FP7-2011-ICT-GC

Duration: 36 months

SMART-LIC – Smart and Compact Battery Management System Module for Integration into Lithium-Ion Cell for Fully Electric Vehicles

GREENCAR – SMART-LIC Project

Deliverable 1.1

Report on WP1

Report detailing System Specification & Requirements

Revision: 1 .8 final (v. 1.8)

Due date: 31-12-2011 (m8)

Actual submission date: 31-01-2012

Lead partner: Centro Ricerche Fiat

Dissemination level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Summary					
No and name	**D1.1 Report detailing System Specification & Requirements**				
Status	Working (in progress)	**Due**	M8	**Date**	31-01-2012
Author(s)	Gianfranco Burzio, Daniela Parena				
Editor	Gianfranco Burzio				
DoW	**Report detailing system specification & requirements:** - Definition of characteristic application scenarios and deduction of the over-all system requirements; - Specification of cell balancing strategy, of requirements for the communication /EMC and for the integration /packaging solutions.				
Comments					

Document history

V	Date	Author	Description
0.1	19-10-2011	G. Burzio	First draft
0.2	02-11-2011	D. Parena	Second draft
0.3	08-11-2011	G. Burzio, D. Parena	Third draft
0.4	06-12-2011	D. Parena	Draft v.4 including interesting parameters to be taken into account
0.5	07-12-2011	G. Burzio, D. Parena	Draft v.5 including updates following review of 30/11/2011
0.6	19-12-2011	G. Burzio, D. Parena	Revision
0.7	17-01-2012	G. Burzio, D. Parena	Micro-vett contribution integrated
0.8	19-01-2012	G. Burzio, D. Parena	Continental contribution (+Micro-vett) and ST remarks integrated
0.9	24-01-2012	G. Burzio, D. Parena	ST (Bison) contribution updated ENAC (Mager) contribution integrated
1.0	24-01-2012	G. Burzio, D. Parena	General revision
1.1	25-01-2012	G. Burzio	General revision
1.2	26-01-2012	G. Burzio, D. Parena	General revision
1.3	30-01-2012	G. Burzio, D. Parena	Conclusions
1.4	30-01-2012	G. Burzio	General revision – Dissemination level: public - Conclusions
1.5	31-1-2012	G. Burzio,D. Parena	Final revision after Conference Call discussion
1.6	06-02-2012	G. Burzio,D. Parena	Feedback from STMicroelectronics
1.7	07-02-2012	G. Burzio,D. Parena	Final version for Peer Review
1.8	07-02-2012	G. Burzio,D. Parena	Final version for Peer Review

Table of contents

Index of figures

1 ACRONYMS

BEV	Battery Electric Vehicle
BMS	Battery Management System
BoL	Beginning of Life
BoM	Bill of materials
BP	Battery Pack
BS	Battery System
CS	Cooling System
CTE	Coefficient of Thermal Expansion
DoD	Depth of Discharge
E	Elastic Modulus
EIS	Electrochemical Impedance Spectroscopy
EMC	Epoxy Moulding Compound
EMF	???
EoL	End of Life
EPI	Electric Power Interface
FEV	Full Electric Vehicle
HV	High Voltage
LDV	Light Delivery Vehicle
LTCC	Low Temperature Cofired Ceramic
NEDC	New European Driving Cycle
o.s.l.	over sea level
PA66	Polyamide 66
PBT	Polybutylene Terephthalate
PLC	Power Line Communication
PHEV	Plug-in Electric vehicles
PI	Power Integrity
RFID	Radio Frequency IDentification
SI	Signal Integrity
SiP	System-in-Package
SoC	State of Charge
SoF	State of Function
SoH	State of Health
SoL	State of Life
TC	Thermal Conductivity
T_g	Glass Transition Temperature

VMU	Vehicle management System

2 SCOPE

The SMART-LIC Project addresses the development of a new Battery Management System (BMS) concept aiming at:

- Lower system complexity by a radical reduction of wiring and connectors, cause of- EMF emissions and major source of malfunctions.
- Higher efficiency of the battery packs because of the local control.
- Increased overall reliability such that failures would be determined by battery cells rather than by electronics and wiring connectors.
- Increased flexibility of the overall energy-power routing such to assure that all cells could perform at their maximum rating independently from the rating of the others.
- Radical overall cost reduction of the overall BMS because of reduced cabling and connectors as well as simplification of the electronics.
- Increased precision in determining the states of charge, of health, and of function of the individual cells and of the entire battery by applying a new cell / battery model, based on electrochemical impedance spectroscopy (EIS).
- Reduced maintenance of the battery packs assured by the monitoring of the single cell (macro cell) with the possibility to switch it off from the rest of the pack.
- Reduced cost of ownership for the end user due a significant increase in battery lifetime caused by the improved management on cell level.

This Report details system specification and requirements through the definition of characteristic application scenarios and deduction of the over-all system requirements.

In details the system will consist of:

- Battery Pack (cells, cabling, fuses, contactors…);
- integrated cooling system;
- BMS master and slave boards with CAN-bus interface;
- Battery System housing with fixing parts.

Electric and electronic components:

- connectors IP57 or higher/lower depending….?;
- voltage, current and temperature sensors;
- insulation detection via BMS;
- additional electric devices like precharge contactors and main rapid fuses (for both poles).

In Figure 1, the HV BS structure is shown and its main parts and interconnection/communication interfaces towards the vehicle put in evidence:

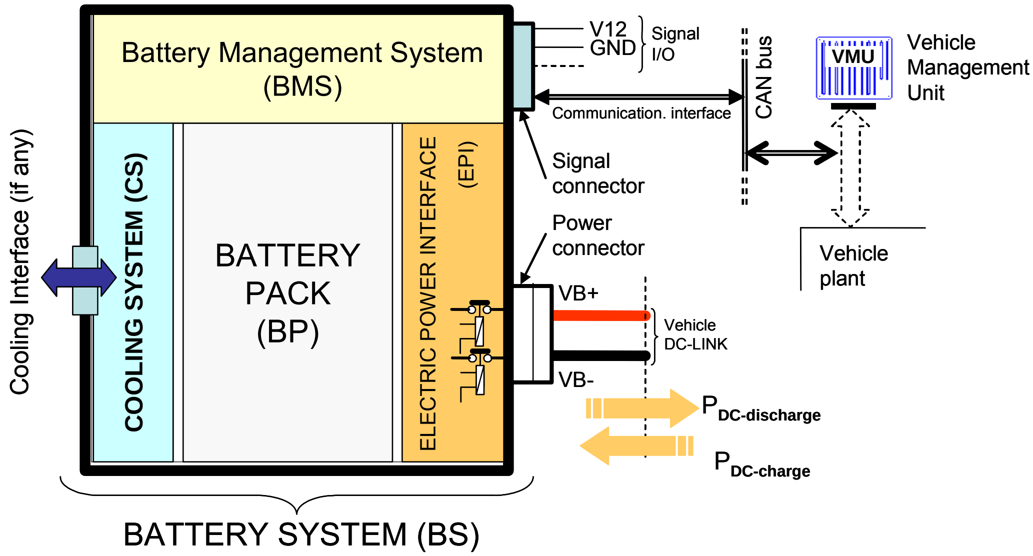


Figure 1. - HV BS structure

BS main functions are:

- provide the energy to the electric traction drive during the vehicle acceleration and constant speed conditions;
- provide energy to auxiliaries systems (electro-hydraulic-steering, DC-DC converters, electro fluid heater…);

Store energy coming from the mains•

recover the energy during braking.

3 EXECUTIVE SUMMARY

3.1 Publishable summary

The SMART-LIC Project addresses the development of a new Battery Management System Module, for integration into Lithium-Ion Cell for Fully Electric Vehicles.

The target achievements are obtained realizing the BMS module as a system-in-package (SiP) directly integrated into the cell for fully electric vehicles, by means of advanced packaging technologies.

This document contains the Deliverable 1.1, *"Report detailing system specification and requirements"*, related to Work Package 1 (WP1) and it concerns:

- Definition of characteristic application scenarios and deduction of the over-all system requirements;
- Specification of the cell balancing strategy, of the requirements for the communication/EMC and for the integration/packaging solutions.

The application scenario definition starts from the State-of-the-Art on existing solutions for the addressed developments; in this section, are also listed and described a set of parameters to be taken into account for the purposed development.

Furthermore, the document provides the needed information about compliance with standard automotive requirements.

The present document will represent the general System Specification and requirements as a reference document for the following addressed developments of the BMS.

3.2 Non-publishable information

All the contents of this document are "non publishable", until the approbation of the concern partner, except the previous paragraph.

4 WP 1 – DEFINITION OF CONCEPT AND REQUIREMENTS

4.1 WP1 structure: contributions & collaborations

Figure 2 shows the general structure of the SMART-LIC Project activities and the detailed objectives of each WP and related tasks. Highlighted in red the WP1 description, including task 1.1 and 1.2 and related deliverables.

Definition of application scenario, that is the goal of Task 1.1, directly impacts on the development of System Architecture that is object of Task 2.1 within WP2.

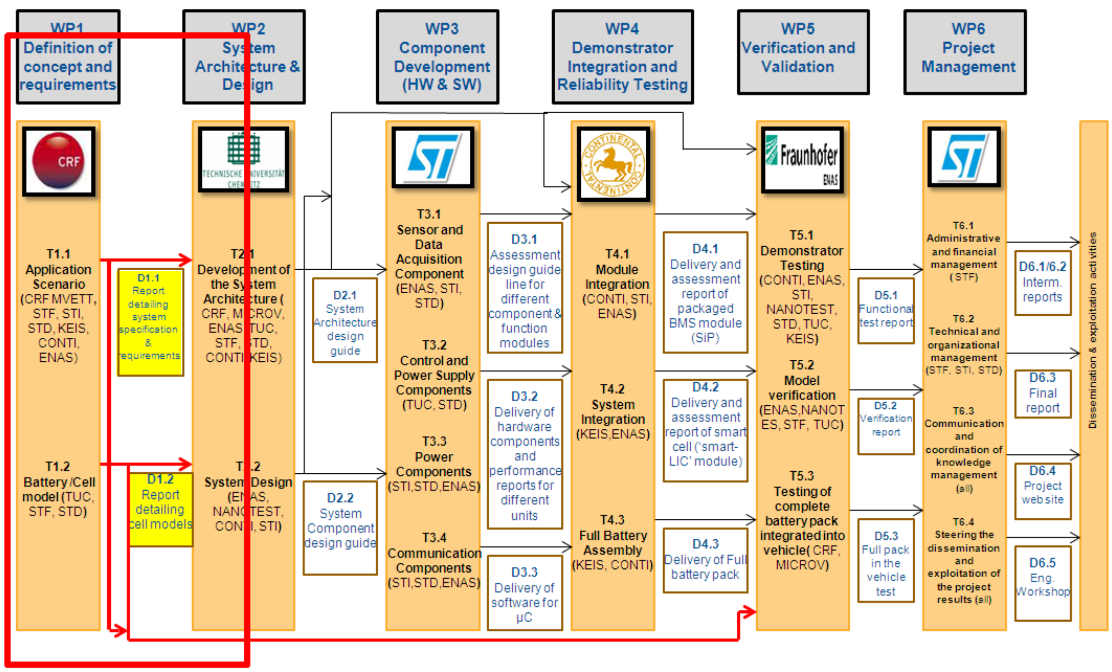


Figure 2. - WP1 Contribution & Collaboration within the Project

Deliverable D1.1 concerns the Task 1.1 of WP1: purpose of this Task is identification, analysis, extraction, and definition of characteristic application scenarios, preliminary to the definition of requirements for the smart battery architecture and of the cell balancing strategy.

Furthermore, the development of a battery/cell model, implementable in the microprocessors distributed in the cells, and of a Real-Time parameter extraction strategy, for battery model parameterization, identification of the battery key parameters to be monitored and definition of an optimized method, determining the state of charge, will follow (Task 1.2 of WP1).

In parallel, assessment of design, materials, and process needs for smart systems packaging and integration is scheduled, as the characterization of conditions for wired or wireless battery internal communication and definition of the requirements.

The ambitious objectives are obtained by realizing the BMS module as a system-in-package (SiP) directly integrated into the lithium-ion cell for fully electric vehicles by using advanced packaging technologies.
Early demonstration of the technology will be made by preparing specific battery packs to be installed both on a commercially electrified vehicle and on a FEV of new concepts.

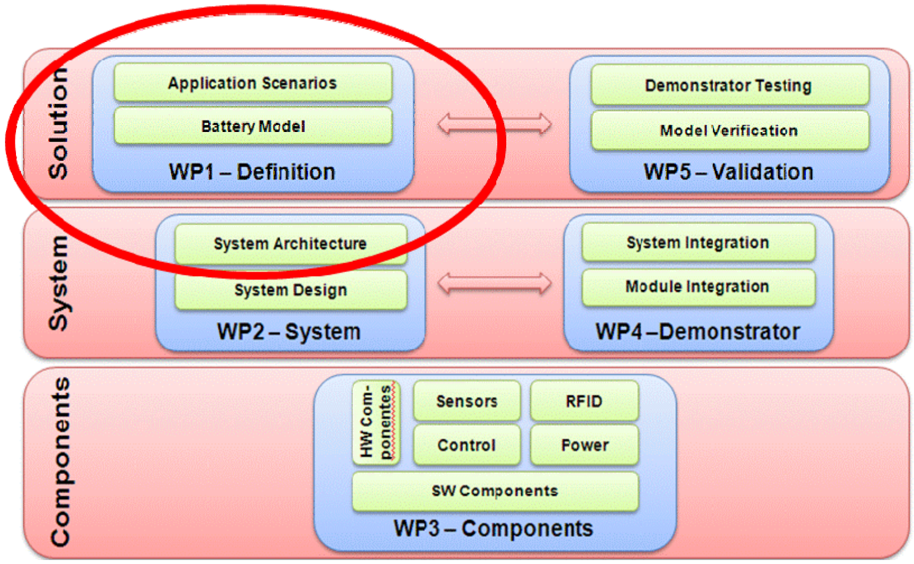


Figure 3. - WP1 Context

Figure 3 highlights the location of WP1 activities in the SMART-LIC Project context, that address solution identification related to the application scenarios, by means of the following items:

- Study of the possible application scenarios for the battery management system;
- Analysis of current BMS and balancing solutions (functionalities & shortfalls), with specification of the development;
- Review of the existing SiP and module integration solutions;
- Study and assessment of the options of wired, optical, wireless communication systems or combinations of them.

4.2 Relations to other activities in the project

This section defines frame of requirements and specifications for Work Package 1 and then consequently for the other Work Packages defining components and modules.
Purpose of WP1 is also to define the requirements framework for the overall project: in particular it has been debated the optimal architecture for SMART-LIC implementation.
Target of this analysis is to consider the best trade off in term of cost and performance between State of the Art BMS and different SMART-LIC implementations.

The following parameters have been considered to carry on this analysis:

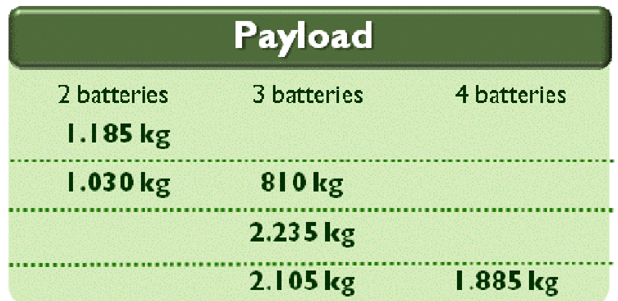
1) Life time of the battery (with and w/o SMART-LIC);
2) Battery cost (with and w/o SMART-LIC);
3) Efficiency and losses of module (with and w/o SMART-LIC).

First point of this analysis is the identification of the optimal granularity of the SMART-LIC module defined as the number of lithium-ion cell integrated in the single module. Introducing a BMS module at Cell Level provides more accurate SoH and SoC monitoring, enabling higher performances in term of Life Time and reducing the maintenance cost but introduces also some drawbacks in term of higher BoM and Efficiency/Losses. The analysis will be completed inside WP2.

5 APPLICATION SCENARIOS OF BATTERY SYSTEMS IN FEVS

5.1 Application Scenario - Vehicle Types

FIAT foresees that first market applications of FEVs will be in the commercial vehicle fleets, in particular for Urban applications. These applications have certain favourable condition that will overcome the FEVs limitation, in particular related to range autonomy. Between the different available vehicle types, FIAT (IVECO) is focussed on commercial vehicles up to 3.5 tons of overall weight. In particular, the IVECO Daily Electric is the reference vehicle for FIAT.



Payload		
2 batteries	3 batteries	4 batteries
1.185 kg		
1.030 kg	810 kg	
	2.235 kg	
	2.105 kg	1.885 kg

Figure 4. - IVECO Daily and related payload

For this vehicle the reference parameters are the following:

Autonomy

- 90 - 130 km (Full loaded)

Max speed

- V max = 70 km/h

Max slope

- = 18%

In its standard configuration it is equipped with 2-4 ZEBRA NaNi/Cl2 battery modules, with battery packs in parallel.

For requirement definition, MicroVett considers an analogous commercial vehicle, Fiorino Electric, with the same range of Daily, and also LCV or City cars, both with series/parallel Battery Pack architecture. Characteristics are shown in the tables below.

	Version	Payload	Max Speed	Battery Modules Configuration	Module configuration
	E6	475kg	100km/h	3S2P	24S2P
	E9	400kg	100km/h	3S3P	24S2P

	Version	Seats	Max Speed	Battery Modules Configuration	Module configuration
	K1	4	100km/h	1S1P	30S1P
	K2	4	130km/h	2S1P	39S1P

Figure 5. - FIAT Fiorino and FIAT 500

5.1.1 Identified Parameters

In order to define the System requirements, is useful an overview of the main parameters to be taken into account.

On the basis of V4G Project achievements and of the Parameter Manual public document (16.12.2010), in the following the most relevant parameters to be taken into account by SMART-LIC Project developments are listed and briefly described [Ref. 1].

5.1.1.1 Types of electric vehicles

In electric vehicle, batteries complement or even replace the current combustion engine; the three main types of EV are:

- Battery electric vehicles (BEV);

- Hybrid Electric Vehicles (HEV)

- Plug-in Hybrid Electric vehicles (PHEV).

All different types of vehicles differ in many technical aspects: the main source of energy of BEV is the battery, which replaces the current fuel tank, and the combustion engine is replaced by an electric motor. Because of limited battery capacity, the range of BEV is limited as well.

In HEV/PHEV the battery is the second energy source in addition to the basic combustion engine. These types of vehicle come in a range of configurations between two extremes:

- full-hybrid with an increased battery capacity plus grid connection to increase electric driving range;
- basically battery vehicles, equipped with a small internal combustion engine functioning as a range extender [Ref. 2].

Definition of international standards concerning the interoperability between facilities, operators and users is crucial; the main reference European standards, concerning Electric Vehicles, are:

- IEC/TC69 “Electric roads vehicles and electric industrial trucks”: inside IEC, the Technical Committee 69 (TC69) is dedicated to electric vehicles.
- CLC/SR69 “Electrical systems for electric road vehicles”.

5.1.1.2 Consumption

The consumption evaluates the amount of energy needed from EV (PHEV) to drive 1 km in the electrical mode.

Usually, consumption is measured on a reference driving cycle's model, so that the real consumption could be higher due to the use of heating, cooling or media.

Parameter range:

- **BEV:** 0,13 ÷ 0,25 kWh/km;
- **City_BEV:** 0,12 ÷ 0,16 kWh/km;
- **PHEV:** 0,15 ÷ 0,25 kWh/km.

The SMART-LIC Project is focussed on small and large commercial vehicles, and for those a few reference driving cycles are considered, without considering NEDC cycle.

5.1.1.3 Composition of different EV types and market penetration

The composition of different EV types describes the percentages of each kind, depending on the penetration rate and the chosen scenario.

Nowadays, many different EV technologies exist and their number is increasing, therefore, an analysis with only one kind of EV could be not exhaustive. Due to non-linear battery charging curve, the charging behaviour for a fleet of vehicles with variable battery sizes will differ significantly from a charging curve with standard EVs.

To determine the percentages a market model has to be used, analysing the parking situation and anticipating the vehicle use per kind, that mainly depends on the driving behaviour in different countries.

The figure 6 shows the Battery Electric Vehicle growth trend, from 2007 to now, and a provision until 2020, in terms of sales, as a global overview [Ref. 7].

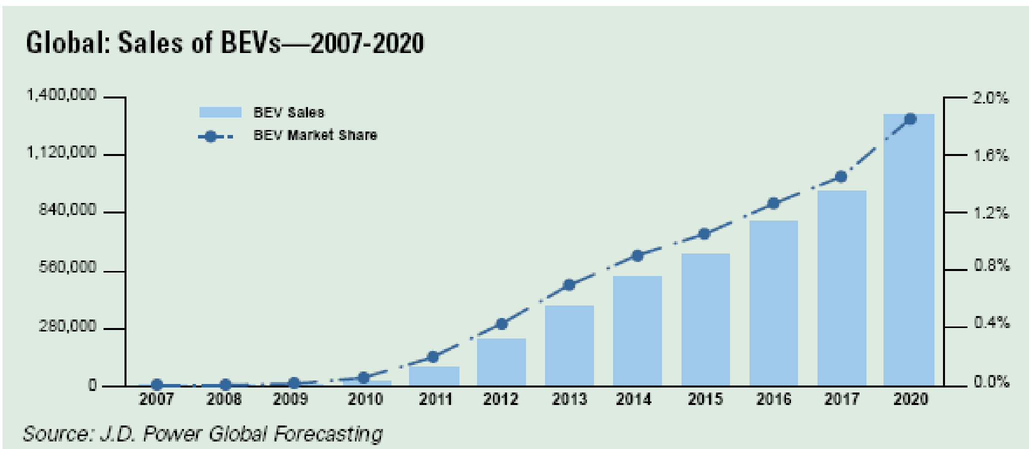


Figure 6. - Battery Electric Vehicle Growth Trend
[Source: J.D. Power Global Forecasting Nov. 2010]

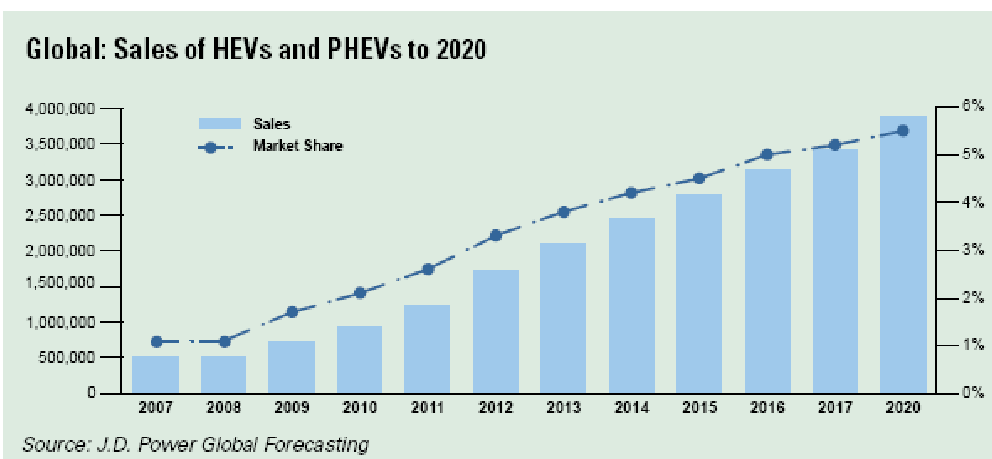


Figure 7. - Hybrid Electric Vehicles (HEV) and Plug-in Hybrid Electric Vehicles (PHEV).Growth Trend [Source: J.D. Power Global Forecasting Nov. 2010]

The figure 7 shows the Hybrid Electric Vehicle and Plug-in Hybrid Electric Vehicles growth trend, from 2007 to now, and a provision until 2020, in terms of sales, as a global overview, while figure 8 summarizes the sales data also for different countries [Ref. 7].

HEV/PHEV												
GLOBAL	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
HEV/PHEV	515,397	515,135	728,215	934,644	1,237,167	1,715,812	2,102,503	2,454,493	2,781,643	3,138,050	3,402,227	3,883,447
Total PV Sales	48,989,462	45,808,919	43,865,494	44,708,783	47,621,688	52,305,128	55,623,828	58,661,294	61,198,064	63,250,564	65,145,316	70,905,762
HEV/PHEV %	1.1%	1.1%	1.7%	2.1%	2.6%	3.3%	3.8%	4.2%	4.5%	5.0%	5.2%	5.5%
US	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
HEV/PHEV	353,152	316,251	291,659	291,116	482,675	801,852	1,051,154	1,287,087	1,466,070	1,583,161	1,586,435	1,672,739
Total PV Sales	16,288,029	13,408,290	10,570,294	11,619,667	13,190,236	15,120,311	15,748,991	16,208,886	16,400,069	16,615,618	16,825,955	17,426,043
HEV/PHEV %	2.2%	2.4%	2.8%	2.5%	3.7%	5.3%	6.7%	7.9%	8.9%	9.5%	9.4%	9.6%
China	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
HEV/PHEV	414	899	1,883	3,781	16,603	31,286	41,285	52,078	64,674	78,387	81,968	97,234
Total PV	5,438,818	5,934,448	8,721,280	8,164,591	9,071,331	11,050,314	12,161,671	13,250,510	14,281,779	15,070,676	15,775,472	17,461,796
HEV/PHEV %	0.01%	0.02%	0.02%	0.05%	0.2%	0.3%	0.3%	0.4%	0.5%	0.5%	0.5%	0.6%
Japan	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
HEV/PHEV	96,498	120,725	348,410	475,872	470,021	562,870	603,239	617,359	648,079	723,931	748,757	874,984
Total PV Sales	4,338,106	4,203,238	3,901,957	4,343,645	4,199,118	4,245,434	4,244,883	4,230,317	4,217,242	4,201,986	4,183,772	4,194,000
HEV/PHEV %	2.2%	2.9%	8.9%	11.0%	11.2%	13.3%	14.2%	14.6%	15.4%	17.2%	17.9%	20.9%
Europe	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
HEV/PHEV	64900	76217	73818	108,241	165,757	213,789	271,434	361,057	455,705	605,538	789,880	977,806
Total PV Sales	19,402,402	18,519,287	16,512,240	15,630,067	15,593,200	16,437,820	17,532,581	18,780,021	19,839,094	20,594,727	21,285,220	23,815,684
HEV/PHEV %	0.3%	0.4%	0.4%	0.7%	1.1%	1.3%	1.5%	1.9%	2.3%	2.9%	3.7%	4.1%

BEV												
GLOBAL	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
BEV	436	1,132	3,517	20,150	89,891	221,815	383,679	530,000	639,822	796,700	943,725	1,311,441
Total PV Sales	48,989,462	45,808,919	43,865,494	44,708,783	47,621,688	52,305,128	55,623,828	58,661,294	61,198,064	63,250,564	65,145,316	70,905,762
BEV %	0.00%	0.00%	0.01%	0.05%	0.19%	0.42%	0.69%	0.90%	1.05%	1.26%	1.45%	1.85%
US	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
BEV	0	151	1310	2002	13792	41566	70440	85946	88414	90,792	97,016	107,998
Total PV Sales	16,288,029	13,408,290	10,570,294	11,868,597	13,955,528	15,318,387	16,086,657	16,478,416	16,611,600	16,823,614	16,996,861	17,426,043
BEV %	0.0%	0.001%	0.01%	0.02%	0.1%	0.3%	0.4%	0.5%	0.5%	0.5%	0.6%	0.6%
China	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
BEV	-	-	-	5,116	17,032	35,070	60,384	90,473	129,591	189,055	217,320	332,775
Total PV Sales	5,438,818	5,934,448	8,721,280	8,164,591	9,071,331	11,050,314	12,161,671	13,250,510	14,281,779	15,070,676	15,775,472	17,461,796
BEV %	0%	0%	0%	0.1%	0.2%	0.3%	0.5%	0.7%	0.9%	1.3%	1.4%	1.9%
Japan	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
BEV	-	-	986	8,282	17,703	30,497	38,398	43,777	47,444	50,290	52,142	67,057
Total PV Sales	4,338,106	4,203,238	3,901,957	4,343,645	4,199,118	4,245,434	4,244,883	4,230,317	4,217,242	4,201,986	4,183,772	4,194,000
BEV %	0%	0%	0.03%	0.2%	0.4%	0.7%	0.9%	1.0%	1.1%	1.2%	1.2%	1.6%
Europe	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2020**
BEV	436	471	338	3,221	38,362	99,824	190,629	269,953	337,892	423,920	530,013	742,020
Total PV Sales	19,402,402	18,519,287	16,512,240	15,630,067	15,593,200	16,437,820	17,532,581	18,780,021	19,839,094	20,594,727	21,285,220	23,815,684
BEV %	0.002%	0.003%	0.002%	0.02%	0.2%	0.6%	1.1%	1.4%	1.7%	2.1%	2.5%	3.1%

Figure 8. - Table of Global HEV/BEV Sales (2007-2020)

[Source: J.D. Power Global Forecasting Nov. 2010]

Major influencing parameter for these market assumptions are the petrol price.

In this case a petrol price of about ???$ per barril has been take into account.

Concerning the expectations of customers and chances of market penetration, a certain amount of uncertainty is related to the EV, mainly due to the following concerns:

- Driving range;
- Lifetime of the battery;
- Cost of the battery;
- Charging time;
- Reliability/fault tolerance (methods to determine if a battery is damaged);
- Possible fraud on battery age / number of cycles;
- Safety aspects;
- Availability of charging stations.

5.1.1.4 Battery technologies for EV

PHEV and BEV have batteries as energy storage of electrical drives, so they are a crucial component in future vehicles. In electric mobility development of BEV´s, research focuses on batteries with high energy densities and, as a consequence, costs, security, charging-time and life-time are very important.

Nowadays the energy density of designed battery systems reaches 1-2% of fluid fuels [Ref. 3]: it's quite low so the size weight and cost/kW/h of the battery is the limiting factor for the driving range. EVs need a very high specific energy, while higher specific power is required for Fast Charge.

Possible types of batteries applied to electric vehicles are:

- several types of Lithium-ion;
- NaNiCl2;
- NiMH;
- NiCd
- Lead acid;
- Super capacitors;
- Redox flow.

Figure 9 shows the traded-offs among the five principal Lithium-Ion Battery Technologies: the farther the coloured shape extends along a given axis, the better the performance along the dimension. As the graphs shows, no single technology wins along all the six dimensions: choosing a technology that optimizes performances along one dimension, inevitably means compromising on other dimensions [Ref. 8].

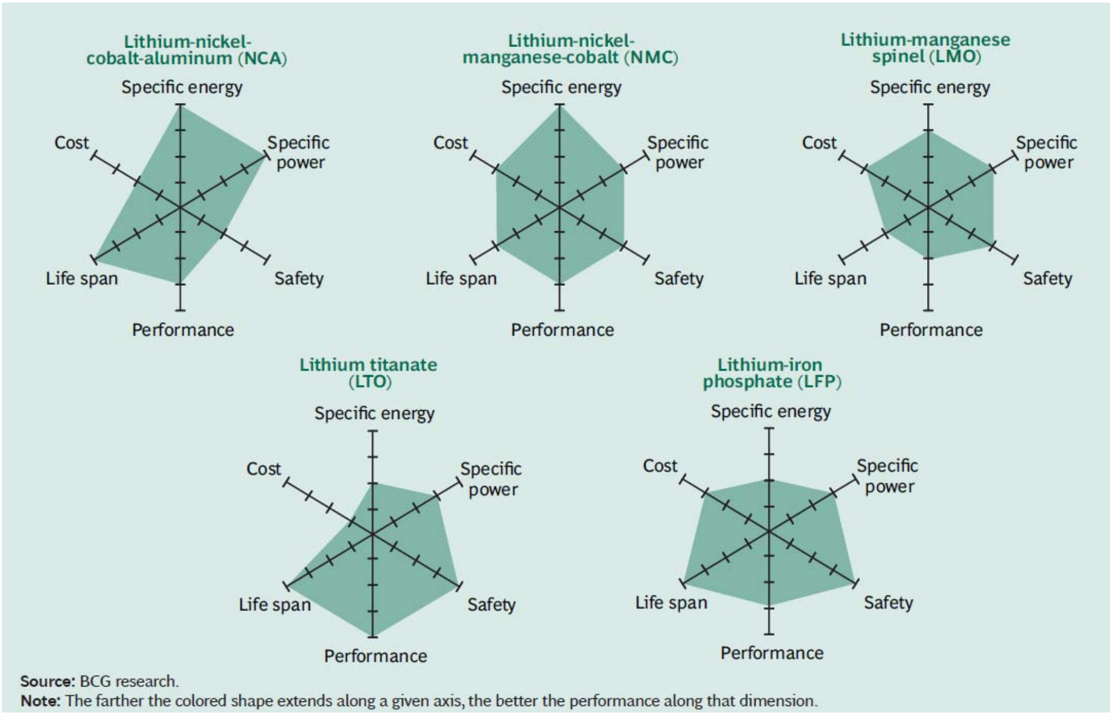


Figure 9. - Traded-offs among the five principal Lithium-Ion Battery Technologies [Ref. 8]

The Lithium-ion battery offers the highest potential of development and employment in BEV and PHEV [Ref. 3], promising high energy density, lifetime and number of cycles. One of the main tasks of research in this field is to find means to increase cell level safety in Li-Ion batteries, keeping high energy densities.

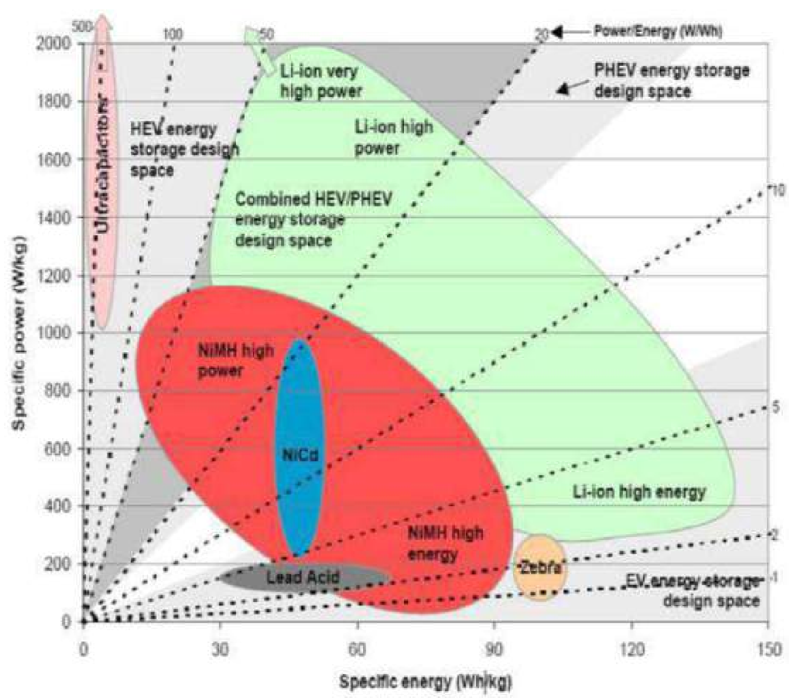


Figure 10. - Specific energy and specific power of different battery types [Ref. 11]

Figure 10 shows the different battery technologies today: the specific energy and specific power of a battery can vary depending on the application, EVs need a very high specific energy, while higher specific power is required for Fast Charge.

In the following table are summarized the Li-Ion-Battery characteristics (values are calculated at system level):

Energy density	130 Wh/kg
disc voltage	3,7 V
number of cycles (80% DOD)	3000

The NaNiCl2- , also called ZEBRA-battery, is a high temperature battery with considerable advantages: cheap substances, high lifetime and high energy density. The main disadvantage is the high self-discharge (for dissipative thermal power) and the fact that Zebra batteries need to be kept at high internal temperatures over the whole operating life.

Energy density	120 Wh/kg
disc voltage	2, 58 V
number of cycles(80% DOD)	1000

5.1.1.5 Battery capacity and C-Rate

Electric vehicles require batteries with a high energy density (kWh/kg), while hybrid vehicles require small batteries with limited energy content, but high specific power (kW/kg). BEV and PHEV can be classified by their range and capacity based on current field trials and electric vehicle fleet. The possible battery capacity can vary depending on different EV (or PHEV) types.

The C-Rate is a parameter related to the battery capacity that is the ability of a battery to be charged and discharged at a certain current [Ref. 1].

The nominal capacity of a battery is a value that may significantly differ, depending on real operating conditions, since there is no fixed definition of an “empty” battery or full battery. In fact, end-of-charge and discharge voltages and currents are used to estimate when these states are reached. However, these are highly dependent on many different factors: decreasing temperature, increasing age or increasing discharged current lead to decreasing capacity.

5.1.1.6 Charging curve for Li-Ion Batteries

As an example, in Figure 11 is shown the charging curve of Lithium-Ion batteries, usually charged with constant current, until they reach their end-of-charge-voltage, which is reached at about 70% SOC. Afterwards charge can be continued with const and voltage, while the current steadily decreases down to zero.

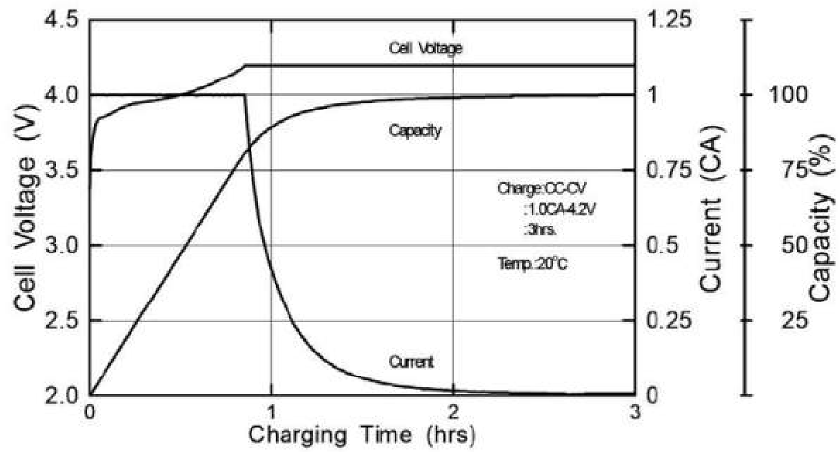


Figure 11. - Charging curve of Li-Ion batteries [Ref. 4]

5.1.1.7 Charging Time and Fast Charge

Long charging times present a technical challenge and a commercial barrier that must be considered: for EV to become the dominant mode of personal transportation, the charging process will have to evolve, becoming either much faster, or far less frequent.

It takes almost 10 hours to charge a 15 kWh battery by plugging it into a standard 120 V outlet, but this time can be significantly reduced by means of fast charging methods that employ more sophisticated charging terminals.

For example, charging by means of a 240 V outlet with increased power (40 amps) can take two hours, while charging at a commercial three-phase charging station can take as little as 20 minutes, but for these charging systems additional cost and weight arise, as they require enhanced cooling systems on board. Battery-swap methods promise to provide a full charge in less than three minutes, but such approaches need OEMs to agree to pack standardization requirements [Ref. 8].

Rapid charge and discharge rates are an important feature of electrical energy storage devices, but cause dramatic reductions in the energy that can be stored or delivered by most rechargeable batteries (their energy capacity). A high amount of the energy is lost in the internal resistance of the battery, which leads to temperature increase and modification of battery storage capacity. Super capacitors do not suffer from this problem, but are restricted to much lower stored energy per mass (energy density) than batteries. A storage technology that combines the rate performance of super capacitors with the energy density of batteries would significantly advance portable and distributed power technology.

A recent research work [Ref. 12] demonstrates very large battery charge and discharge rates with minimal capacity loss, by using cathodes made from a self-assembled three-dimensional bicontinuous nano-architecture consisting of an electrolytically active material sandwiched between rapid ion and electron transport pathways. Rates of up to 400C and 1,000C for lithium-ion and nickel-metal hydride chemistries, respectively, are achieved (where a 1C rate represents a one-hour complete charge or discharge), enabling fabrication of a lithium-ion battery that can be 90% charged in 2 minutes.

Prototypes for both nickel metal hydride (NiMH) and lithium-ion batteries, using cathodes of nickel oxyhydroxide (NiOOH) and lithiated manganese dioxide (MnO2), respectively have been created. An electrolyte then fills the remaining holes. This design provides large areas of contact between the nickel, cathode, and electrode without sacrificing much cathode volume.

The biggest drawback is the increased amperage: the major obstacle to uptake of these batteries is the larger current necessary to charge the batteries so quickly. EV, in particular, would need to be adapted to properly handle the swift movement of so many electrons.

NiCd batteries have long been considered, but show the memory effect and problems in recyclability.

Furthermore, the batteries based on new chemistry probably will be available for production on a significant scale by 2020.

5.1.1.8 Battery lifetime

The battery lifetime depends mainly on the usage, the temperature and aging. To illustrate the typical battery degradation, Figure 12 shows the number of cycles depending on the DoD (depth of discharge) for a Li-Ion battery cell [Ref. 4]. If a battery is used with 80% of its DoD, the battery lifetime is 2000 cycles. If only 3% of the DoD is used, more than 800000 cycles are possible.

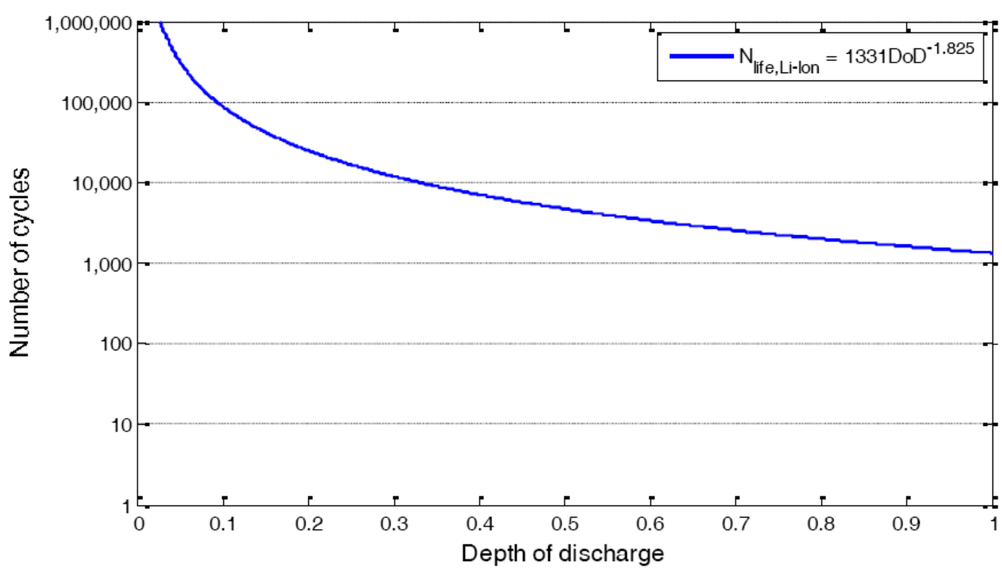


Figure 12. - Battery cycle life dependent on DoD for Li-Ion batteries [Ref. 1-5]

The following equation is used to estimate the number of cycles N_{life} to determine the battery lifetime depending on the DoD:

$$N_{life} = a * DoD^{b}.$$

For a Li-Ion battery the parameter values are:

a = 1331 and **b = -1,825**.

This equation is used to calculate the cycle life of Li-Ion batteries, but some very important parameters are not taken into account in this equation, such as:

- Temperature;
- C-Rate;
- Different Li-Ion battery chemistries;
- Battery dimensions;
- Battery ageing due to calendar life;
- Long time periods with discharged battery status.

5.1.1.9 Battery investment costs and costs of battery life cycle and degradation

These are two aspects to be evaluated from an economic and an environmental point of view, and the second parameter strongly depends on the first one.

As a rough estimate of the SMART-LIC Project the BMS cost target is considered to be within 10% of cell cost.

In order to support this hypothesis, we refer to the following evaluations of long term key success factors for battery system components in terms of costs [Ref. 9]: in the scheme of figure 13, the Battery System costs are divided in different costs types that is: system integration and components, cell manufacturing and materials. Furthermore, a percentage of potential reduction and long term levers have been estimated.

It results that the cost for the electronic portion is around 20%, so the Project target of 10% is reasonable.

	Type of Costs	%	Reduction Potential	Levers	%
Battery System Costs	System Integration	10%	Low	→ Learning effects → Automation of processes with increasing standardization	3%
	System Components	20%	Medium	→ Increasing purchasing volumes / increased component standardization → Optimization of system design	7%
	Cell Manufacturing	28%	High	→ Machine and equipment optimization (learning effects, reduction of variants on single line) → Capacity utilization	14%
	Cell Materials	42%	Medium	→ Shift to lower-cost primary materials and related processing costs → Increasing purchasing volumes	26%

Figure 13. - Long Term Key Success Factors [Ref. 9]

One cost reduction is clearly related to the battery production volume: Figure 14 shows how the battery system development cost shared on every battery produced decrease with the increase of annual production volume.

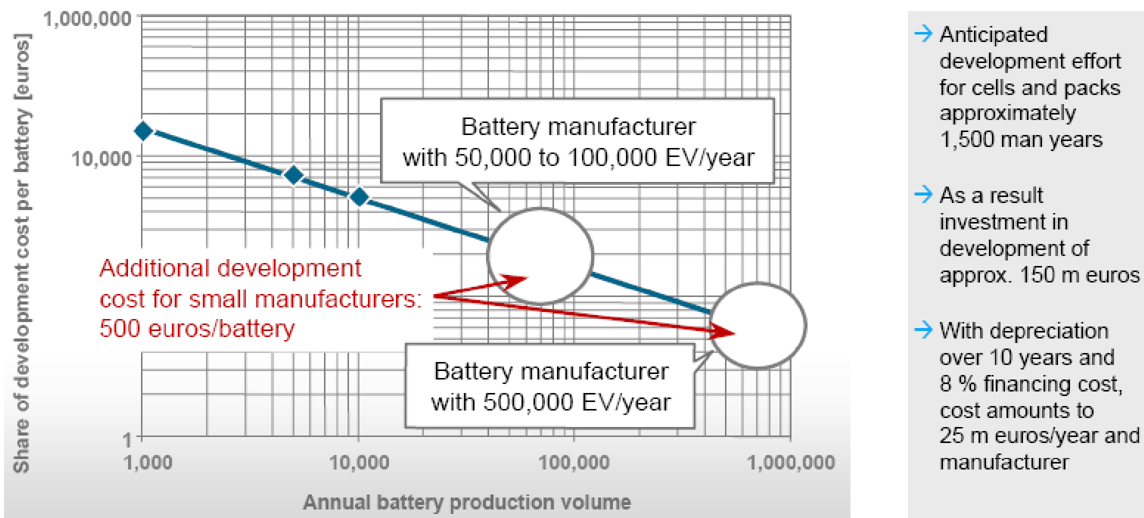


Figure 14. - Long Term Key Success Factors [Ref. 9]

Finally, the graph of figure 15 shows the evaluation of cost reduction for several components, due to different improvements, driving to the best cost scenario: it has been estimated that increase in specific energy and in cell manufacturing efficiency will drive down costs below 250 EUR/kWh.

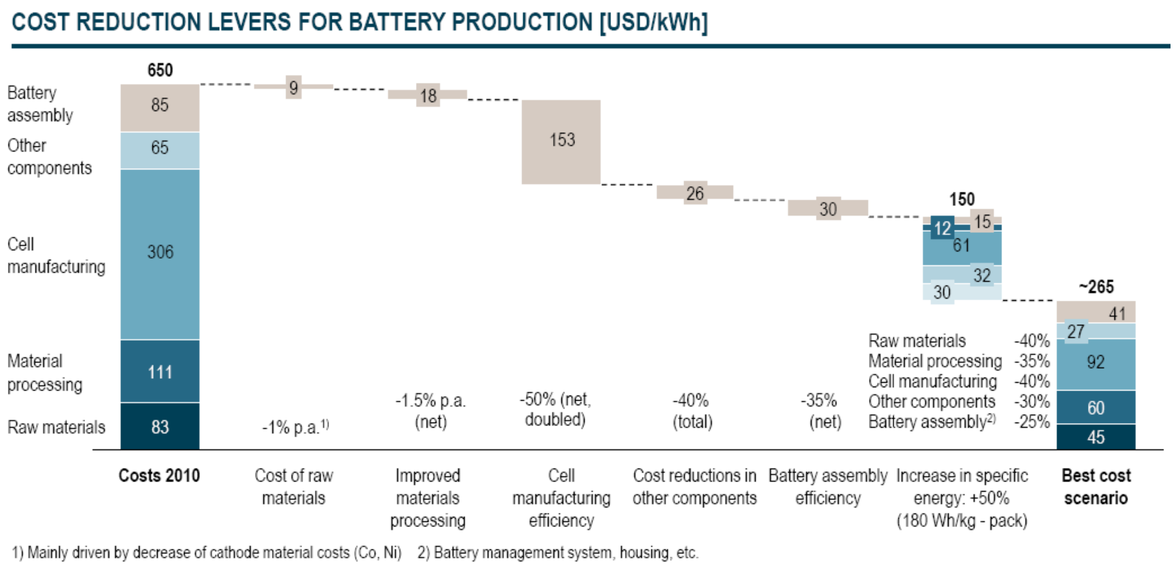


Figure 15. - Cost reduction levers for battery production [Ref. 10]

A widely spread concept which helps managing and evaluating the life-cycle of products is called the LCC (Life Cycle Costing). This lifecycle can be classified into the phases shown in the following figure:

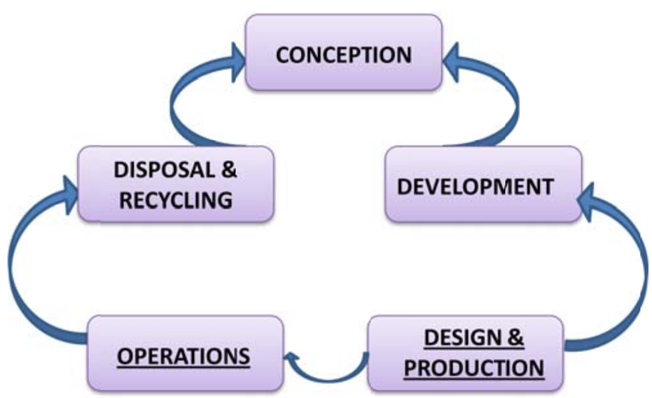


Figure 16. - Life cycle costing

Conception costs are those which occur during the first phase of the life cycle costing, like planning or monitoring costs. This phase concentrates mostly on the minimization of investment, operation and upkeep costs.

Development process include costs of market analysis, research and development costs, advertising, machine tool, storage and plant maintenance costs. In this phase, high investments must be defrayed and the costs are carried over a long period, and also an investment risk, concerning the realization of the product, has to be taken into account.

Design and production costs are the costs of materials and manufactures, the labour costs, to be differed between fixed and proportional costs. All in all are the production costs very important when it comes to production decisions and price decisions.

Operations costs occur during the use of a product or a technology, when there is no influence on costs reduction. This phase is also helpful in order to optimize the operating procedure.

Disposal and recycling costs arise after the product or the technology is used.

Also the battery degradation costs have to be estimated: where there is no experience with the new battery types and new BMS, models have to be used. However, the battery degradation process is too complex to use a physical battery model so a simplified cost model based on the DoD can be suitable to estimate the costs of battery degradation [Ref. 5].

5.1.1.10 Second life applications of batteries

Battery reuse and recycling is the final step in the value chain of electric vehicle batteries [Ref. 8].

The business case for EV depends heavily on investment and the performance of the batteries used. To improve the business case for EV, the total cost of ownership needs to be reduced and the battery performance needs to be enhanced. The total cost of ownership can be brought down by lowering the initial purchase cost and/or by increasing the value of a used battery, e.g., by finding ways of reusing them (second-life applications).

During its time as an electric vehicle's power source, a battery will lose some of its capacity; it results in the range of the vehicle (how far it can go between charges) decline. Drivers will regard this as a drawback and will ultimately be inclined to replace the battery, so this will mark the end of the battery's life as a vehicle power source. However, although the battery may no longer be good enough for continued use in an electric vehicle, it will still be able to accept a charge and to discharge electricity. So it may as well still be good enough for other applications, such as grid-connected storage.

Electric car batteries have up to 70% capacity remaining after 10 years of use, this allows them to be used beyond the lifetime of the vehicle for applications, and, for example, smart grids can take advantage of their capacity to store intermittent renewable energy.

The evaluation of possible battery reuse must take into account what kind of testing is needed to characterize the battery before use in a second-life application and if it's advantageous to disassemble the whole battery and re-use its constituent cells, instead of keep and reuse the batteries intact. [Ref. 13]

In case of recycling, deconstruction and cleaning, preparatory to material and components recycling, has to be evaluated. [Ref. 8].

SmartLIC will allow the riskless handling of battery cell blocks due to the fact that the cells can be disconnected from the cell block terminals, allowing to disassemble/transport the battery or parts of it (i.e. individual cell blocks) without the risk for electric shocks to the operator.

The second life may play a big role in combination with photo voltaic (PV) installations for grid management and/or for charging EVs over night with energy collected during the day by the PV systems.

5.1.2 Current BMS and balancing solutions

5.1.2.1 State of the Art BMS

Typically BMS use inductors (less frequently Capacitors) to store the energy for balancing.
Passive balancing is today a no active balancing HV Battery, currently in production.
Relays or other devices such as electrically or pyrotechnically triggered fuses/breakers are needed to disconnect poles in off-state / crash situations.

In Figure 17 the general scheme of a Battery Management System is shown, considering a Central Battery Management Unit.

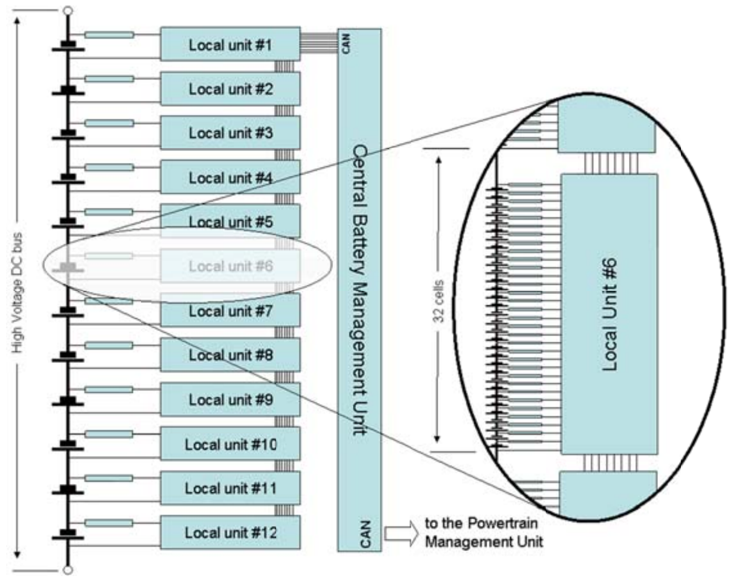
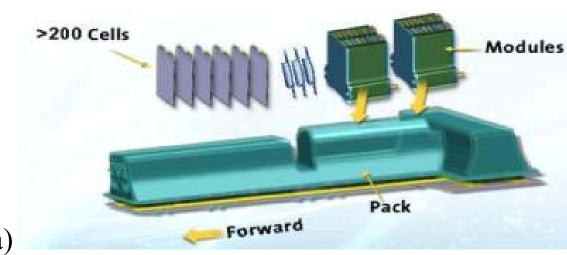


Figure 17. - General scheme of a Battery Management System


(a)


(b)

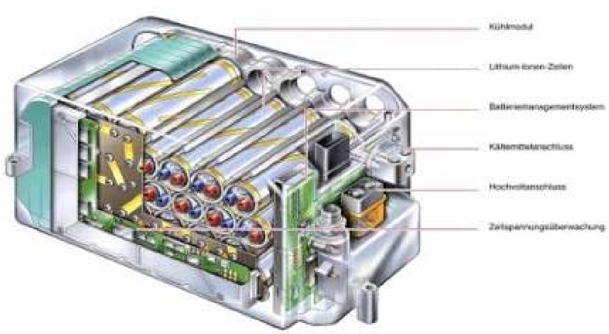

(c)

Figure 18. - Examples of BMS in use

Figure 18 shows three different BMS in use: SB LiMotive (9.a), General Motors (Chevrolet Volt) (9.b) and Daimler (MB S400)(9.c).

The current generation of BMS uses less semiconductor content than the Smart-LIC system and allows only simple balancing concepts with certain drawbacks.

Further disadvantages of today's BMS are the passive balancing which converts charged energy in heat only. All the connections between the local units are hard wired and isolation barriers are needed to get data in and out of the system. Furthermore some local units need individual uC and not all uC may have the same software code to fulfil its functions. The hardwiring imposes also some level of risk due to the high voltage potential between the poles. Not to forget that the high number of wire connections increase the failure rate due to contact failures over time. Today's BMS do not allow the exchange of (malfunctioning) local units – as active Li Ion cells should not be short circuited a potential removal of a local unit has to be done by trained electricians due to the high voltage levels. Typically today's BMS give only a usable capacitance range from 20% to 80% of the total capacitance and the worst cell/local unit is limiting the capacitance of the whole battery.

3.1.2.2 Smart-LIC WP1 objectives and benefits

From the State-of-the Art described above, the first objective of SMART-LIC WP1 is the design of a new system architecture for BMS at cell level, allowing to monitor and control each individual cell, with advanced balancing, active and passive, system.

The new BMS should improve performances, mainly in terms of charging efficiency and battery lifetime, with reduced costs, thanks to architecture simplification, SiP, and optimization of ownership costs.

Special attention to reliability and lifetime issues is mandatory from the beginning of development stage, in order to implement new lifetime models. This item includes considerations about incorporated safety devices, isolating of individual cell, as the active cell identification and authentication, aimed to plagiarism protection.

Another objective is the introduction of battery state determination, through the implementation of Electrochemical Impedance Spectroscopy (EIS), in-cell measurements of U, I, EIS, T, P and a more accurate determination of SoC, SoH,…SoF.

Finally, the testing of packaged BMS module (active + passive), demonstrating the functionality of 'smart-LIC' module will be an important result of the research activity, providing novel combined testing methods and new models for verification of developed lifetime.

"Limp home" function: as an additional module will be present in each pack stripe for balancing functions, in case of detection of a failed module, it can be switched permanently off without affecting system performance.

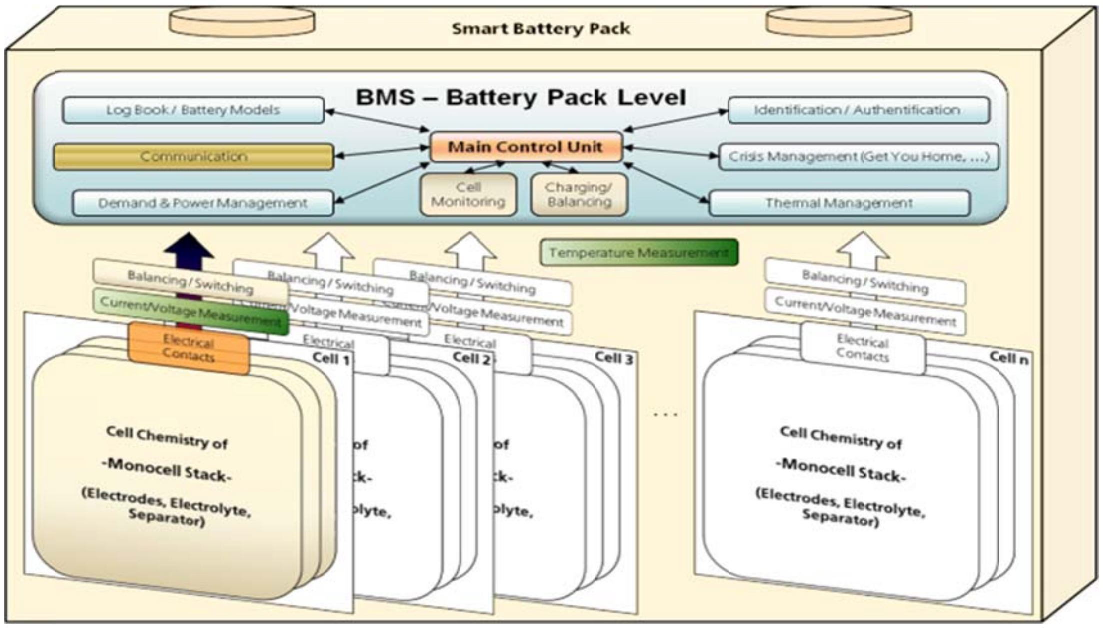


Figure 19. - BMS – Battery Pack Level

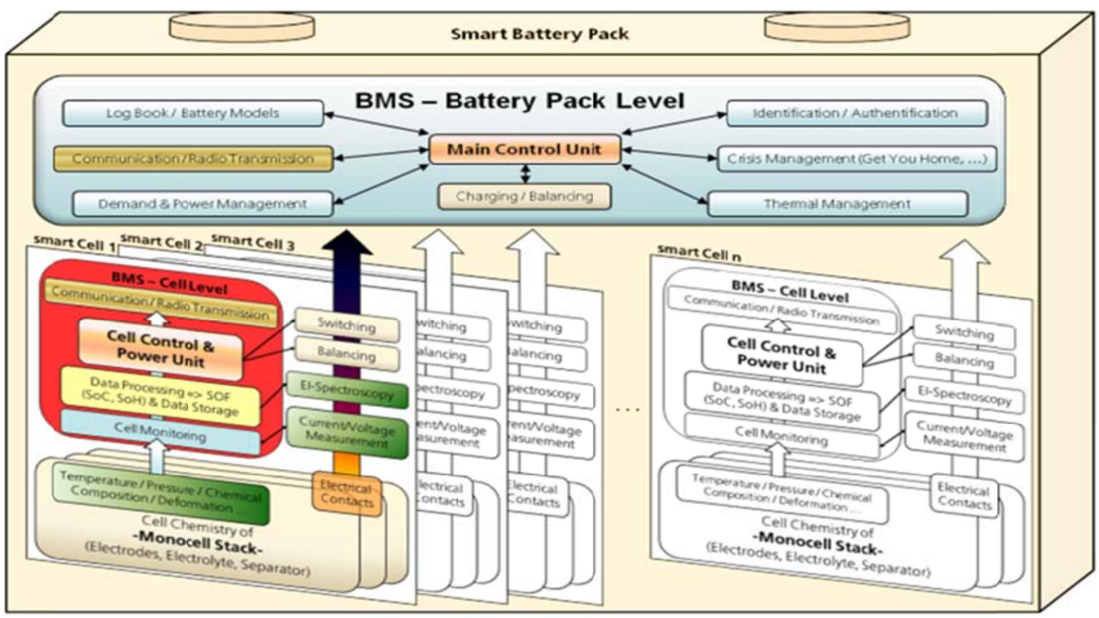


Figure 20. - BMS at Cell level

Figure 19 and 20 highlight the innovative aspects introduced by SMART-LIC: the first one is referred to a battery system considered at BMS at battery pack (and module) level, while the second one shows BMS at cell level.

The advantages on battery back level are manifold and start with the fact that the packs are independent intelligent units that can be hot swapped. The internal intelligence makes the pack interchangeable.

There are no galvanic control connections due to the intended wireless communication. This intrinsically safe communication system allows also a contactless diagnosis from the outside without the risk of high voltage injuries. The wireless communication leads to a reduced number of internal hardwire connections, thus increasing the reliability over time.

The capacity of the battery is due to the active balancing not determined by the worst cell/cell pack and therefore the capacity range from close to 0% until close to 100% of the battery can be used. Balancing the cells actively does not convert energy in heat, but transports excessive energy from a slightly smaller to a bigger cell – utilizing the full range.

This allows even to add cells/cell blocks in order to run isolated impedance spectroscopy without influencing the nominal battery voltage. The higher content of electronics provides more possibilities for diagnosis (impedance spectroscopy) and increase of safety (switching the battery packs off).

The concept foresees switches that enable a disconnection of the cells from the poles and during/after a crash the battery poles could be short circuited – having 0 V at the poles. The same can be done in the case of an external short circuit.

The concept of switchable cells/cell blocks provides the programmability of the battery voltage – addressing various types of motors/inverters with the same battery.

In the case of degrading battery cells or cell blocks, the architecture allows to take the cell/cell block off the stack and replace it at a later point in time.

The advantages of higher capacity, more reliability, long term & stable battery performance, better maintenance, exchangeable cell blocks, non-galvanic communication, more diagnosis and better safety strategies are possible when using more semiconductor content that today's system contain. In particular low ohm switches, RF circuitries and automotive uC with analogue signal capabilities are needed. Sensors can be added to further increase the safety of the operation of the battery.

5.1.3 Review of existing SiP and module integration solutions

Packaging/system integration is another main goal of the Project, aiming to realize a reliable, secure and cost effective packaging of ECU (BMS module) for harsh environment, including the investigations for suitable material selection, aimed to the integration of BMS module into the cell.

Current BMS are built on organic substrates with SMT-Devices. The BMS is integrated on module level by welding them to the metal strips of the individual cells within the battery housing. The metal casing is offering sufficient protection of the electronics from external influences.

The chip-level devices are packaged by over moulding with epoxy-moulding compounds or potting with different thermoplastic or duroplastic polymers.

Figure 21 shows a state of the art energy storage system from Continental with a BMS positioned outside the battery pack but inside the overall housing.

Electronics in more aggressive environments require more robust designs. High temperature electronics with service temperatures of up to 150 °C are either built on Ceramic Substrates like LTCC, DCB or alumina thick film or on organic High Density Interconnected (HDI) substrates. The electronic components consist of bare-die assemblies without polymer packaging of the individual chips. The electronic is protected by a silicone gel against thermal stresses and vibration. The protection against environmental influences, like moisture, aggressive vapours or liquids is realized by a housing made out of thermoplastic polymers like PA66 or PBT which is sealed with a top-cover which is mounted on the housing, as shown in figure 21.

These assemblies are very complex and offer a lot of joints which can be causes of leakage. Therefore, other packaging technologies have to be applied and analysed for electronics which are operated under severe conditions.

Figure 21. - Lithium Ion Energy Storage System with overall BMS outside the battery-cell pack

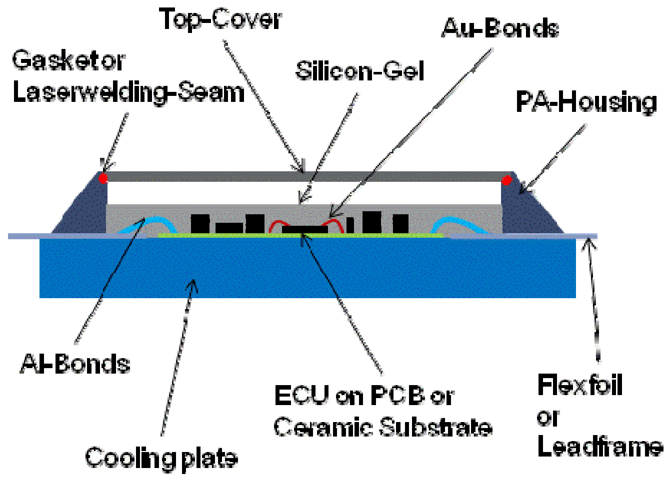


Figure 22. - State of the Art packaging for high temperature resistant electronic in harsh environment

5.1.4 Options for communication systems

Communication vs. EMC is one of the main objective of Smart-LIC Project, addressing and evaluating different solutions for communication to central BMS (wireless, wire-based, electr./opt., etc.). Consideration of shielding and EMC issues, caused by Signal and Power Integrity (SI/PI) is a crucial aspect.

The choice of Communication System requires to consider different aspects, technical and economical, in order to identify the optimum solution.

The communication from cell block to cell block is mainly done via isolated, wired CAN busses, while the communication to the external world is also done by isolated, but wired CAN link.

Wired communication means that the communication channels are implemented into cables but this solution involves a certain number of problems, first of all the cost intensive cabling.

Furthermore, problems due to different Voltage Level of each Cell-Pack have to be taken into account, as the EMC/EMI aspects and the Signal Integrity. For this reason the isolation transformers must be from very good quality and symmetry.

An alternative solution is the communication over Optical Fibre, but also in this case the cost for intensive cabling has to be evaluated and has to be considered the fragile optical connections.

On the other hand, this type of communication ensures an excellent Signal Integrity and does not pose any problem dealing with different Voltage Levels. Particularly in the internal space of a battery box, special conditions prevail, because the power rails emits a lot of transient noise from the cruise controller and the recuperation unit.

Another option for the communication method could be Power Line Communication (PLC). PLC means modulation of a digital protocol onto the battery poles. PLC as it is announced for batteries in 2012/13 has major drawbacks: low cost versions do not provide bi-directional communication – a high communication complexity in a multi cell environment and the need for isolated readout is resulting. PLC - like it is used in power metering applications are not tailored for mOhm battery cells and some of them need a periodic voltage zero crossing which is not given inside the batteries. A special PLC protocol called GreenPhy (GP) protocol may become important for the charging of Electric Vehicles – a standardisation is ongoing (ISO 15118) and STMicroelectronics is following the development of this standardisation. Usage inside a cell block seems – from today´s point of view – for many cell blocks in a battery commercially not feasible.

The wireless solution will be compared with PLC solution in order to understand the relative pros and cons.

Finally, the wireless communication seems to offer the major advantages, since it presents no problems with different Voltage Levels, guarantees Signal Integrity, like the communication over Optical Fibre, and in addition it's cheap and easy handling in case of maintenance of Cell-Packs. On the other hand it is more difficult to comply to EMC/EMI requirements, because the desired signal has levels in mV and mA in an environment of spurious signals with hundreds of voltage and amperes.

The drawbacks could be related to inhomogeneous field distribution, reflections and absorptions inside the Battery Box.

The investigation is focused on three scopes.

- Transmission in an electric cavity
- Transmission in Waveguide mode with open wedge-faces or absorber-faces
- Inductive Near field communication

The basic investigations are accomplished means with the help of numerical 3D simulation. The model can be seen in Figure 23. Inside the battery box the field distribution differs depending on the frequencies, the mode, and the geometry. The goal of the investigation is the determination of the boundary conditions of the different transmission possibilities. It is crucial that transmission is possible at all positions of a cell pack.

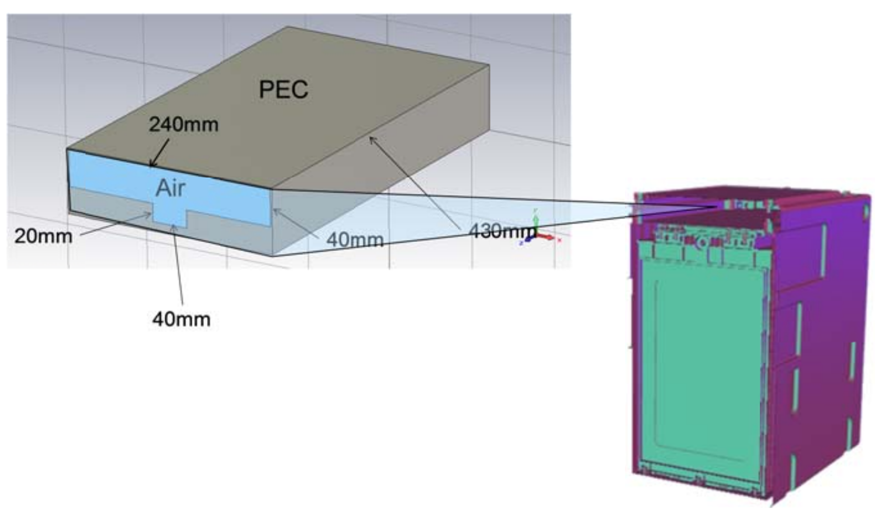


Figure 23. - Model of the Battery Box

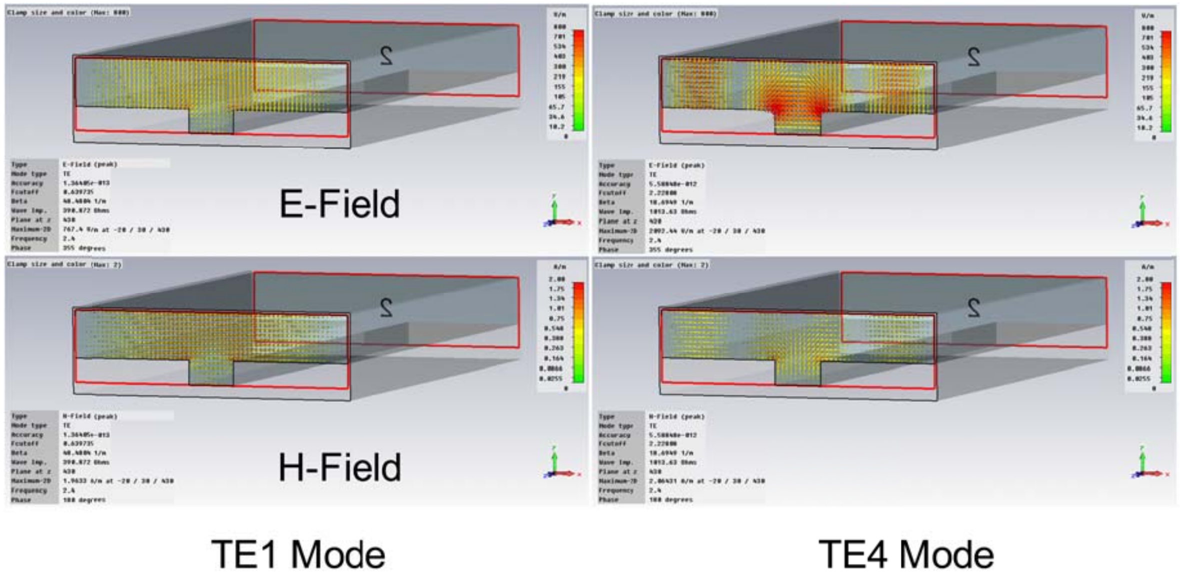


Figure 24. - TE Mode of the battery box

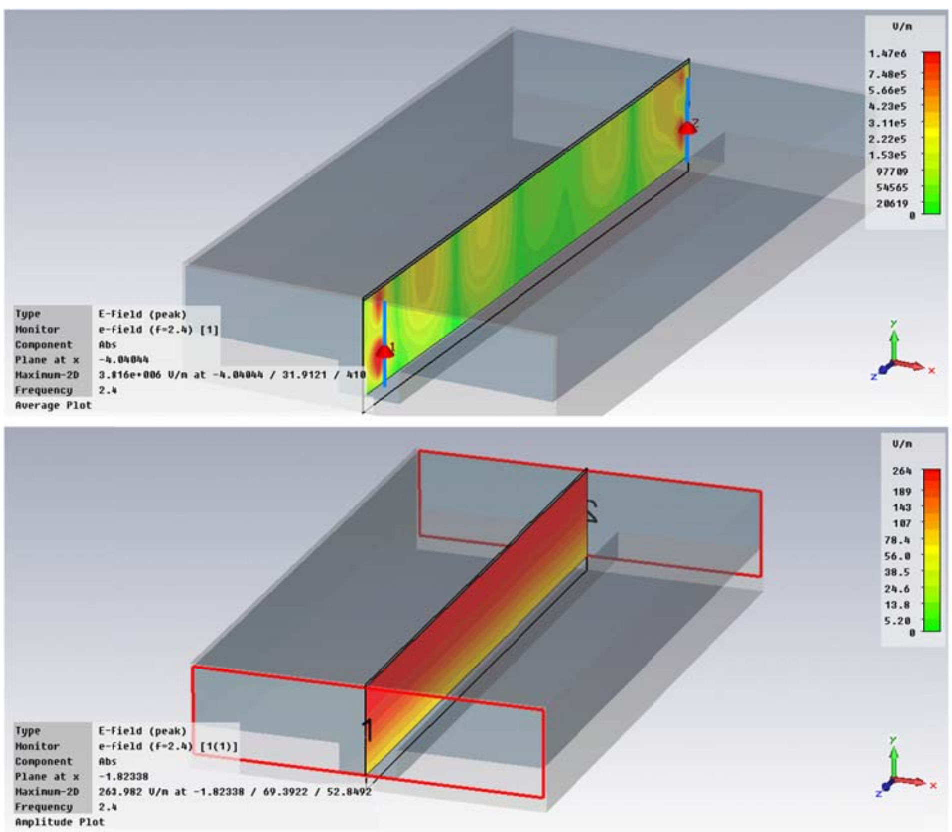


Figure 25. - Cavity vs. Waveguide E-Field longitudinal

5.2 High Voltage Battery management

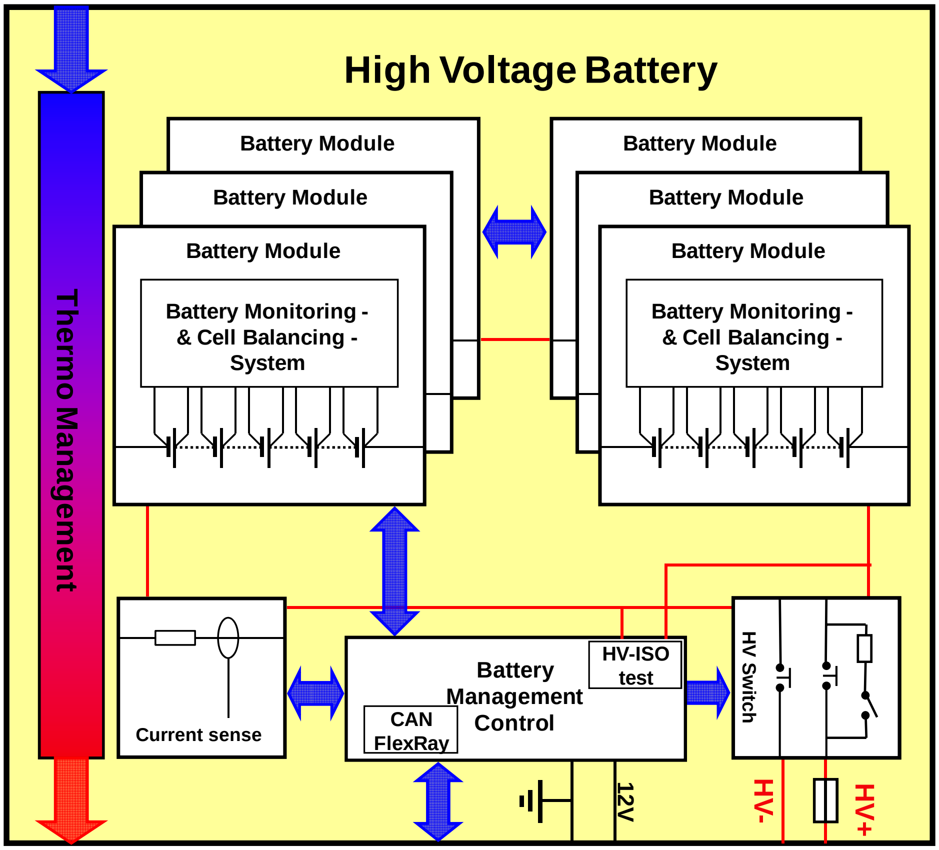


Figure 26. - High Voltage Battery System's Structure

Figure 26 shows the High Voltage Battery System's Structure, which single components could be described as follows:

- **High Voltage Switch:** connect the Battery to the high voltage bus of the car. Additional connectors are requested to the charger applications.
- **Battery Module:** contain a cluster of 4 to 12 battery cells with a cell balancing, voltage and temperature monitoring inside an Application Specific Integrated Circuit Utilizing inductors/caps to store Energy for balancing.
- **Battery Management Control:** Central Intelligence doing SoH, SoC calculation, balance control; thermal management; internal and external data ex-change; high voltage isolation test. The BMC is supplied mostly from the 12V supply with power management.
- **Current Sense:** contains resistive or inductive current measurement and wake up function.

Figure 27. - System's General Structure

Generally speaking, the possibility of intervention or modification on a defined structure depends mainly on the impact on energy/power and on voltage.

Pre-charge function which is present on the High Voltage Switch unit can be removed due to the presence of switches in each module.

6 SYSTEM REQUIREMENTS CAPTURE

6.1 Application context

The first point to be investigated is the target application for the SMART-LIC battery system to be developed in the Project; mainly in terms of:

- The vehicle types in which the battery system should be later integrated (at least theoretically);
- Minimum range;
- Typical energy consumption of the envisaged test vehicle type.

Some specific problems are investigated by means of the questionnaire, mainly concerning the smart battery system architecture, for instance the possibility to bypass one cell block in a string of cell blocks and, in general, about the structure and distribution of string cell blocks.

The questionnaire analyses also the requirements regarding the energy storage capacity, the maximum output power/current and battery voltage.

In terms of battery pack organization, several solutions are available, for instance: serial connected cells, serial connected modules, parallel connected strings or battery pack system.

Indications about the standard requirements to be complied are also needed, concerning the several aspects of the Project goal, that are, generally speaking, the standards used in Automotive applications, in particular:

- EMI standards for Electromagnetic interference;
- ESD standards, for Electrostatic discharge;
- EMC standards, for electromagnetic compatibility.

6.2 Questionnaire

In order to collect information about system requirements a questionnaire has been provided to partners, investigating the main aspects of the object.

The questionnaire is divided in two parts; the first one collects information/suggestions about the following Main Requirements:

1. Environmental Conditions;
2. Electrical Requirements;
3. Mechanical requirements;
4. Communication requirements.

In each area, some secondary requirements have been identified, such as:

- Operative and storage temperature;
- Vibrations to that the system could be subjected;
- Energy efficiency;
- Power and voltage levels;
- Discharge and recharge processes;
- Lifecycle;
- Modularity;
- Volume and weight;
- BMS power supply;
- Data communication protocol and speed.

The second part of the questionnaire concerns the target application in terms of vehicle type, the preferable Battery Pack structure and collects indications about standards to fulfil, especially by the safety point of view.

The cost target is also addressed in the questionnaire, but more general considerations are reported in the following.

6.3 Requirements definition: questionnaire analysis

6.3.1 Questionnaire results

The first part of the questionnaire aims to define the main requirements concerning environmental conditions, electrical and mechanical aspects and communication requirements.

Answers from CRF and Microvett have been collected in the table below.

Main Requirement	Secondary requirement	Centro Ricerche FIAT	MicroVett [General]	MicroVett [EDYF "Fiorino Elettrico"]	Note
Environmental Conditions	Operative Temperature	-20 + 50 C	-20 + 50 C	-20 + 50 C	
	Storage Temperature	-30 + 70 C	-25 + 60 C	-25 + 60 C	
	Vibration (Sinusoidal)	□5÷12 Hz constant displacement (5 mm)□ 12-200 Hz: constant acceleration (peak value: 30 m/s2)	ISO 12405-1	ISO 12405-1	ISO 12405-2 is more appropriate
	Vibration (Random)	□5-10 Hz slope 30 dB/oct Power spectral density: 213 mg2/Hz @ 10 Hz□ 10-1.000 Hz slope -3 dB/oct Power spectral density: 213 mg2/Hz @ 10 Hz	ISO 12405-1	ISO 12405-1	ISO 12405-2 is more appropriate
Electrical	Usable energy	20 kWh	10-50kWh	20kWh	per battery pack, up to 4 for the overall battery system
	Energy Efficiency	90%	90%	90%	ratio between discharge and charging energy
	Power (discharge)	60 kW	26-60kW	60kW	20% charged - max 10 sec
	Power (regenerative braking)	60 kW	5-20kW	20kW	80% charged - 15 sec
	Voltage (min during discharge)	200 Vdc	3V/cell	3V/cell	EOL - 40% charged - max discharge
	Voltage (max during regen. braking)	400 Vdc	4.2V/cell	4.2V/cell	absolute max value
	Self Discharge	<3%/month	<1%/month	<1%/month	
	Fast recharging	80% in 30 min	50kW (3C max)	50kW (3C max)	
	Life (cycles min)	1600	1500	1500	
	Life (years min)	8	5	5	
	Modularity	in parallel (pack level)	series/parallel	72 cell series / 4 parallel (organized in modules	up to 4
Mechanical	Volume (battery pack)	less than 150 liters	(440x160x270)mm X 3 to 18	(440x160x270)mm X 6	
	Weight (battery pack)	less than 230 kg	80-500 kg	160kg	
Communication	BMS Power supply	9-16 Vdc	12 V dc	12 V dc	
	Data communication	CAN Bus	CAN Bus	CAN Bus	
	Communication speed (Kb/s)	250			

Figure 28. - Specification table

The questionnaire results analysis allows drawing conclusions about the System Specification that are summarized in chapter 7, grouped by subject.

	Centro Ricerche FIAT	MicroVett [General]	MicroVett ["Fiorino Elettrico"]
Target Application	Commercial Vehicles Range: 70 to 150 km	LCV or City cars	Commercial Vehicles Range: 70 to 150 km
Battery Pack organization	Battery packs in parallel	series / parallel archit.	series / parallel archit.
Safety Requirement	Standard ISO 12405-3		ISO 12405-3
Limp Home			5km
Cooling	No specific requirement	Air natural	Air natural
Any standards to fulfill (EMI, ESD,...)?	Yes the standard used in Automotive applications	ECE10	ECE10
Cell failure fault tolerance	With minimal impact on energy/power and no impact on voltage	Appreciated	Appreciated
Cripted communication	Yes	No	No
Cost target?		BMS within 10% of cell costs	BMS within 10% of cell costs
Second life	Yes.	No	No

Figure 29. - Requirements of the overall BMS ensemble

6.3.1 Packaging and integration requirements

Actually cells are fitted in plastic trays which ensures mechanical sustain. On the top side of the trays bus bars and conventional BMS is present. The system shall not exceed the dimensions of the actual assembly.

Since Current System in Package solutions are based on mounting the electronics within the battery housing but outside the cell package, requirements for the electronic packaging are relatively simple.

In the Smart-LIC approach this is not the case, since the electronics are placed close to the cells. Except the microelectronic part, there will be a power electronic module with switches. These components generate electric losses and thus lead to strong heating of the components.

As the module shall be integrated directly on cell level, the thermal management of this power module needs a sophisticated solution. Compared to conventional packaging solutions, like shown in Figure 13 Over moulding can provide a effective means for a homogeneous head dissipation, since the thermal conductivity of the Epoxy Moulding Compound (EMC) is much higher than that of air (0.025 W/mK) or silicone gel (0.1 W/mK). Most commercial EMC have a thermal conductivity of ~1.0 W/mK since they consist of silica-filled Epoxy materials. New developments by the usage of filler materials with higher thermal conductivity will lead to materials with even higher values. Therefore by the design of a asymmetric moulded package it is possible to dissipate heat once through the moulding compound and once through the back side of the electronics substrate, Figure 30.

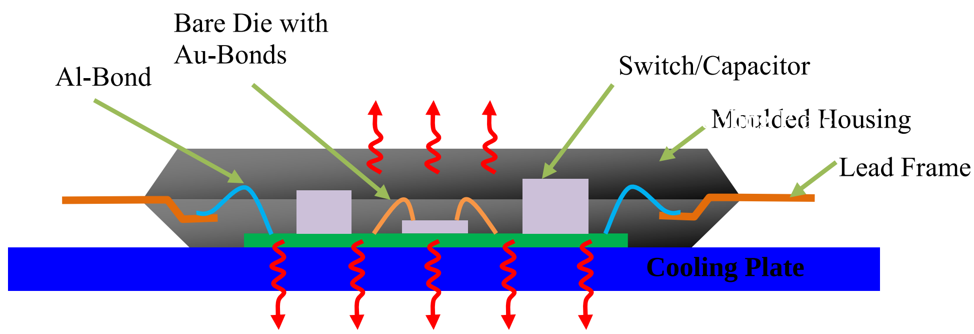


Figure 30. - Design and Heat-dissipation through a asymmetric, moulded electronic package

EMC offer the advantage of being thermally and chemically very stable. Therefore they can withstand temperatures above 200 °C which can emerge in electronic power modules. Further on they are resistant against fluids and vapours like oil, moisture and acidic substances which can occur inside or close to the battery cells.

Possible Material Suppliers are companies like Hitachi Chemical, Nitto Denko, Kyocera Chemical, Shin-Etsu Chemical, Henkel, Sumitomo Bakelite or Duresco.

The Material Requirements for EMC are listed in Figure 31.

Property	TC	CTE	E	T_g	Mould Shrinkage
Unit	W/mK	ppm/K	GPa	°C	%
typical	0.8 - 5	9-25	15-30	120-240	-0.04 - 0.2
aspired	3	9-16	15-20	150-200	< 0.05

Figure 31. - Typical and aspired Material Parameters for Epoxy Moulding Compounds

6.3.2 Safety requirements - ASIL according to ISO26262

Concerning safety, the main reference standard is the standard **ISO 12405-3**, "Electrically propelled road vehicles - Test specification for Lithium-ion traction battery packs and systems -- Part 3: Safety performance requirements.

According to ISO/WD 12405-3 (Li-ion based BS) Safety performance requirements, for higher than 60 V_{dc} systems, complying to R100 regulation, a galvanic insulation has to be assured:

- between the positive terminal and vehicle body;
- between the negative terminal and vehicle body;
- between BS and 12 V link.

Internal battery insulation sensor is required.

The International Standard **ISO 26262** provides requirements, process and methods to mitigate the effects of systematic faults and random hardware faults. This Standard treats the concepts of Functional Safety applied in automotive field, obtaining the absence of unacceptable risk due to hazards caused by mal-functional behaviour of systems.

This International Standard is applicable to E/E safety-related systems installed in passenger road vehicles, but not in vehicles for drivers with disabilities. Additional requirements for vehicles for the transport of hazardous goods are not covered by this International Standard.

The ISO 26262 redefines the first three SIL levels (Safety Integrity Level) of the IEC 61508 standard in four levels, named ASIL (Automotive Safety Integrity Level), specifying the risk and its requirements for risk reduction. The value of the ASILs is from D, which represent the more critical, to A and is determined by the Risk Assessment. The QM value represents a Not safety critical function. The ASIL, associated to each specific hazard, is determined by the application of the Risk Assessment procedure.

The ISO 26262 shall be applied during the entire automotive design flow:

- development process (including such activities as requirements specification, design, implementation, integration, verification, validation and configuration);
- production process;
- operation process;
- service process;
- decommissioning process;
- management process.

It provides a safety lifecycle, strictly related on a V-Model, in supporting on the Automotive Design Flow and is based on a specific approach to evaluate the risk in automotive field.

Furthermore it defines the guidelines for the risk assessment to apply in order to select the hazardous situations evaluating in term of risk classes (Automotive Safety Integrity Levels, ASILs). ASILs, Safety Goal and Safe state is used to define the safety requirements that allow to obtain an acceptable residual risk.

The ISO 26262 standard provides requirements for the verification, validation and confirmation measures to guarantee the robustness of the safety barriers applied during the safety lifecycle is intertwined with common quality process.

ISO 6469-1:2009 – "Electric road vehicles – Safety specifications”
Part 1: On-board rechargeable energy storage system (RESS), E3Car can only recommend.

For higher than 60 Vdc systems, according to R100 regulation a galvanic insulation has to be assured:

- between the positive terminal and vehicle body
- between the negative terminal and vehicle body
- between BS and 12 V link

Internal battery insulation sensor is required.

7 SYSTEMS SPECIFICATIONS

The main target application of the SMART-LIC BMS is on commercial vehicles for urban missions, as addressed in the questionnaire. In the following the questionnaire results are summarized.

7.1 Electrical specification

- **Cell configuration (modules)**

  In terms of battery pack organization, the most suitable solution seems to be a modular configuration, with different battery packs in parallel (pack level) up to 4.

- **Energy**
  - Usable energy: 20 kWh per battery pack; up to 4 for the overall battery system;
  - Energy efficiency: 90% (ratio between discharge and charging energy;
  - Maximum power required: 60 Kw, with a battery voltage between 200 and 400 V (280 V suggested);
  - BS usable energy (EoL): ≥ 20 kWh.

- **Voltage**
  - Minimum voltage during discharge: 200 V_{dc} (EOL – 40% charged – max discharge);
  - Maximum voltage during regenerative braking: 400 V_{dc} (absolute max value);

- **Current**

Rated current: ?

- **Power**
  - BS value of power during discharge: 60 kW (20% charged – max 10 s);
  - Regenerative braking: 5 ÷60 kW (80% charged in 15 s)
  - BS discharging regenerative peak power: 60 kW for 15 s @ 25°C up to 80 SoC%.

- **Calendar Life**

The expected calendar life is 10 years (and anyway more than 8).

- **Cycling Life**
  - Total number of cycles>= 1600
  - Cycle type: down to 20 SoC %@ 20 kW of power discharge
  - Capacity retention: >= 80% of initial capacity

- **Efficiency**

Battery energy efficiency (25°C, SoC range 20÷80%): >90%.

- **Self discharge**

The allowed self-discharge rate per month shall be ≤ 3 % of the rated capacity.

- **Fast charge ability**

The BS shall be able to guarantee charging up to 80% SoC in not more than 30 min.

7.2 Mechanical requirements for the smart battery architecture

- **Volume**

Less than 150 liters

- **Weight**

Battery pack: < 230 kg

7.2.1 Environmental conditions

- **Crash and Vibrations**

Concerning vibrations, the standards ISO 125405-1 and, more properly, ISO 125405-2 have to be complied. Furthermore, BS has to meet the shock and vibration requirements of FIAT 7Z9.300 or equivalent:

- Sinusoidal:
  - 5÷12 Hz constant displacement (5 mm)
  - 12÷200 Hz: constant acceleration (peak value: 30 m/s^2)
- Random (rms acceleration 3,15 g between 5 and 1.000 Hz):
  - 5÷10 Hz slope 30 dB/oct Power spectral density: 213 mg2/Hz @ 10 Hz.

- **Thermal requirements**

- Ambient temperature range: -20°C ÷ 50 °C
- Operative temperature range: -20°C ÷ 50 °C
- Storage temp. range: -30°C ÷ 70 °C
- Humidity range: 0 ÷ 100%
- Operating altitude: ≤ 2.000 m o.s.l.

- **Cooling type**

Preferably forced air or liquid if necessary (to be defined).

- **Cooling Power Dissipation**

Max 4 kW_{Th} continuous @ 50°C.

7.3BMS (Battery Management System)

7.3.1 Functions

A battery management system (BMS) is an electronic device that manages a rechargeable battery in order to:

- Control the battery operation
- Protect the battery from damage
- Prolong the battery life
- Maintain the battery in a health state
- Provide the user with reliable and secure information about operational status of the battery (during lifetime/at occasion of change of ownership).
- Identify individual cells or complete packs as OEM products

The BS shall be equipped with a BMS in order to:

- provide system control;
- acquire the main electrical parameters;
- allow an easy diagnostic for preventive and corrective maintenance;
- Opening main contactor if insulation problem appear.
- Monitor the battery
- Protect the battery
- Assure thermal management
- Power limits (temperature, time, State of Charge)
- Full battery power equalization capability
- Battery cell disconnection capability
- Operation in the noisy environment of high-power converters that may operate within the SBM [14].
- Indicate the residual value of a battery

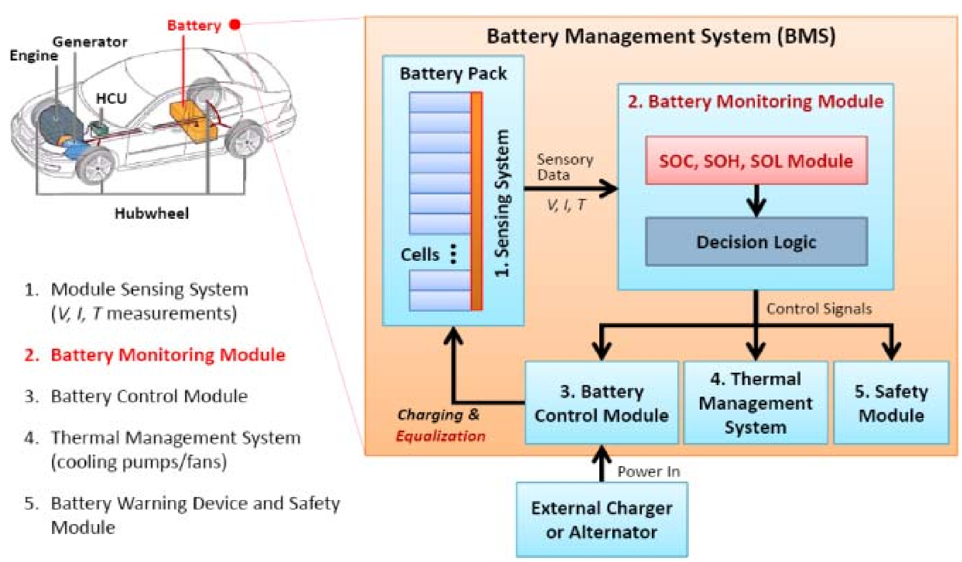


Figure 32. - BMS environment
[source: Martin Klein: LG chem. Power, 2011 PHM conference BMS Workshop]

Signal female/male connector to be defined (at least IP 57 degree of protection is required and automotive specs compliant).

The BMS must provide:

- monitoring of voltages, temperatures, current;
- real time max admissible discharge and charge power;
- SoC calculation;
- SoH calculation;
- SoL calculation;
- Cell balancing.
- Allow information to the driver (or an extract of the above defined data) (especially for range estimation and –in case of resale- the residual value of the battery)
- Robust design (automotive grade)
- Thermal management
- Fault detection and diagnostic
- Safety
- Low cost
- Cells protection
- Light volume

The primary emphasis of BMS research is to extract maximum performance from rechargeable batteries while minimizing degradation and extending lifetime. Specific research topics under BMS include:

- Physical and chemical basis of cell degradation;
- State-of-charge estimation for various cell chemistries;
- State-of-health estimation for various cell chemistries;
- Remaining lifetime estimation for battery systems;
- Cell, module and system-level performance monitoring;
- “Fuel gauge” applications for primary and secondary batteries;
- Innovative charge/discharge management and control systems at cell, module, and system levels;
- Battery usage monitoring for warranty assurance;
- Range-extending control strategies;
- Managing power demand from battery charging systems;
- Cell monitoring and cell balancing management for certain chemistries;
- Secure communication between cells and central unit.

7.3.2 BMS outcomes (title not clear)

- SOx and Power Management are critical BMS functions;
- To make the BMS affordable and to reduce the time to market, focus on the functions most critical to enhancing cell performance and life;

- Electronic hardware drives piece cost and a good part of development costs;
- Book-shelf and modularize to increase re-use of circuits and SW to drive up volumes and drive down costs.

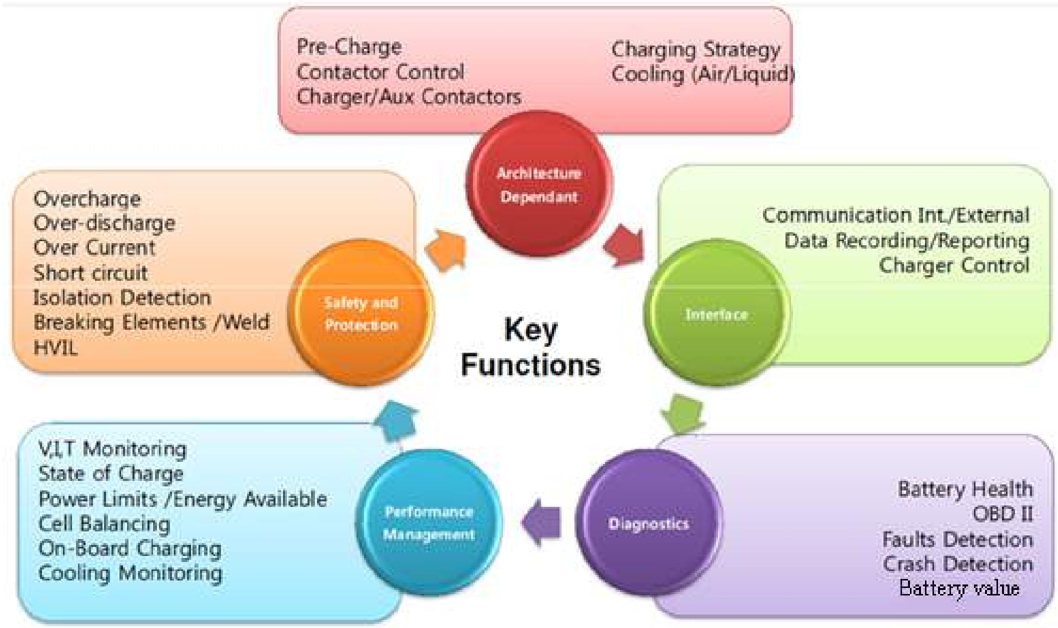


Figure 33. - Key functions of the BMS
[source: Martin Klein: LG chem. Power, 2011 PHM conference BMS Workshop]

For the sake of safety and the sake of cells, a Li-Ion BMS must:

- Prevent the cell from exceeding a safe operation limits;
- Prevent the temperature of any cell from exceeding a limit. This is a safety issue that prones to thermal runaway;
- Prevent the voltage of any cell from dropping below a limit;
- Prevent the charging current from exceeding a limit (which varies with cells voltage, cell temperature and previous level of current);
- Prevent the discharging current from exceeding a limit.

A BMS is essential when charging a Li-Ion battery. As soon as any cell reaches its maximum charged voltage, it must turn off the charger. A BMS also balances the battery to maximize its capacity. After many cycles of this process, all the cells will be at the same voltage, fully charged. Hence the charge in balanced between strong and weak cells. A BMS is also essential when discharging to low cut off voltage; it turns off the leads [15].

Design & Development Strategy	Cell Protection	Computation Optimization	EE HW Design Robustness	SW Design Robustness	Size & Weight	Time to Launch	Piece-Cost Management	ED&D Cost Management
Move all but cell protection, battery monitoring to vehicle-level controller		+	+	+	+	+	+	+
Repeating, common electronic circuits should be book-shelved for re-use on multiple programs			+			+	+	+
Next Generation ASICs to in increase circuit integration (and reduce part count)		+	+		+	+	+	+
Highly modular SW		-		+				+
Hardware-independent SW		-		+				
Make SOx only as complex as necessary for the intended roles (i.e., HEV, PHEV, EV)	+	+		+		+		+
Make HILs an integrated part of the Validation Process				+		+		+

Figure 34. - BMS design strategies
[source: Martin Klein: LG chem. Power 2011, PHM conference BMS Workshop]

7.3.3 Communication protocol

Data communication (battery bus SAE J1939 compliant) is realized here by means of CAN bus, at speed of 250 kb/s (as indication).

7.3.4 Communication interface

Battery Module composed of battery itself, BMS and other components inside the module.

Internally: components need to withstand the environment; interface needs to be defined.

7.3.5 EMC

The references and applicable standard is: **72/245/CEE – 2004/104/CE.**
The BS has to be designed to withstand and operate under internal and external electromagnetic noise.
The BS has not to cause electromagnetic emission which could disturb or effect in any case operation mode of any devices surrounding.

7.3.6 Connectivity (mechanical / electrical)

This aspect has to be compliant with standard automotive requirements. For the connector a water tightness of IP57 is required.

7.3.7 Temperature requirements (which voltage at what temperature?)

The interface between BMS & air condition must allow maintenance of the voltage at the right level e.g. CAN identifier.

7.3.8 Memory requirements (what shall be stored / how long / for which purpose?)

Essential data needs to be stored in order to be able to evaluate the residual (monetary) value of a battery.

Data which will be stored can be the following:

- Kilometer counter (“odometer), (very important data in order to avoid having a chance to compare battery packs of different provider).
- Battery energy flow counter
- Number of charging cycles
- Charging rates
- Safety data
- Vehicle parameters,

7.3.9 Black box (stored data, how long?)

At the moment no black box functionality is specified.

7.3.10 Cryptography

The need of encrypted communication has been taken into account, defining cryptological levels for tools, data storage and communication.

At the moment, encrypted communication exists.

In order to secure all the data, most part of the blocs (Batteries, BMS, Black Box, Interior display...) must include an encoded bus.

The cryptography will be managed by software.

State of Art BMS software can include the following functionalities:

- Automatic systems that link batteries for charging and isolate batteries for discharging;
- Simplicity of installation;
- Monitoring voltage of the vehicles batteries;
- Spike voltage protection to EFI and automotive computer systems;
- Ability to be installed into a large range of vehicles;
- Detection of counterfeit products.

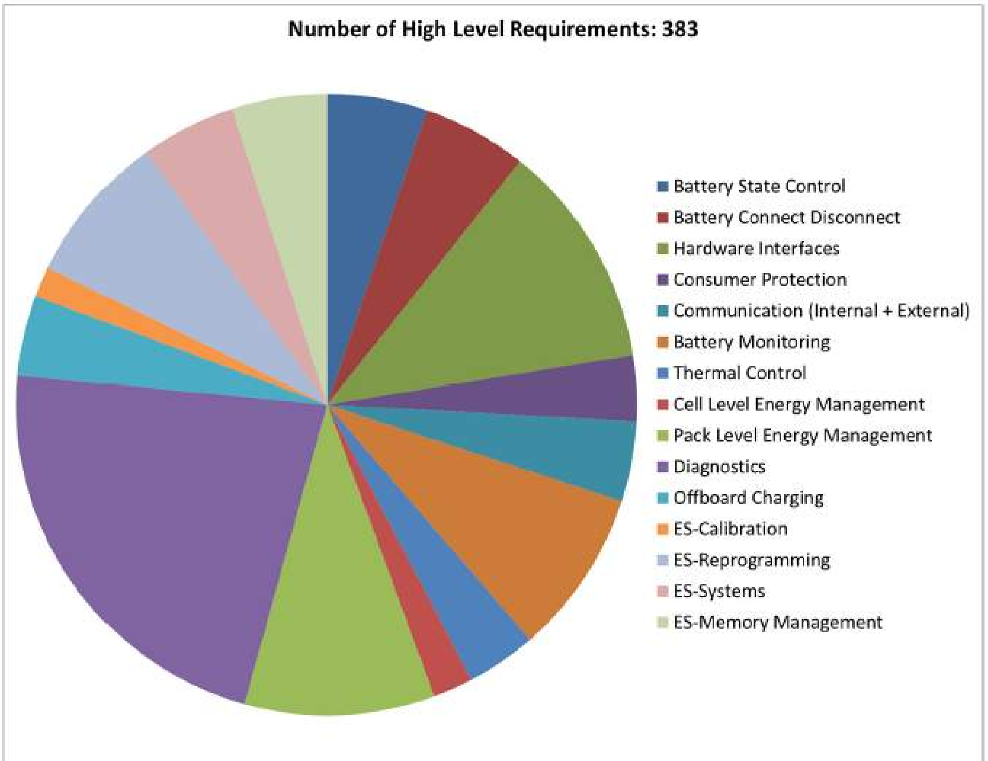


Figure 35. - Software tasks
[source: Martin Klein: LG chem. Power 2011, PHM conference BMS Workshop]

8 CONCLUSIONS

The SMART-LIC Project addresses the development of a new Battery Management System Module for Fully Electric Vehicles, to be integrated into Lithium-Ion Cell.

In the frame of this goal, the present document contains the Deliverable 1.1, *"Report detailing system specification and requirements"*, related to Work Package 1 (WP1).

The characteristic application scenarios have been identified, on the basis of the State-of-the-Art on existing solutions for the addressed developments, and the over-all system requirements have been deducted, also on the basis of a dedicated questionnaire.

This resulted in definition of specifications for the cell balancing strategy, requirements for the communication/EMC and for the integration/packaging solutions.

Furthermore, the document contains the needed information about compliance with standard automotive, concerning safety requirements.

System specifications have been defined, in terms of electrical and mechanical requirements, and specific functions of Battery Management System have been addressed, in particular concerning communication.

The Deliverable D1.1 will be used as the general System Specification and requirements as a reference document for the following activities scheduled in the other Work Packages addressing developments of the BMS, in particular in WP2, Development of System Architecture and System Design.

8.1 Contribution to overall picture

This document gives an overview about all issues (as far as identified) regarding:

- Battery pack (cells, cabling, fuses, contacts…);
- Integrated cooling system;
- BMS (Battery Management System);
- Battery system housing fixing parts.

Many items that concern components, modules, subassemblies, and communication are already discussed in the consortium of smart-LIC.

8.2 Relation to the state-of-the-art and progress beyond it

The smart-LIC consortium has in this first document identified the state of the art and the actions that will be suitable. The State-of-Art regarding the BMS is one of the main issues for the success of the project.

8.3 Impacts to other WPs and Tasks

This document and the work described herein will influence the definition of components. Thus, WP 1 is the first entrance for the outcome. It then influences directly the component and module work packages (WP2 and 5).

8.4 Contribution to demonstration (what aspects of the work that will be demonstrated

This work will contribute to the realisation of demonstrators and will be discussed in the next deliverable.

8.5 Other conclusions and lessons learned

The BMS and communication are important issues. During the preparation [2]of this document, it became obvious that these issues are often underestimated by the technical population. It is therefore even more important to increase the communication around these items in the consortium during the next phases of the project.

Furthermore it needs to be tracked what kind of problems occur during the introduction and operation phase of new BEV/PHEVs (i.e. Chevrolet Volt – post crash fires) in order to better underline the advantages of SmartLIC in this market.

9 REFERENCES

NOTE: List and number all bibliographical references in 12-point Times New Roman, single spaced, at the end of the delivery report. When referenced in the text, enclose the citation number in square brackets, for example [1]. Where appropriate, include the name(s) of editors of referenced books.

[1.] RWTH – Szczechowicz, G4V – Grid for Vehicles – WP1.3 – *Parameter Manual*, 16.12.201;

[2.] IEA, RETRANS Project, "Opportunities for the Use of Renewable Energy in Road Trasport", 2010

[3.] http://www.dges.de/alternative-antriebe/4.html - 01.05.2010., 05.05.2010;

[4.] Forschungsstelle für Energiewirtschaft e.V. Elektrofahrzeuge Elektrizitätswirtschaftliche Einbindung von Elektrostraßenfahrzeugen, Endbericht 2007;

[5.] ISE Fraunhofer, J. Link and others, *Optimization Algorithms for the Charge Dispatch of Plug-in Vehicles Based on Variable Tariffs*, Working Paper Sustainability and Innovation, No. S3/2010;

[6.] http://www.4sgroup.eu

[7.] J. D. Power & Associates, *Drive Green 2020: More Hope than Reality?* - Special Report, November 2010

[8.] Boston Consulting Group, *Batteries for Electric Cars: Changelles, Opportunities and the Outlook to 2020*, December 2010.

[9.] J. Fetzer, S. Butzmann, H. Fink (SB LiMotive), *Li-Ion Batteries – for the Future of Mobility* - 16.07.2009

[10.] Roland Berger, *Powertrain 2020 - The Li-Ion Battery Value Chain – Trends and implications*, 15 Internationaler Fachkongress Fortschritte in der Automobilelektronik, Ludwigsburg, 7. Juni 2011

[11.] BERR, *Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plugin Hybrid Vehicles*, 2008

[12.] Huigang Zhang, Xindi Yu & Paul V. Braun, *Three-dimensional bi-continuous ultrafast-charge and -discharge bulk battery electrodes*, Nature Nanotechnology 6, 277–281 (2011)

[13.] ERA_NET, NEO/EOS-LT Program (Energy Research Subsidy, Long-Term, New Energy Development)

[14.] *Designing a new generalized BMS* (John Chatzakis, Kostas Kalaitzakis, Nicholas C. Voulgaris, and Stefanos N. Manias*, Senior Member, IEEE)*

[15.] Davide Andrea, *BMS for large Lithium-Ion Battery packs*