model has been developed and experimental tests on battery cells has been performed to serve as input for the model. EIS is an experimental technique used to characterize electrochemical systems, such as batteries. The method measures the impedance of a system over a range of frequencies and the mass-transport properties and kinetics of the cell. Reports from the experimental tests and model development and parameterization has been written. The work with model development using Electrochemical Impedance Spectroscopy has been done in corporation with AB Volvo.

4.4 WP 4 – Battery Management System Functionality

The aim of the work package was to achieve strategic knowledge within battery management system (BMS) functionality and algorithms. There is a number of different functionality in the BMS, for example monitoring the cells (voltage, current and temperature), estimate State-of-Charge (SOC), state-of-Power (SOP), state-of Energy (SOE), state-of-health (SOH), cell balancing functionality, diagnostic functionality and power limit manager.

Volvo Car Group has identified cell algorithms and battery management SW as areas of strategic importance. The long-term strategy is to bring the battery control algorithm development in-house. The advantages are reduced lead-time, increased quality and thereby reduced warranty risk due to wrong usage of the cells. This would reduce the dependence and reliance on suppliers. This is strategically important for VCG preparation of a widening of the electrification offer in the future and will give opportunity for use-optimization with focus on the customer needs.

By optimization and use of adaptive functionality in the battery management system Volvo Car Group can increase the battery utilization for maximum customer attributes, securing the battery life, reducing the lifetime cost and risk of high warranty costs. Due to future battery standardization and commonality the BMS will be one of the foremost possibility to differentiate VCG battery system against competitors.

Objectives & Achievements

The main objective, to gain strategic knowledge within BMS functionality has been achieved. The objective was also to develop BMS algorithms of strategic importance for Volvo Car Group. Within the project a Thermal Manager Control has been developed. More extensive work with development of VCG BMS control algorithms has been done in other projects, such as SOF (State-Of-Function), BATMAN and continues in Livslång batteristyrning.

Realization, Activities & Results

Within this work package we have analyzed the battery control algorithm system that we at VCG consider necessary in order to control a Li ion battery over its life to be able to optimize fuel efficiency, electric range and CO2-emissions over the vehicle's entire life.

Based on the work in the project we have designed a split of the algorithms, based on which VCG can make decisions on what to bring in-house and what to leave for implementation at the supplier. Some of the identified algorithms have already been brought in-house. To take this kind of functionality in-house, a proper development process is needed. VCG has developed a working methodology for AUTOSAR as part as our normal development process. It is recommended that this requirement-driven development is followed even in this field.

The main activity within the work package has been to perform in-depth analysis of our supplier´s algorithms. In the work we have analyzed and worked with different improvements. We have analyzed the benefits and disadvantages with their design choices and internal processes. A result of the work carried out in NGBS has been that we have identified further core areas where further knowledge is needed to fully bring key development in-house. One of these is the development of battery control algorithm specialists. Work to increase the knowledge in-house and in the Swedish automotive cluster has started through internal and external research projects. Further knowledge on the ageing behavior of Li-ion cells as well as their internal electrochemical processes have also been identified and are approached in yet other research projects, one of which has had a PhD student working in it for over a year to this date.

The research and development work conducted in the project has been essential in building the foundation needed on Battery Management System development. We have learned that the broad field covered by the work package has parts which needs to be studied much more in detail in separate research projects. Without the project many valuable lessons would have been learnt too late within the BMS algorithm area. Instead, Volvo Car Group and the Swedish Automotive Cluster has a solid head-start within the area that has been seen in conferences attended by VCG specialists.

4.5 WP 5 – Cell Balancing

Battery systems with Li ion cells needs to have a cell balancing system. Balancing of the cells is made to bring the SOC of the individual cells closer to each other. This is necessary to get as much energy as possible out from the battery system. The SOC for individual cells may diverge because of different cell capacities, different cell self-discharge, different cell temperatures. Lack of knowledge about cell balancing will exposes Volvo Car Group to risks for high warranty costs and restricted customer usage of the battery system.

Objectives & Achievements

The main objective is to acquire strategic knowledge within cell balancing. This includes knowledge about the different reasons why the cell balancing occurs, knowledge about different techniques and concept (active and passive balancing) and acquire knowledge about different supplier solutions. The objectives are achieved and strategic knowledge with cell balancing is acquired.

Realization, Activities & Results

The main activities have been to evaluate different strategies and concepts of cell balancing for different HEV/PHEV/EV applications. Cell balancing tests has been performed on cells in a prototype module. Supplier benchmark and evaluation has also been performed within the work package.

Active and passive balancing has been evaluated. Passive balancing will not give much higher capability to the battery system if the imbalance is due to different capacity of the individual cells. However, it will increase lifetime of the complete pack though. If the imbalance is due to different self-discharge of the individual cells, this can normally be almost completely compensated by passive balancing. The main conclusion is that since the quality and homogeneity of the automotive cells that Volvo Car Group are using are very high the need for balancing is low and therefore passive balancing is sufficient. A balancing strategy has been worked out internally at VCG that constitutes as the base for balancing implementation in future projects.

The main results is the acquired knowledge about how cell balancing can be performed, with different concept. In addition, what kind of different strategies can be used, for example when should the balancing take part? Another result is the knowledge from the evaluation of different supplier's cell balancing hardware. A benchmark of different ASIC:s used for balancing and cell monitoring is made in WP 2.

4.6 WP 6 – Battery Usage

The customer benefit by building strategic competence within Volvo Car Group is to understand how to use the battery systems in an optimal way and deliver range and performance. Too aggressive usage on the other hand may lead to premature battery end of life. Full cell knowledge will provide competitive edge, the OEM that can utilize the battery in the best way will have a cost / performance advantage. A verified adaptive usage strategy and functionality is crucial to minimize the risk for premature end-of-life and high warranty cost together with loss due to reduced brand value.

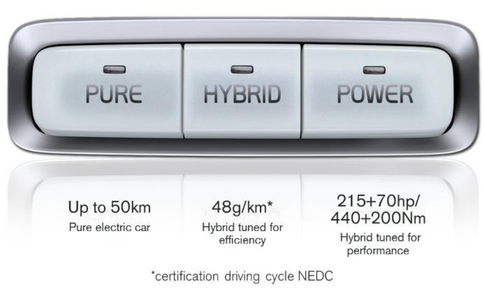

Figure 3. Different driving modes in the V60 PHEV.

When the project started, there were no high mileage in-use vehicles available because the first Volvo PHEV was not realized yet. There was a need within Volvo Car Group to build knowledge and collect in-use data to understand the battery usage and verify the first estimation of battery detoriaton severity. Within VCG, a communication node was under development to be able to collect data and send it regularly through 3G to VCG. The system was used to develop the methodology within fault handling for different components. Within this project a plan was set up to bring back in-use data from a fleet of V60 test cars and eventually customer cars that was equipped with flight recorders that collected battery signals. The need within the battery area was to verify the customer assumptions made, develop the customer models (customer severity) within the life model, correlate the battery usage to the battery ageing in the life model, verify the model and to develop and verify usage strategies and functionality to secure the battery life. The VCG life model and process was developed in work package 7.

Achieved knowledge of battery usage together with a developed life estimation model, have enabled Volvo Car Group to prolong the battery life by using developed battery usage strategies. Lack of knowledge about battery usage exposes VCG to risks for high warranty costs.

Objectives & Achievements

The main objectives, to gain strategic knowledge how the customer usage, the battery usage, and how this different usage detoriate the battery have been achieved.

Realization, Activities & Results

To be able to develop a methodology for predicting the battery life for real customers, information about the customer's habits such as driving behavior and driving pattern together with specific battery parameters was needed. The data collection started with a few test cars and has continued during the project to a larger test fleet including real customer vehicles.

The signals of interest from all the different components (for example the battery system) are collected in a device that store the data continuously. The equipment contains the measuring assignment that can be changed over time dependent on the interest from the developers for different components. Every time the vehicle is turned off, the collected data is sent through 3G network with a transponder. The data is uploaded in the data portal at VCG. The data could then be analyzed during the production development and used to develop fault handling.

Within this project, the data collection method developed was used to understand the customer usage of the battery and how the ageing was affected by the different usage. An analysis tool was developed for analyzing the battery usage. The project started with to identify the information interested to understand the battery usage. A number of questions was asked. What did we want to know about the usage behavior and battery behavior? What do we need the information for, what kind of format do we need? Which signals should we collect to get the desirable information? Moreover, in the end how should the information be analyzed and presented?

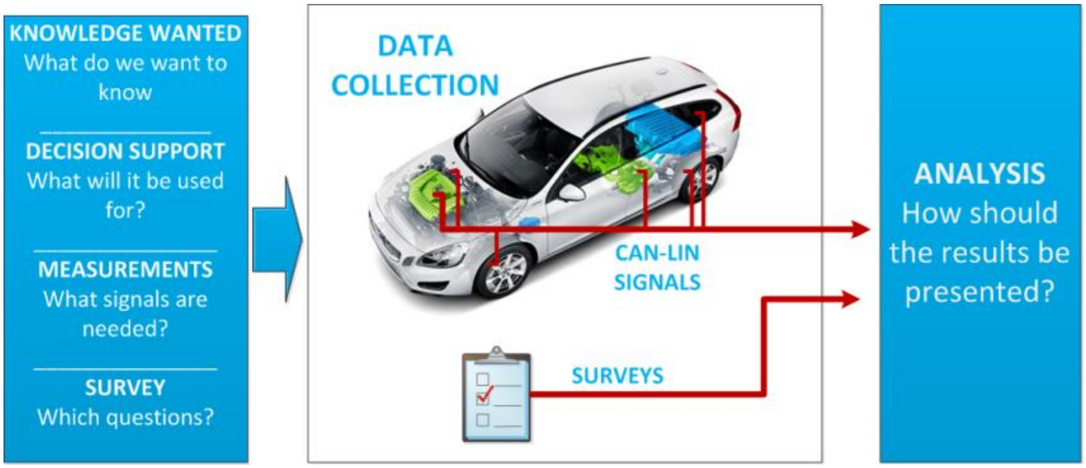

Figure 4. The process for developing the analysis tool to understand the battery usage and the corresponding ageing.

A large number of analysis was performed an gave us information of the battery usage and the corresponding battery degradation. This information is used in developing the life estimation model for the battery dependent on specific customer behavior. Battery diagnostics together with fault codes are also collected to develop the battery fault handling.

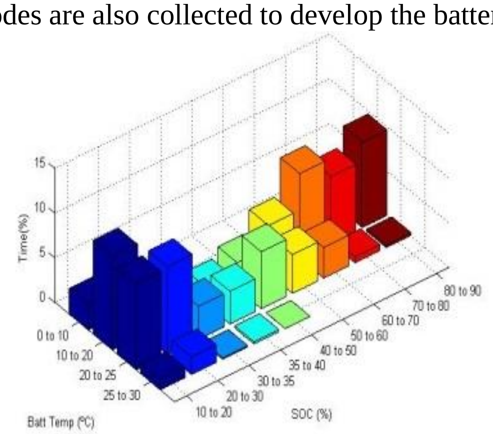

Figure 5. Example of battery temperature vs SOC histogram.

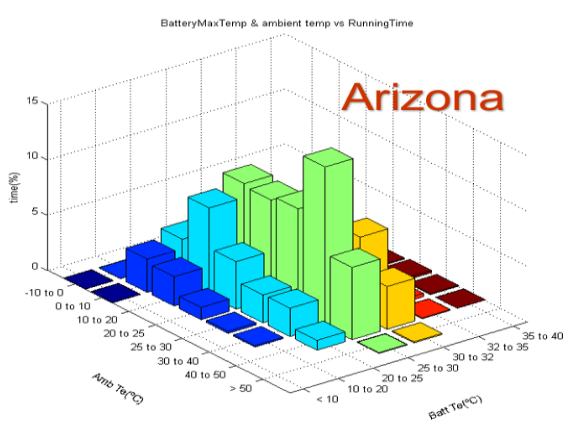

Figure 6. Example of ambient temperature vs battery temperature in a vehicle in Arizona.

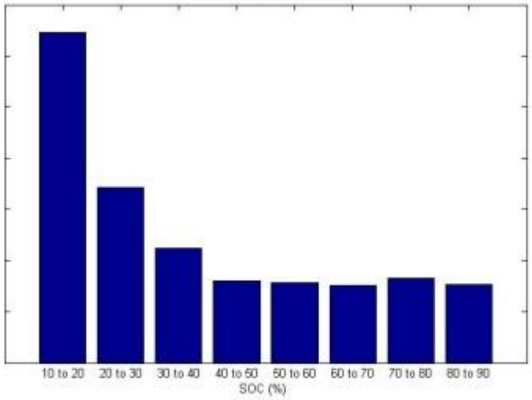

Figure 7. Example of SOC histogram during driving.

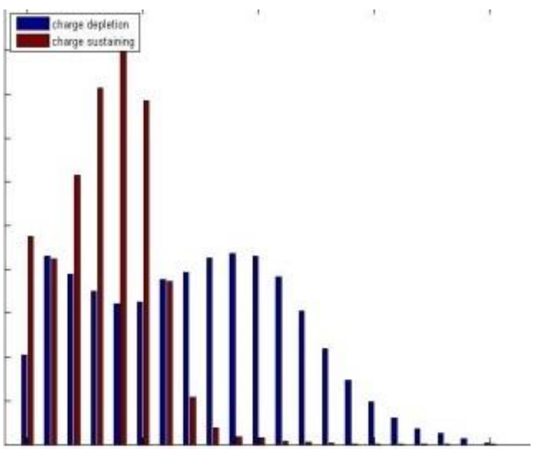

Figure 8. Example of RMS current during two different driving modes.

Within all the customer production vehicles, Volvo Car Group have developed a regular system health data collection. The system makes it possible to collect parameters and diagnostics when the car is at the workshop for maintenance. It is called diagnostics-read-out (DRO) and a set of battery parameters can be red out and sent to Volvo Car Group for further analysis. The knowledge is used to develop on-board diagnostics for customer usage and system usages and fault handling. For the battery system, we has within this work package developed the (DRO) system to do on-board diagnostics for the customer and the battery health. With the information, we can develop customer driving profiles, develop and verify battery life estimation models, develop powertrain vehicle control functionality, adaptive usage functionality, analyze failure scenarios and develop and verify our battery usage strategies for different applications.

VCG need to continue to perform a lot of testing both in lab and in test vehicles to understand how different driving behavior's contribute to the battery degradation. For example, test cells, modules and systems with different driving profiles, different charge currents, different RMS (root-mean-square) current limitations, different SOC windows and different temperature ranges.

The electrical range is crucial and very much discussed parameters for an electrified vehicle. The range depends on the energy amount in the battery. With time, the degradation of the battery will decrease the energy content and thereby the electrical range for the customer. But the electrical range does also depends very much on a number of other parameters, such as ambient temperature, battery temperature, driving behavior, speed, electrical load, climate compartment loads and pressure in the tires. The vehicle driving resistance depends very much on the ambient temperature and the car uses approximately 30% more energy during the winter in Sweden compare to the summer. With a brand new car, an effect outweigh the degradation of the battery during the approximately first two years. When the driving train is used, the vehicle drives more and more easily and uses less energy during the approximately first two years. How this effect together with how the yearly seasons will influence the electrical range has been analyzed in the work package. For instance, the customer will experience a yearly range difference of more than 20% due to the different behavior for the car during winter and summer in Sweden.

With the acquired knowledge from the project's WP 6 and 7 about customer usage, how specific battery usage affect battery detoriation and the development of life estimation models, a prolong life functionality has been developed. Volvo Car Group specific battery usage strategies has also been developed to make sure that VCG secure the battery life by using the battery system in an optimal way and deliver range and performance for different applications. The usage of the battery is controlled by a number of different limits to make sure that we do not have extensive and unwanted detoriation of the battery. One of the developed prolong life functionalities is the RMS (root-mean-square) current functionality. The functionality limits the discharge and charge current to certain RMS currents avoid higher current during longer time periods.

4.7 WP 7 – Battery Life

The battery life for a Li ion battery used in automotive applications is today difficult to predict. There are no standardized life test methods and no life estimation models. Considering the fast technology development, there is an extensive research within the area of cell chemistry development and battery degradation.

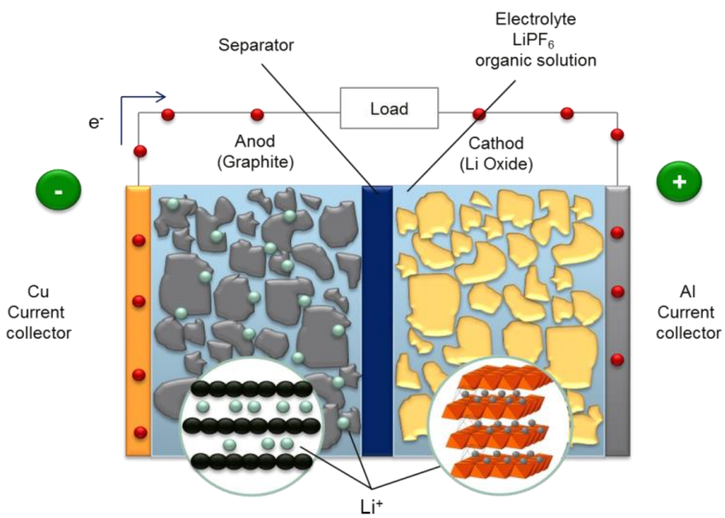

Figure 9. A schematic picture of the discharge process where the Li ions (which are the electric carrier) leaves the anode and intercalates into the cathode.

Li ion battery cells are complex systems and the ageing mechanisms are very complicated with different intrinsic processes that are non-linear and interact with each other and occur at a similar timescale. Therefore, the ageing processes cannot be studied independently and the capacity decrease and power fade experienced do not originate from one single ageing process. Examples of degradation mechanisms in the different internal cell components (anode/cathode and electrolyte) are loss of Li, dissolution of active material, structural disordering (anode/cathode), modification of surfaces, parasitic reactions or transformations, material degradation, loss of contact with current collector and degradation products hindering or limiting electrochemical reactions. All these processes contributes to the loss of active material and the internal resistance increase which give a loss of capacity/energy and power of the battery.

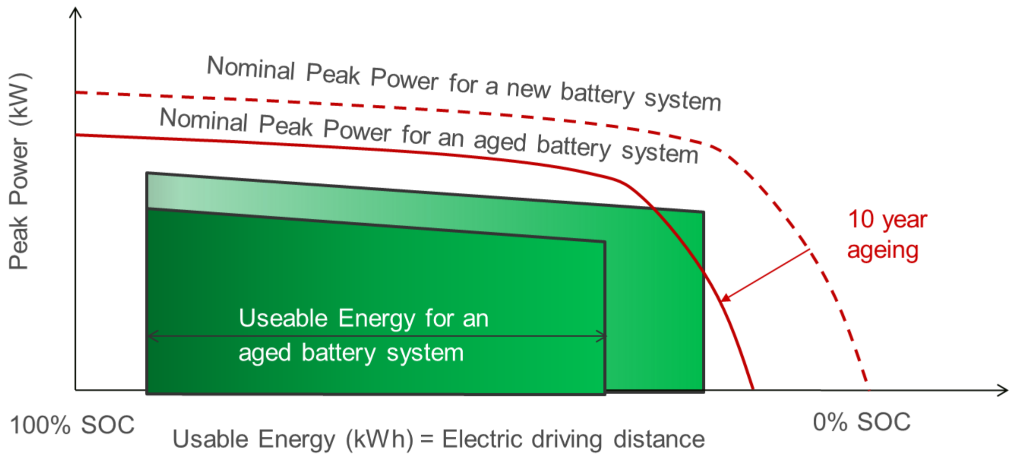

Figure 10. A schematic picture of the typical peak power and usable energy when the batteries ages. In a PHEV application, the decrease in power will start the combustion engine more often and the decrease in energy will increase fuel consumption and decrease the electrical range.

There is a large research area within Li ion cells trying to map, understand, and model the different degradation mechanisms and processes. Nevertheless, from the automotive perspective these different models of different ageing mechanisms cannot be used for a life estimation model suitable for predicting the battery service life in a vehicle. Therefor it is very important for Volvo Car Group to achieve knowledge what parameters affect the ageing and how we can prevent the aging of the battery to avoid expensive warranty event with exchanging of the battery. Lack of confidence in what causes battery degradation and in life estimations exposes VCG to risks for high warranty costs.

Objectives & Achievements

The objectives of the work package was to gain strategic knowledge within battery cell characteristics and life performance of supplier's cells. The objective was also to develop battery life estimation models to be able to secure the battery life in the vehicle but also to be able to optimize the battery usage and be able to prolong the battery life (WP 6). All objectives have been achieved in WP 6 and 7.

Realization, Activities & Results

A part of the work package has been to gain more knowledge about how battery cells ages, specify which macroscopic parameters contributes and quantify how much they degrade the batteries in turns of capacity fade and internal resistance increase. To understand what parameters that are relevant and how we can use the battery, information from how the customer use the vehicles and thereby the battery was needed. This information was collected in work package 6.

To be able to use the cells in the most optimized way, it is important to investigate the effects of the degradation contributors for the specific cell types. Each cell type has to be evaluated through tests and analysis, even small changes to cell or its operating environment can have a big impact on its degradation rate. The State-of-Health (SOH), which is a battery health indicator and shows the degradation of battery, is normally divided into SOH Power and SOH Energy since the main degradation effect are capacity fading and increased internal resistance. It is important to consider effects of degradation throughout the whole life cycle of the battery, from BOL to EOL (end-of-life). Degradation contributors can normally never be considered separately since they are always in combinations with each other affecting the battery state of health.

There are two different ageing effects, the calendar ageing and the cycle ageing. The calendar ageing is the degradation that occurs to the battery without being used. The degradation is strongly influence by the temperature and state of charge of the cells. To reduce degradation it is important that the vehicles are equipped with an active thermal system that reduce the temperature of the cells during both driving and parking. In general, the battery degradation is most severe at high temperature and high SOC levels during parking.

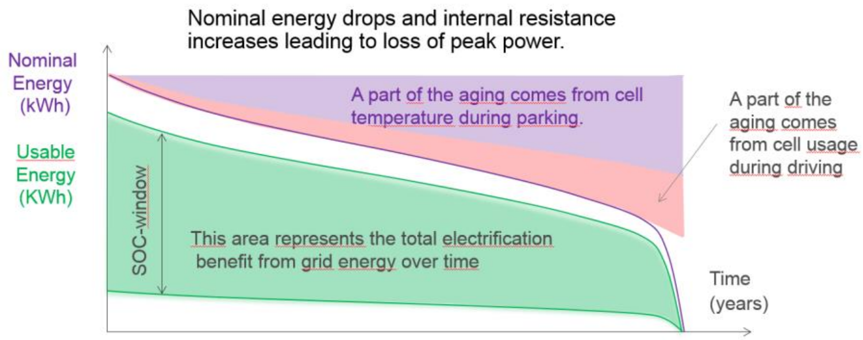

Figure 11. Schematic picture of the usable energy change over time and the contribution from cycling and calendar ageing. This is a general picture for a PHEV application and the amount depends very much on the application together with the customer usage and the cell chemistry used.

The cycling ageing is more complex compared to calendar ageing. Cycling ageing depend on the number of cycles performed, amount of energy throughput, how deep the charge/discharge is, current levels, charge levels and temperatures. For example, the degradation depends on the SOC swing, the larger the window, the greater is the ageing. In general a HEV battery that have a much smaller SOC swing compared to a PHEV (that need a larger SOC swing for the electrical range) will be able to cycles much more cycles with the same acceptable degradation. On the other hand, an EV application does not need as much cycles, because the customer does not charge full charge-cycles so often and therefore it is possible to have a larger SOC window.

Cell balancing functionality is important (and discussed in WP 5) due to different ageing can occur for different cells or modules if they are not balanced. Temperature differences on cell-, module and pack level are also important to consider and optimize to reduce the effects of cyclic and calendar ageing. The battery system contains a number of battery and cell limits to avoid excessive use of the battery. These limits are for safety reasons but also for not degradation the battery too much to be able to fulfil the life requirements. Volvo Car Group have for example different, voltage and current limits, SOC limits, power limits for different usage. As mentioned before, VCG have also developed specific RMS current limits to avoid to high current during longer times. Within this project VCG have gain knowledge how these different parameters mentioned above affects the degradation. Due to this VCG have been able to develop battery usage strategies for different applications (that for example includes functionality as RMS current limits) to make sure that we secure the battery life for the customer.

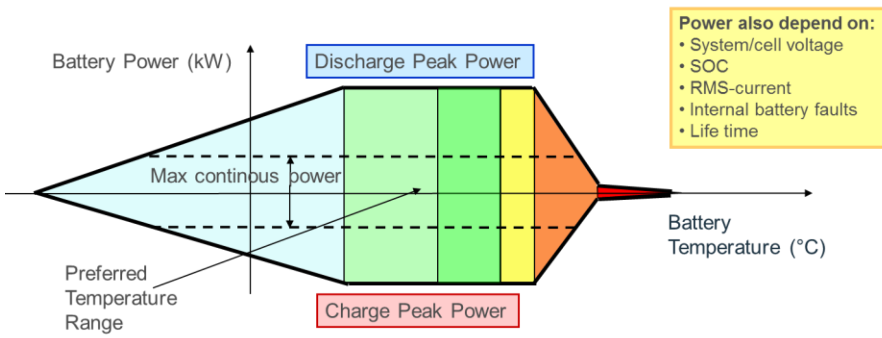

Figure 12. Schematic picture of the charge and discharge power limits dependence of temperature.

To understand the ageing mechanism and the parameters effect on the degradation, extensive testing is required both in lab and in the field. The cell development today is extremely fast and during a vehicle project, that takes about 3 years, the cell chemistry can often change several time. Even small changes in the cell chemistry will need extensive testing. The challenge from an automotive point of view is that due to the complexity of the ageing mechanisms it is very difficult to develop relevant accelerated life tests. The life tests must be accelerated to that extent that useful results will be provided before the start of the vehicle production. However, at the same time, they cannot be accelerated to fast because then they lose its relevance to the normal customer usage of the battery in the vehicles. In general, the testing takes several years before results are provided that could be used in life estimation models to predict the battery life. Volvo Car Group have developed accelerated test methods, both on cell, module and system level.

Volvo Car Group have within the work package achieved knowledge within battery usage and how specific usage affect the ageing of the battery to be able to develop a life model process. The VCG battery life model process is a tool used in the vehicle projects to design the battery system dependent on the attributes requirements of the vehicle. The battery life model process is used to estimate the battery life and verify the design and usage strategies of the battery system. The information from the different part in the process (for example; customer assumptions, usage assumptions, results from tests of cells, modules, battery systems in lab, results from field data from both test vehicles and customer vehicles and life predictions) will be fed back in the process and in the project for modification or verification of the system design and the usage strategies.

The life model process describes the different step from early in time the project design and assumed battery usage strategies to the life prediction in the end. The life estimation model gives life predictions (in turns of capacity and power fade) dependent on the customer usage, battery temperature histograms and experimental cell data used as input. Dependent on the result from the life prediction the usage strategies can be updated continuously during the vehicle project time.

From the project requirements, load case assumptions are assumed. This is assumptions about the customer usage, in which market the cars will be sold and how the customer will drive and charge, for example driving cycles and driving patterns.

For the different markets, we define different scenarios, classify different areas as worst climate, severe climate, and so forth. Within the life model process, we have models simulate the temperature on the battery cells, dependent on the usage, cooling/heating strategies, ambient temperatures, battery placement within the car and so forth. The load cases are later verified during the complete vehicle testing. Different temperature load case together with the customer load case are used as input in the life model.

Dependent on the application, project design and assumed battery usage, experimental test matrix for testing cells, modules, systems including complete vehicle are produced. The results from the accelerated life testing (different combinations of calendar and cycling testing) using different power profiles (statically and dynamical) are used as input in the life model. Field data from testing fleets and eventually from the customer cars is also used as input to the battery life model. In the life model, the degradation from the different modes are de-coupled and calculated separately and the life, in turn of capacity fade and internal resistance increase are estimated over the years.

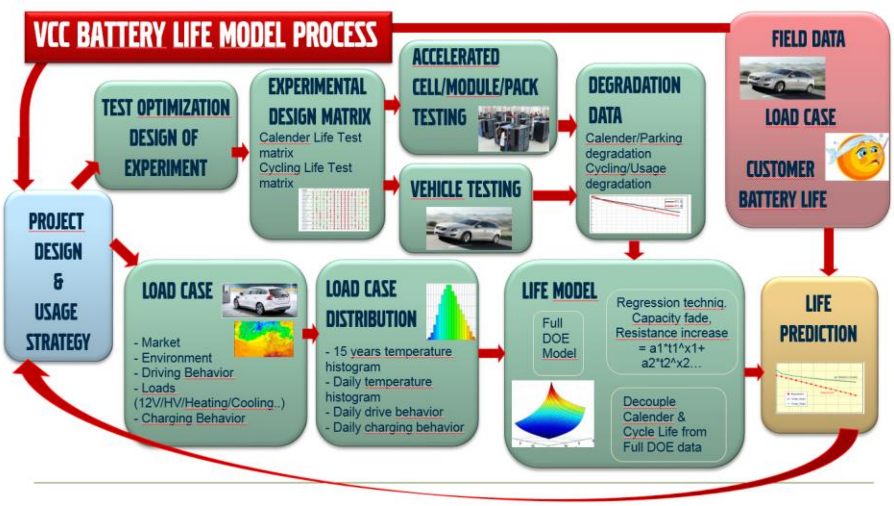

Figure 13. VCG developed battery life model process.

4.8 WP 8 – Field Test Equipment in Hybrid Applications

It is difficult to determine the lifetime of the battery used in a PHEV due to the complex ageing process of the battery cells, together with uncertainty about how the cell will be charged/discharged and the environmental conditions that it will be exposed to. Extensive testing is therefore performed, both in lab and in actual vehicles, in order to evaluate how the cell capacity and power performance deteriorates over time. The tests need to be performed over a long time span, but realistic tests in a real test vehicles are expensive and only possible late in the development process. Hence, within this work package we evaluated the need to perform cell life test early in the project with conventional test vehicles without electrical drive train.

Objectives & Achievements

Scania and the Royal Institute of Technology (KTH) has developed a field test equipment used in Scania's test vehicles. The aim was to evaluate the need for, and develop a field test equipment for VCG that could be placed in a passenger car with a conventional powertrain. The equipment would cycle and stress a battery cell in the same way as it would be if the cell was in a battery used in a corresponding plug-in-hybrid electric vehicle. VCG decided not to continue with the development of the field-test-equipment. The reason was that it was not cost effective and the PHEV test cars developed within normal production projects should instead be used to evaluate the battery life on vehicle level. Knowledge of customer specific driving behavior and the corresponding battery usage in real life has been achieved in other ways, such as using flight record equipment and DRO information in real customer cars.

Realization, Activities & Results

Scania's field-test equipment was evaluated and revised requirements for implementation in VCG vehicles was developed. The system contains a specific VCG developed software where the hybrid components were modelled. This software was developed in the project and the hybrid components as well as the strategy that regulates their operation, were modelled in MATLAB/Simulink. A method was also developed to estimate the battery cell's state of charge (SOC). The theoretical current through the cell were calculated in the system as if the vehicle was assumed to be a PHEV. The calculation was based on real-time data from the vehicle during driving. The equipment was discharging/charging the cell according to the corresponding calculated current. The status of the battery cell where monitored and parameter check-up tests (capacity and resistance) were performed regularly on the cell during the time in the field. The vehicle driving performance and the results from the parameter tests were stored in the equipment.

4.9 WP 9 – Electro-chemical Safety

The purpose with this work package is to ensure long-term elimination of safety issues that corresponds to Volvo Car Group's core brand values. Accident analysis conducted on electrical vehicles, such as HEV, PHEV and EV involved in accidents shows that the high-voltage components and battery system does not impose any risk to the occupants in the event of crash and that electrical vehicles are as safe as combustion engine vehicles.

Objectives & Achievements

The main objective was to gain strategic knowledge within electro-chemical safety aspects of battery systems, which has been obtained. Strategic knowledge within post-crash behavior was gained by a number of activities. Mechanical loads to battery cells/modules in crash accidents was investigated. Mechanical properties of battery cells was identified. A finite element model (FEM) of cells and modules was developed and validated. Battery damage mechanisms by physical tests and numerical reconstructions was investigated.

Realization, Activities & Results

The work within this work package has been concentrated on evaluating the supplier's safety knowledge, the safety aspects of the supplier's cells chemistry and form factor and the safety aspects of the supplier's battery systems.

An extensive work has also been conducted by develop and validate finite element models (FEM) of battery cells and modules. This FE models can be used in complete vehicle crash simulations and to predict electrical failure in crash tests. By this work, Volvo Car Group has gained knowledge of the mechanical properties of battery cells that can be correlated to the cell structure. The purpose is to avoid mechanical testing for each new cell types.

Identify typical mechanical loading to battery module/cells in crash events was done by accident analysis of electrical vehicles involved in crashes. Information from the project RÄDDNINGSKEDJAN was used. VCG has conducted a large series of crash tests of C30 EV, V60 PHEV and XC90 PHEV. A thorough review of these tests were carried out to understand mechanical loadings to traction batteries and damage patterns in crash tests. In the same way, many CAE crash simulations with complete vehicle models in different load cases together with internal conducted cell and modules safety tests has been performed and analyzed within this project.

4.10 WP 10 – Energy Efficient Cooling System

An active thermal system is necessary in all hybrid applications to be able to regulate the cell temperatures and secure the battery life. To be able to development and optimize an energy efficient thermal system for both the customer compartment and the battery system a number of activities and analysis are required. What are the prerequisite, does it require liquid cooling or air cooling system? Modelling of thermal flow, heat transports between cells and cooling structure in module and thermal resistance need to be done. How will the battery usage, with different driving profiles affect the cell temperatures? What thermal strategies are needed for different applications; is heating necessary, should there be cooling during/before/after charging, should there be cooling during parking. How could the usage of a thermal system with both passive and active cooling be optimized. How should the battery system best be insulated? How can the system be design and manufactured to optimize for lifetime cost and weight? The purpose was to develop a more efficient thermal system for batteries, enable long-term cost reduction per commodity variant, and reduce Volvo Car Group exposes to risks for high warranty costs by securing the battery life.

Objectives & Achievements
The objective were to gain strategic knowledge within battery thermal system to be able to develop a more energy efficient battery thermal system, which has been fulfilled.

Realization, Activities & Results
Within the work package three main activities has been conducted. The first activity was an evaluation of the existing V60 PHEV thermal system by modelling of the complete system (battery, chiller, radiator, pumps, piping and valves). All components in the model was calibrated and put together into a transient system model. The system model was verified using test data This system model can be used for further understanding of how the system works and for optimization of different operating conditions and for comparative studies.

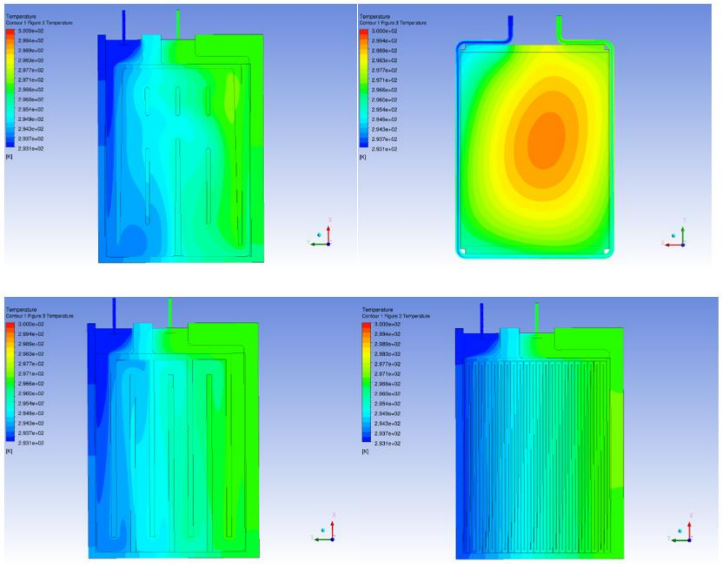

Figure 14. Temperature difference within different cooling plate design.

A design concept study of different cooling plates (including the one used in V60 PHEV) has been performed using CFD modelling. The calculations were done with fixed flow rates and applied to different geometry designs. The results comprise fluid velocities, fluid pressure and temperatures. The heat conduction between the cooling plate and the cells were evaluated and analyzed.

The last activity was to analyze the cooling performance with an indirect cooling concept without any water interconnections within the battery system. Experimental tests were performed on a prototype module and the cooling performance and the temperature gradient within the cells were analyzed.

5. Results and Deliverables

The main results and deliverables from the project are:

- Strategically important battery knowledge achieved within all battery areas
- Battery supplier evaluation performed
- Competitors benchmark performed
- Design guidelines developed
- Commodity business plan developed
- VCG battery strategies (design, cell, usage, prolong life, cooling, buisness)
- VCG life model process and estimation model developed
- VCG battery lab established
- Battery test methods developed
- Battery models developed (electrical, thermal, plant, controller, EIS, life, crash)

- Knowledge within BMS functionality and cooling system

The results from NGBS has gradually been utilized in product development at Volvo Car Group within the project time frame.

5.1 Delivery to FFI-goals

The project contributions to FFI Energy and Environment objectives may be summarized as below:

- Continued development of strategically important base technology.
- Development of innovative concepts within areas of vehicle technology.
- Development and introduction of more efficient development methods

The project will contribute to a successful implementation of Volvo Car Group's electrification strategy in the future. By VCG's successful sales of PHEV vehicles, the project has contributed to FFI Energy Environment's following overall objectives,

- 50% energy efficiency (kWh/km) by 2020 through competitive cars.
- Energy consumption per vehicle produced (from a lifecycle perspective) shall be reduced by 20% by 2020.
- Emissions such as noise, particles, nitrogen oxides and so forth shall be reduced so that the levels of these pollutants can be met in particularly sensitive areas and major cities.
- The Swedish automotive companies will become a world leader in the development of energy efficient and environmentally friendly vehicles, such as electrified vehicles.

6. Dissemination and Publications

The work will continue within the battery area within several internal projects. The project results and extended knowledge within battery system has also been used within external founded projects such as Next Generation High Voltage Topology, State-Of-Function, Metodutveckling för livslängdsprediktering, Räddningskedjan, Ageing Mechanism and how to prolong battery life, BATMAN, EverSafe and Livslång batteristyrning. This has also been communicated externally in different presentations, seminars and conferences.

7. Conclusions and Future Research

The aim of the VCG project Next Generation Battery System was to create a platform of knowledge and competence based on high voltage automotive battery system technologies. The intention was to develop this platform one step ahead of the past, i.e. to prepare to go from low volume vehicle production to large scale production in the future. This was realized by performing custom comprehensive system design and optimization that would fit for large PHEV volume production. A prerequisite for future large-scale production is that the development of electrified vehicles must result in affordable products to the end customer still delivering the attributes, which support the brand name. The NGBS project has been a very successful and valuable project for Volvo Car Group. It has achieved its, in some cases, very aggressive objectives, in a very satisfied way. The obtained battery system knowledge and the VCG developed battery strategies within the different battery areas is a need to minimize cost, weight and volume, deliver a premium car experience, and satisfy the customer's desire when it comes to electrical range and performance in future electrified cars.

Volvo Car Group’s core values are safety, quality and environment. The focus on the environment comprises people’s health, energy efficiency and resource efficiency including the VCG’s electrification strategy, to offer a large portfolio of electrified vehicles in the future. For Volvo Car Group, the future mobility is the same as a sustainable mobility.

8. Participating parties and contact person

The project has been an internal project at Volvo Car Group.
Project leader: Theresa Granérus (theresa.granerus@volvocars.com)