High energy density Li-ion cells for traction

Berichterstattung

Projektinformationen

EUROLIION

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Final Report Summary - EUROLIION (High energy density Li-ion cells for traction)

Executive Summary:
Development of EVs for the transport sector is high on the list of EU priorities for economic recovery within the framework of the Green Car Initiative. Most work to date has focused on technical development and market analyses. Important challenges will also be faced in terms of durability, safety, cost and the required charging infrastructure.

Although conventional Li-ion cells have become widespread, some have too low energy density for transport applications. Others are either too expensive or do not meet environmental or safety standards. The EU-funded project 'High energy density Li-ion cells for traction' (EUROLIION) focused on developing novel Li-ion batteries that combine high energy density, low cost and enhanced safety. Benefits were obtained through a change in materials. The new cell has an innovative silicon (Si) anode (negative electrode), novel low-cost salts, and a modified iron or manganese/nickel-based cathode (positive electrode).
These electrode materials are cheaper and can store higher charge densities than the conventional electrodes. In addition, they require a higher operating voltage to increase cell energy density.

Scientists defined new formulations for synthesising nano-Si materials for the negative electrode, and different binders and additives. The produced Li-ion cells with a positive electrode that includes a combination of lithium, nickel and manganese demonstrated stable cycling. With a novel well-purified salt as an electrolyte, the nano-Si electrodes showed satisfactory capacity retention. More lithium salts were also synthesised, tested and even further purified since some were found to degrade the positive electrode.

Scientists produced and tested 20 cylindrical cells with commercial lithium iron phosphate (LFP) and graphite electrodes, and 20 cells with LFP and nano-Si electrodes. These tests served for cell modelling. A safety assessment according to the test procedure was carried out. Finally, a full vehicle simulation was performed.

EUROLIION has paved the way for widespread use of EVs by developing higher-efficiency, cheaper and safer rechargeable batteries. The new technology should enhance the competitiveness of the EU while supporting its dedication to a low-carbon–output and sustainable economy.

Project Context and Objectives:
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Initial Goals
The research described in this project aims to develop a new Li-ion cell for traction purposes with the following characteristics:
- High energy density of at least 200 Wh/kg
- Low costs i.e. a maximum of 150 Euro/kWh
- Improved safety

Other important goals that are being targeted on are:
- a specific power of at least 1000 W/kg during normal operation
- durability, reflected by a life time of 10 years and a cycle life of 2500 cycles
- operating temperature from -40 oC to 50 oC
- using environmentally friendly and sustainable materials
- protecting European technology

Description of work performed and main results
The work of EuroLiion is constructed along 8 WPs. The work concerned introductions of new materials, in which various steps required an iterative process so as to come to the final cells. The work performed since the beginning of the project is described by WP.

Coordination, management and dissemination (WP1, WP2)
WP1 The project started with a kick-off (KO) meeting where the structure of the project was explained in all its aspects, followed by every six month a project meeting.
WP2 concerned coordination of the R&D part. Here important decisions were taken such as the type of electrodes to be used, i.e. LNMO and Si as purchased by CEA with commercial electrolytes. Besides, the consortium decided to adjust the cell size to 18650 and pouch cells since these sizes were more appropriate according to the available coating sizes at CEA and EU safety reasons.

Materials synthesis (WP3, WP4, WP5)
WP3: two new formulations for electrode fabrication were defined for nano-Si electrodes, including different binders and additives as analysed with a synchrotron, AFM, NMR and XPS. Initial Li-ion cells with

optimised LNMO positive electrode were performed. Using well-purified LiTDI salts, the nano-Si electrodes show a good capacity retention in the defined electrolyte.
WP4: novel electrolyte salts were synthesized and tested. The nano-Si electrolyte interface showed partial decomposition of the novel salt. Exposure to LNMO also led to decomposition. Most of the degradation seem to be caused by the high voltage of the cell.
WP5: work was focused on the optimisation of the LNMO electrode, achieving an adequate electrode formulation, a decent cycleability, and stable adequate capacity. It was decided to use LNMO as cathode material in the 3rd series of test cells. For this reason, about 4 kg was purchased form EuroSupport according to the recipe developed within EuroLiion.

Electrode and cell manufacturing (WP6)
WP6 concerns the fabrication of the electrodes, made with the formulations achieved in WP3-WP5 with the formulations decided in WP2. Twenty 18650 cylindrical cells have been produced with commercial LFP/Graphite electrodes and twenty 18650 cylindrical cells with LFP/nano-Si for testing in WP7. The 3rd series of test cells contained 20 pouch cells with LNMO/nano-Si.

Testing and benchmarking of the cells (WP7)
WP7: cycle life testing of the prototype cells has been performed at ±0, +23 and +45ºC, following the procedure developed here. Tests were used to extract necessary parameters for cell modelling, which was further necessary for the development of the battery management, i.e. the algorithm for estimation the SOC. A safety assessment according to the test procedure was carried out. Finally, a full vehicle simulation was performed. For the 3rd series of test cells, it can be stated that the response of cell ranges from good to acceptable. The results might be positively compromised by the high internal resistance and the high ratio of surface to volume.

Eco-design and costs assessment (WP8)
In WP8 an evaluation was carried out on the new cell design and components regarding its LCA, recyclability and cost. The differences are minor when the materials are considered, while the production shows bigger differences. The new LNMO/Si cell design shows slight improvements compared to state of the art LFP/G. It shows an important aspect of an environmentally friendly battery design such as energy input for production, metal scarcity, etc. The suggested scarcity of Li seems no longer relevant due to huge Li sources, therefore recycling of Li was no longer studied.
Three recycling processes are identified, a pyrometallurgical, a hydrometallurgical, and a physical route. The 1st method gives basically a slag containing a Li product that is incorporated in e.g. construction materials, the 2nd one uses a separation technique from where components are recovered via dissolution/precipitation reactions. The 3rd route includes almost full dismantling of the cell so as to recover as much materials as possible.
Cost wise the EuroLiion goals of 150€/kWh could not be reached, mostly because of the high price of nano-Si. There is also no cost advantage compared to state-of-the-art NMC/G or LFP/G. However, if the price of nano-Si drops and the cell design is optimized, the LNMO/Si cell has great potential to be significantly lower priced than those cells and also to undershoot the ambitious EuroLiion target.
Another important conclusion is that recycling cannot be seen separated from battery costs and the LCA. Hence, the LNMO/Si cell has the potential to reduce cost and environmental impact, but needs further development and engineering towards a mature technology.

Expected final results and potential impacts
Electrification of transport is a priority in the Community Research Programme. It also figures prominently in the European Economic Recovery Plan presented in November 2008, within the framework of the Green Car Initiative. Besides that the policy related to battery-powered vehicles is mainly focused on technological optimisation and market development, future challenges in this field include reliability and durability of batteries and super-capacitors, reducing battery weight and volume, safety, cost reduction, improved hybrid electric power-trains, charging infrastructure and plug-in solutions.
A successful introduction of electric cars in the market requires the development of cheap, safe, reliable, light, small, highly efficient, and high power electrochemical storage devices – batteries. The introduction of electric cars will have an enormous impact on the production volume of rechargeable batteries, as this has never been achieved before. Clearly this put a strain on the availability of some raw materials, and therefore, attention has been paid toward selection of materials that are abundantly available.

Outcome
The outcome will be a newly developed cell, manufactured and tested by end-users. The new cell consists of:
- a newly formulated Si-negative electrode
- newly designed low cost salts
- modified positive electrodes.

Project Results:
System and test procedures definition

Objectives and outcome in short
This section includes the system integration activities with the following objectives:
- making the decisions for the project milestones;
- test procedure selection for performance and safety assessment;
- support the development of new material and the integration in prototype and large cells;
- specification for HEV Heavy duty trucks and EVs;
- dissemination of the results.

In the end the following objectives have been realised:
- making the decisions for the project milestones, i.e with respect to system definition:
  - the electrolyte salt was be distributed rather than the electrolyte solution
  - a negative electrode with commercial nano-Si was selected, rather than with nano-Si from TUDelft due to too much gas formation during production
  - a commercial electrolyte was selected due to better stability and compatibility towards the selected LNMO
  - for the cathode material the TUDelft material (LNMO) was selected;
- test procedure selection for performance and safety assessment

System definition
Battery materials used in the demonstrator cells – In summary, the 1st generation cells contained Si versus

LiFePO4 (LFP) with an electrolyte of 1M LiPF6 in EC/DMC/DEC. The 3rd generation cells contained Si vs LNMO with an electrolyte of LiPF6 in EC/DMC/DEC. The 2nd generation cells were not made as we were not able to stabilize the new LiTDI salt-based electrolyte against the LNMO cathode - unfortunately, this new salt as used in the electrolyte was not compatible with our cathodes foreseen in the consortium's lithium ion cells.
In both generation cells, the Si used had a particle size of 100-150nm. For the cathode material, LFP and LNMO had particle sizes of 100nm and 5000nm, respectively. The voltage versus metallic Li and the specific capacity for those materials were 3.3V and 150mAh/g, and 4.8V and 120mAh/g, respectively.

Electrode composition – The 1st generation cells were 18650 cells, whereas the 3rd generation cells were pouch cells. A more detailed description is given at the fabrication of the cells.
The anode composition was 150nm Si (69%), CMC (7%), Graphene (11%), PAMA/SBR (~3%), and Citric acid/sels (~8%).
The cathode composition was 5µm LNMO (92%), PvDF (4%), SuperP (2%), and VGCF (2%). It is stressed that the LNMO material has been produced by EuroSupport, Uden, NL according to the recipe developed within the consortium.

Test Procedure definitions and methods
The procedure as foreseen aimed to provide the full details required to create a procedure to assess Si-based cells on performance, including abuse testing. Several items have been described, where a procedure was developed aiming to provide full details required to analyse and characterize the developed cell in terms of operational performance, efficiency, and durability (calendar- and cycle life).

Negative electrode formulation

Objectives and outcome in short
Objectives in terms of performances was mentioned earlier. However, the capacity of the new Si negative electrode cannot be less than 1500 mAh/g following 500 cycles at C/5, by the end of the project, electrodes loading being in the range of today's energy Li-ion technology. For that purpose, the objectives have been broken down into well-defined objectives:
- prepare and test commercial Si and other Si-based materials with various structures (e.g. 2D structures, amorphous Si) and compositions (e.g. Zintl's phases);
- prepare, optimize and test alternative binders to CMC;
- increase the power density through the use of electron conducting binders and doped Si;
- address the volumetric capacity issue by tuning the porosity;
- study the Si degradation mechanisms during cycling.

In the end the following objectives have been realised:
- nano-Si powders produced via the LA-CVP technique have been delivered to various partners for further processing;
- Si powder delivery from commercial suppliers rather than from TUDelft;
- a formulation for Si coating has successfully made and supplied to CEA for implementation in WP6;
- prepare and test commercial Si and other Si-based materials with various structures (e.g. 2D structures, amorphous Si) and compositions (e.g. Zintl's phases);

- preparation and optimization of Si electrode formulation with CMC as a binder;
- preparation, optimization and testing alternative binders – e.g. aliginate;
- addressing the volumetric capacity issue by tuning the porosity;
- studying the Si degradation mechanisms during cycling;
- an overview of various (reported) Si materials has been given with regard to size and morphology.

Investigation of aging mechanisms of Si electrodes

A bibliographic review has been written on the aging mechanism of Si electrodes and contains the following items:

- effect of particle size;
- Si/C Composite;
- binder effect - formulation / composition;
- Li Insertion mechanism;
- effect of cycling procedure;
- the problem of coulombic efficiency vs electrolyte degradation;
- the surface chemistry of Si electrode studied by XPS;
- commercial Si.

Li NMR studies have focused on understanding the difference between micron sized, 150 nm and 15 nm Si. We have completed a study of the 150 nm Si (33:33:33 CMC:C:Si) composition. The local structure formed on cycling is similar to that seen for micron Si (Key et al. J. Am. Chem. Soc., 131, 9239, 2009) but the kinetics of lithiation is easier. In summary:

- Li15Si4 formed on discharge to 0V, indicating that it is important to use a cut-off voltage of >50 mV. The behaviour is different from the 15 nm Si where no Li15Si4 is seen and the atomic/electronic structure and nature of the clusters are different.
- 29Si NMR studies are on-going to obtain more structural information about the nature of the clusters. 1D NMR spectra have been collected.
- FEC/VC studies were performed and the synthesis of 13C enriched electrolytes were initiated to allow for more detailed SEI studies. Preliminary syntheses with non-enriched starting materials were performed to produce EC.

Synthesis of new Si particles and their characterization

TUDelft has produced crystalline Si nano-particles (SiNP) with laser assisted CVP. Several batches of about 30 g of the above material have been delivered to partners for further analyses and processing. The production rate that has been achieved so far is about 50-100 g/day. During the research it was found that the SiNP can be collected without any air exposure avoiding any contamination of the Si surface. However, once exposed to air (moisture) it starts to react violently. It was already known that an oxygen layer on Si surfaces seems to be essential for good Si/Binder interactions, therefore the SiNPs are allowed to oxidize only at the surface by accepting a small leak in the set-up. These Si active materials are characterized in terms of morphology and composition by BET, XRD, TEM, and EDS. The particle size can be controlled by the laser power applied. The particle size is roughly 20 nm with a small size distribution as calculated by proper analysis of the BET, XRD and TEM results.

The most surprising result concerns the nature of the Si surface made at TUDelft. Despite the very high surface area of this Si (> 110 m2/g), it contains less than 7% of Si dioxide. EDS measurements show small amounts of oxygen, of which most is coming from adsorbed CO_2 – a common phenomenon found in EDS analysis.

Electrochemical tests were performed on these casted films according to the following procedure: 1st cycle, current at C/50, voltage range of 50 mV to 0.9V followed by consequetive cycles recorded with a current at C/10 and a voltage range of 175 mV to 0.9V. The active material was 0.75 mg in these pouch cells.

Development of new associations of Si with binders and carbons

The Si-binder system was analysed in an in-situ cell with Small Angle and Wide Angle X ray Spectroscopy (SAXS/WAXS). Modelling of the preliminary measurements shows a Si particle size of 10nm diameter (before lithium insertion) which is in good agreement with the TEM results. Furthermore, the WAXS data illustrates the feasibility of monitoring the particle crystallinity during charge and discharge. It seems, that during the Li-uptake and donation the CMC binder loses its partially crystallization.

CNRS-LRCS and CEA identified a strong reactivity of Si with water leading to hydrogen gases coming from the electrode slurry. This reaction does not allow a homogeneous and smooth casting of the Si electrode at CEA scale (100 meter of electrode need to be deposited). This reaction is due to the oxidation of Si with water according to the following reaction:

$Si + 2H_2O \Rightarrow SiO_2 + 4H_2$.

At CNRS-LRCS, we have demonstrated that the hydrogen production is enhanced when the temperature increases and decreased at low pH value. The consequences of these measurements are some modifications of the electrode processes at CEA. In order to suppress the formation of hydrogen gases, we have produced a small, dense and protective layer of SiO_2 at the surface of the Si powders by thermal treatment of Si powder at 400°C during 2 hours. Higher temperatures produced to a too high SiO_2 layer whose consequences are very poor electrochemical properties. This thermal treatment has been implemented at CEA.

Besides, there was an interest to explore a new binder: PAA-g-PEO. The behaviour of the binder has been analysed by comparison with the state-of-the-art CMC binder. In order to optimize the electrode behaviour, various mass ratios and compositions have been tested. Despite these preliminary results, it seems that the new binder have certain potential.

Formulation of defined association of particles / binder for better cycleability

A first formulation with optimised slurry rheological properties and stability, and improved conductive additive (carbon black) distribution thanks to the use of a dispersant was released earlier. Formulation 1 (Si 66%, Citric acid 15.5%, CMC 6.8%, AcB 10.1%, PAMA 1.7%) with AM loading 2.5mg/cm^2 achieves at C/5: 370+/-45 cycles at 1200mAh/g_Si (790mAh/g_electrode ⌠ 3mAh/cm^2) with LP30+10%FEC+2%VC electrolyte, coulombic efficiency 98.5+/-0.5%.

A second formulation with modified conductive additive (exfoliated graphite nanoplatelets, which is a cheap graphene) was released at month 18. Formulation 2 (Si 66%, Citric acid 15.5%, CMC 6.8%, Graphene 10.1%, PAMA 1.7%) with AM loading 2.5mg/cm^2 achieves at C/5: 200 cycles at 1800mAh/g-Si (1200mAh/g-electrode, agreeing with 4.6mAh/cm^2) with LP30+10%FEC+2%VC electrolyte, coulombic efficiency 99.85+/-0.1%.

Moreover, we made full cells with a Si electrode (Formulation 2) and a LNMO electrode, and we showed, if

the Si electrode is fully lithiated/delithiated vs Li metal before the full cell assembly, a full reversible cycling for 50 cycles. In this case, the electrolyte contained only FEC as the additive.
Initially, it was noticed that during manufacture of the electrode gas (hydrogen) evolution took place resulting in an inhomogeneous coating. This however was solved by pre-oxidising the Si at 400 oC, and, hence, proper coatings were produced in the end.

Compatibility of the new electrolytes with the Si electrodes - Effect of additives
Initially, the optimized formulation has been tested on their the electrochemical performances of the Si-electrodes using conventional two electrode Swagelok cells with different liquid electrolytes:

- a 1M LiPF6 solution in an EC-DMC mixture;
- a 1M LiPF6 solution in an EC-DMC mixture with VC and FEC additives;
- a 1M LiTDI (salt from Warsaw) solution in an EC-DMC mixture;
- a 1M LiTDI (salt from Warsaw) solution in an EC-DMC mixture with VC and FEC additives.

In parallel, electrochemical tests were performed with the 33/33/33 composition with LiPF6 EC-DMC as reference but also with different concentration of LiTDI in EC/DMC in coin cells configuration. The polarisation of Si electrodes observed with 1M LiTDI electrolyte has been reduced thanks to the optimisation of the ionic conductivity of the electrolyte.
Other parallel tests showed that the best cycling is with FSI-salt and LiPF6 with VC. However, the SiOxFy compound formed on the surface of the Si particles as a function of cycling is also formed with the use of the FSI salt.
Furthermore, we studied the cycleability of Si electrodes based on the Si purchased by CEA with the following formulation Si(33%), CMC(33%) and Csp(33%) and with four different electrolytes: LP30 (LiPF6 in EC/DMC), LP30 with additives (2%VC and 10% FEC), LiTDI (LiTDI in EC/DMC) and LITDI with additives (2%VC, 10% FEC). Electrochemical cycling tests were performed without any capacity restriction. We can observe that whatever the salt LiPF6 or LITDI, the capacity strongly decrease when no additives are used and this capacity retention is strongly improved when VC and FEC are added in the electrolyte. When LiTDI is compared with LP30, the capacity retention are very similar. It is vital that this LiTDI is strongly purified in order to obtain good quality results. It is als important to recall that LiTDI doesn’t contain any fluor atoms so the battery safety will be strongly improved since the major sources of toxic gases emitted during a battery fire is hydrofluoric acid.

The conductivity of LiPF6 is typically 11mS/cm, and decomposes between 65-80°C. It further hydrolyzes so as to form HF. LiTDI does not generate HF, and has typically a conductivity of 6.7 mS/cm, and is stable in water and up to 250°C. Unfortunately, above 4.6V is showed significant degradation in electrochemical cells. Nevertheless, against Si it showed to be very stable. It however, required additives to perform adequately, such as FEC. Despite the required existence of FEC, aging of the LiTDI electrolyte in contact with Si occurs. This phenomenon is still not fully clear.

Electrolyte formulation

Objectives and outcome in short

- Synthesizing and analyzing new battery electrolytes based on an imidazole salt.
- Use of only one salt in the optimized mixture of solvents.
- Ionic conductivity of the electrolyte of minimal 5mS•cm-1 and lithium transference number of 0.4.

- Cycling ability and electrolyte-electrode compatibility with both electrode materials.

In the end the following objectives have been realised:

- the equipment (glove box) was installed and infrastructure built;
- synthesis of the salt in the volume able to fulfil the requirements of the Partners in WP4;
- test Optimization of the electrolyte;
- materials sent to partners;
- detailed instruction with procedure of electrolyte preparation and purification;
- optimization of the electrolyte;
- compatibility test with anode showed good performance;
- compatibility test with cathode showed poor performance;
- preparation and submission of scientific papers together with other partners of EuroLiion.

Electrolyte formulation and testing

In summary, the recommended electrolyte solution is EC/DMC (1:2) 0.31 mol/kg LiTDI. However, for better performances at lower temperatures, the suggested solution will be EC/DMC/DEC (1:1:1) 0.5 mol/kg LiTDI. The solubility in battery grade solvents like cyclic and linear carbonates (DMC, DEC, EC, PC) is very good, i.e. at least a concentration of 2M can be reached. Obviously, the salts are also very soluble in water and forms actually very stable complexes, which allows even a certain water concentration in the electrolyte used as this will then scavenged the moisture. This was further confirmed when using a 6mole% water concentration in a commercial electrolyte where no reaction was observed with a lithium metal electrode. However, it is still highly advised to keep it as dry as possible to minimize the moisture influence on other eventual parasitic reactions.

In the end, around 80 different compositions were tested. Most of the compositions reached the values of the conductivity and transference numbers required in the project, i.e. ~4-5 mS/cm and 0.5 respectively. Moreover, several discussions led to the conclusion to use stabilising agents such as FEC and VC. This will be done outside the context of EuroLiion.

Compatibility with negative electrode

The results have been tested along other tasks, but are anyhow summarised here as follows:

- without capacity limitations, the cycle life is strongly affected by the mechanical resiliency of the electrode;
- without FEC, TDI electrolyte shows poor performance. Adding FEC (Novolytes) improves the TDI electrolyte performance.
- when Si is cycled with capacity limitations, TDI is much worse than LiPF6, but without capacity limitations, TDI is slightly worse than LiPF6;
- the highest capacity (3000mAh/g over 70 cycles) was found with Si based anodes for the electrolyte EC/DMC (1:2) 0.31 mol/kg LiTDI+2% VC+10%FEC. An important improvement for LiTDI was obtained with the additives VC and FEC on the capacity retention. LiTDI+VC+FEC (Aldrich) based electrolytes offers a better capacity retention than LP30, however this additive is responsible for a significant polarisation effect. LiTDI + VC + FEC (Aldrich) based electrolytes offers a poorer capacity retention than LP30 +VC +FEC;
- without additives we obtained a reversible capacity for nano Si composite anodes of about 900mA/h by using EC/DMC (1:2) 0.63 mol/kg LiTDI electrolyte for over 500 cycles

In addition, water treated Si electrode have been analysed as well. In summary:
- in case of LiTDI based electrolyte, a capacity was reached which was inferior to the one with LiPF6 but a better efficiency and cycle life was obtained, currently over 250 cycles and still running;
- the lithiation process of the Si differs significantly from the classical system, which has been observed by the very strong differences in the derivatives curves cycled with LiPF6 and LITDI.
- when using LiTDI, the peak at 0.6V in the derivative curve is always absent, and since this peak is typically assigned to the formation of Li15Si4, is is most plausible that Li15Si4 is not formed here;

Compatibility with positive electrode
As decided, LNMO will be the cathode material for the 3rd series of prototype cells. In that respect, the LiTDI salt was tested accordingly, with the following results:
- LiTDI salt from WP4 is not working well with the LNMO cathode;
- on the other hand the electrolyte used with the first generation cells (LiPF6 EC-DEC 1:1 + 2% VC +10% FEC) is not working well with the cathode due to the VC additive;
- the most efficient electrolyte seems to be: LP30 (EC/DMC 1:1 + LiPF6) + 10% FEC;
- LiTDI works with electrode materials having a potential of <4.5V vs Li/Li+;
- water contamination might be an important degradation source.

Behaviour in full cells
As decided earlier, LNMO would be the cathode material for the 3rd series of prototype cells. Since this LNMO was not compatible towards the LiTDI electrolyte, it was decided not to focus anymore on this subject. Nevertheless, several earlier results reported on real cells consisting of LNMO cathode and Li as anode, showed huge fading. Hence, due to this move, no results of these cells were generated.

Positive electrode formulation

Objectives and outcome in short
The main objective of WP5 will be the development of sustainable, low-cost and safe cathode material, e.g. LFS-F and LNMO.
The objectives are then defined as follows:
- surveying and evaluating the existing theoretical models with respect to electrode behaviour;
- optimization of modified LFP with regard to performance towards high-rate but safe material;
- synthesizing and characterization, with the aim to improve the performance of LFS-F along with the knowledge achieved from the other objectives;
- synthesizing and characterization, with the aim to improve the performance of LNMO along with the knowledge achieved from the other objectives;
- defining the positive electrode formulation of the novel viable cathode material;
- assessment and delivery of viable cathode materials;
- defining an adequate process for recycling LMNO.

In the end the following objectives have been realised:
- delivery of 4kg LNMO (produced by EuroSupport) to CEA for cathode electrode making;
- surveying and evaluating the existing theoretical models with respect to electrode behaviour;

- optimization of modified LFP with regard to performance towards high-rate but safe material;
- synthesizing and characterization, with the aim to improve the performance of LFS-F along with the knowledge achieved from the other objectives;
- defining the positive electrode formulation of the novel viable cathode material;
- assessment and delivery of viable cathode materials;
- defining an adequate process for recycling LMNO;
- Based on survey, a new general model with respect to electrode behaviour was introduced;
- LFS-F was synthesised according to several routes. One route was found suitable for scale-up so 10 g of the material could be delivered on time;
- defining and assessment of the positive electrode formulation of the novel viable cathode material;
- synthesizing and characterization, with the aim to improve the performance of LNMO;
- LMNO with a reversible capacity of ~143mAh/g (theoretical 146.7mAh/g) and a fading of less than 1% after over 100 cycles was successfully synthesised;
- assessment and delivery of viable cathode materials;
- data sheets of the above.

Theoretical investigation of transport in insertion cathodes – impact of nano-architecturing and Composition

A new approach to evaluate charge carrier transport and transfer in insertion cathodes has been developed, based on various simple assumptions. First we divide the whole transport in a cathode into three steps. Secondly, we assume that upon increasing the C-rate, the charge cannot penetrate into the whole active particle but merely to a certain penetration depth. The topography of the moving front is optional. The sharpness of the boundary between the new and initial phase is not very important. Six cathode materials were analysed based on the above theoretical approach. The analysis has revealed the following common features of the studied materials:

- decreasing the particle size below about 200-300 nm, there remain only two main transport steps:

a) the transport of charges from their reservoirs (collector, electrolyte) to the active particles (wiring step)
b) the transport inside the active particles (solid state transport step);

- the wiring step starts to prevail at an electrode loadings of 10-20 mg/cm2. An esential part (usually more than 50%) of wiring is the transport of electrons from the current collector to the active mass. The total wiring resistance is between 5 to 20 Ω/cm2 of the current collector.

This means that the maximum currents that can be sustained when wiring is the limiting step are on the order of 0.1-0.4 A (or 10-40 A/g) in 10 mg electrodes. Practical results published in the literature confirm this estimation. Additionally, due to wiring it is unreasonable to expect much higher current values. So when higher currents are measured one needs to check the results with respect to possible artefacts, e.g. wrong estimation of mass etc.;

- in most materials, the electronic conductivity seems to be better than the electronic one.

This means that optimization of electrode mass needs to be focused on providing sufficient ionic conductivity/supply – such as maintainance of porosity etc.;

- decrease of particle size is the only really effective way to improve the rate performance and also safety at higher power, e.g. prevention of excessive heat generation. However, any agglomeration needs to be prevented in order to exploit the actual benefits of decreased particle size;
- the role of surface decorations is certainly not to decrease the insertion resistance. The latter is already very small in standard nanosized materials. The role is better ascribed to either prevention of

agglomeration of improvement of wetting the particles by the electrolyte.

Adjusting LFP-based materials with enhanced rate capability safety

We have addressed the issue of surface decoration from the perspective of transport enhancement. The following conclusions can be made, based on the application of the general transport scheme:

- The impedance of charge transfer through the active surface is much smaller (up to 1000 times)than the impedance due to several other transport steps. This particularly holds for nanometric active materials. Similar results are obtained, regardless if impedance is extracted from impedance spectroscopy of from galvanostatic curves. This result can be viewed as follows: decorating the active surface itself has no sense if our goal is merely to improve the transport of charge through the surface layer;
- indirectly, surface decorations can improve the overall transport if they help wet the active surface area with electrolyte. This can be realised via creating additional micro- or low-end-mesoporosity. Minute amounts of ceramic additive have been shown to work in the case of nano-titania.
- in some reports, the role of surface decorations could have been misinterpreted, which is the case where the amount of conductive additive is very high;
- there is another, completely different role of surface decorations – the chemical or electrochemical protection against degradation of active material or degradation of other electrode components (particularly the electrolyte). This particular role was addressed when reporting on the effect of surface decoration of LNMO (see next points);
- during degradation of LNMO due to progressive cycling the impedance of medium frequency arc increases enormously; the other impedance features exhibit moderate or negligible changes;
- the possible effect of the lithium counter electrode was ruled out in two ways – by replacing the counter electrode after certain number of cycles with a fresh one and by making a symmetrical cell without lithium (two LNMO electrodes partly charged and used as anode and cathode);
- a closer analysis of the meaning of medium frequency arc shows that its origin is the contact area between the aluminium foil and the first layer of the electrode composite attached to this foil;

Synthesis and characterization of LFS-F

Tavorite $LiFeSO_4F$ material reversibly intercalates Li^+ at 3.6V and displays a sustainable reversible capacity of 140 mAh/g with good rate capability. Besides, it can be prepared at $T<300\,°C$ by using either ionic liquids or polymers as reacting media or by a ceramic process. Whatever the media used, the reaction involved consists in reacting stoichiometric amounts of LiF and $MnSO_4{\cdot}H_2O$ for time spans ranging from 24 hours (liquid) to 72 hours (ceramics). Nevertheless a crucial step towards the success of these reactions resides in the use of an iron monohydrate precursor free of Fe^{+3}. Several synthesis methods were analysed, and described in more detail below.

For such purpose, the iron monohydrate precursor is made by (i) dissolving stoichiometric $FeSO_4{\cdot}7H_2O$ (Aldrich, 99%) in distilled water under nitrogen bubbling, (ii) adding a pinch of ascorbic acid to convert any Fe^{3+} salts to Fe^{2+} salts, (iii) precipitating the mixed precursor by adding ethanol, (iv) drying the recuperated solid, and finally (v) heating it either using ionic liquid or under vacuum to remove 6 H_2O.

- For ionothermal synthesis, ~1 g of precursor mixture (LiF + $FeSO_4.H_2O$) was mixed with 5 ml of EMI-TFSI inside a Teflon-lined autoclave, stirred for 20 min before slow heating to 280-295 ºC (at 5 ºC/min), and keeping it for 24 h before gradual cooling by switching off the furnace. The reaction product was recovered by washing the ionic liquid twice with ethyl acetate and drying the powder at 60 ºC.
- For solid-state synthesis, the reaction mixture was uni-axially pressed into pellets, loaded inside a Teflon-

lined autoclave (in Ar filled glove-box), slowly heated to 290-300ºC (5ºC/min) and annealed for 24-50 h before slowly cooling to ambient temperature. The final product was simply ground in mortar-pestle for further study.
- For polymer synthesis, 1g of precursor mixture (LiF + FeSO4.H2O) is mixed with polymer powders (i.e. PEG (Mw: 20,000) or PEO (Mw: 250,000)) and the overall mixture is placed inside a Teflon-lined autoclave before heating the bomb at 300 °C for 48 hours. For T >60 °C the polymer becomes liquid and does not decompose until 320 °C.

It is worth noting that the obtained powders, whatever the aforementioned methods, showed comparable electrochemical performances. In contrast, the different processes in terms of scalability differ. Although Ionic liquids can easily be recycled they are very costly. Polymers present advantages in terms of handling, but the powder recovery is cumbersome. So it results that the synthesis of LiFeSO4F using the solid-state process remains more attractive for large scale production as there are no solvents to store or waste that need to be treated during the process.

Solid state reaction:

- First, FeSO4. H2O was prepared starting from FeSO4. 7H2O treated with ascorbic acid to eliminate all iron (III) impurities before being heated at 180 °C for 1 hour under 1.5 bar pressure of Ar flow.
- Next, the obtained FeSO4. H2O was mixed with stoichiometric amounts of LiF and ball-milled under Ar using shock machine (Spex) for 15 to 20 min to obtain a homogeneous mixture. Then, the powder mixture was pelletized in ~0.8g pellets which are placed all together (8 to 10 pellets) in an alumina boat and annealed in a tubular furnace under argon flow (0.5 bars). The furnace temperature was raised to 300 °C at a rate of 10 °C/min and maintained at this temperature for 48 hours. The resulting materials were single-phased with occasionally minute amounts of FeSO4 powders and had electrochemical performances comparable to those obtained by either ionic liquids or polymeric-based processes. Scaling such a process to kgs batches is now just a problem of dimensioning tubes and furnaces.

Formulation of LiFeSO4F:

Active materials (LiFeSO4F tavorite) are mixed by hand milling in an agate mortar with Super P carbon black in a ceramic mortar for 30 mins. Then PVDF dissolved in NMP solution is mixed with mixture of AM and Csp powder in glass bottle by magnetic stirring for 30min. Then the slurry is casting on aluminium foil and dried. The charging capacity is quite low at present time due to a non-sufficient optimisation of the formulation. With the increase of Csp, capacity and its retention get better. The optimized formulation ratio is 75 % AM, 15 % Csp and 10 % binder.

Diffusion coefficient of LiFeSO4F

The lithium diffusion coefficient in LiFeSO4F has been determined by three different techniques namely Galvanostatic Intermittent Titration Technique (GITT), electrochemical impedance spectroscopie (EIS) and Potential Relaxation Technique (PRT). A value of 10(-15) cm2/s was measured for the all three techniques with better precision with PRT. This value is in good agreement with the ones predicted by DFT calculations.

Synthesis and characterization of LNMO

LNMO has acceptable Li-ion and electron conductivities even in micrometer-sized particles, which infer

that surface, rather than bulk, kinetics are the predominant factor in charge transfer properties. Hence, we analysed the roles of chromium in a conductive oxide coating and as a bulk dopant in LMNO. LNMO and LiCr0.08Ni0.042Mn1.5O4 were synthesised using a Carbon Combustion Method. In summary, stoichiometric quantities of Li2CO3, Mn3O4, NiO and Cr2O3 (for the preparation of the LiCr0.08Ni0.042Mn1.5O4) were mixed together with carbon black (Li:C molar ratio=4:1) and grinded for 30 minutes with a ball-mill machine (Fritsch P-0150). The mixture was first heated up to 950°C at 2ºC/min and kept there for 12 hours. In a second heating step, the material was allowed to cool down slowly to room temperature in 24 hours for oxygen uptake. To form the chromium oxide layer, LNMO was immersed in an aqueous solution of various concentrations of Cr(NO3)3. The powders were exposed to the solution for 2 hours. The solution was then placed in a furnace at 120°C for 2 hours to allow the water to evaporate. The remaining powder was rinsed with ethanol, dried again and it was finally annealed at 600°C for 8 hours.
The powders have a BET surface area of 0.32 m2/g. XRD analyses showed that the powders are mainly phase pure. ICP-OES analyses gave atomic ratio of the Ni and Mn transition metals that agrees well with the intended stoichiometry. The Cr content runs from 0.07mole% to 2.4mole% of the total transition metal content. The layer thicknesses of the coating were then calculated based on the BET surface area, the ratio of the Cr vs. the other transition metals and accepting a density of 5.22 g/cm3 as taken from Cr2O3. Combined SEM and EDX was carried out on the powders, and very nice octahedral crystals with a particle size of 3-5 µm were obtained. EDX analyses showed that the Cr is homogeneously distributed in the sample. It is stressed that this is the case for all samples prepared and tested.
XAS analyses, co-financed by the Netherlands Research Organisation (NWO), was carried out on the Dubble beam line (BM26B) at the ESRF, Grenoble, FR, to measure the change of valences of the various elements during operation (charge/discharge). Cr-Ox coated as well as doped LNMO was analysed in-situ. The measurements showed that Cr was always +3 irrespective whether it is in the structure on the surface as well as it is independent on the state of charge of the cell. Hence, this may indicate that chromium acts as a catalyst for electrochemical processes occurring at the interface.
The EXAFS region indicates that Cr exists in an octahedral coordination for all the samples (doped / coated / cycled / pristine). Regarding the coated samples, chromium adopts a spinel-type structure of the underlying lattice rather than the typical corundum structure of Cr2O3. This could indicate that instead of being only a "coating", Cr is partially "penetrating" into the underlying material.
The electrochemical tests done with commercial electrolyte, showed a small amount of LiMn2O4 impurity, which is highly reversible in the charge/discharge behaviour. The obtained capacity is ~143 mAh/g (theoretical 146.7 mAh/g), and the fading is less than 1% after over 100 cycles at low rates and about 120 mAh/g at 1C.

In summary, it can be said that:
- optimised doped and coated LNMO with Cr-O was synthesised;
- particle sizes were 5 µm with a specific surface are of 0.32 m2/g;
- the capacity is about 120 mAh/g (@1C).

In that regard the following batches were delivered to the respective partners :
- the first batch of 30 g were sent to CNRS-IMN at the beginning of 2014;
- a second batch of ~1 kg was sent to CEA mid 2014;
- a third batch of ~4 kg produced by EuroSupport with the TUDelft recipe was sent to CEA.

Optimization of electrode formulation

Different optimised electrode formulations for LNMO were identified. It could be possible to achieve a very good cycleability with these formulations at 8 to 10 mg of LNMO per cm^2. However, the cycleability of the same formulations but with higher loadings of ~25 mg of LNMO per cm^2 is still not satisfactory. Let's note that to match a $3mAh/cm^2$ capacity at the negative electrode, 30mg of LNMO per cm^2 at the cathode is required.

Moreover, we made full cells with Si (Formulation 2) electrode optimised in WP3 and LNMO electrode, which formulation was optimised in WP5, and we showed that if the Si electrode is fully lithiated/delithiated versus lithium metal before the full cell assembly, the LNMO//Si cell shows a fully reversible cycling for 50 cycles. The electrolyte contained only FEC as the additive.

Integration and scaling-up

Objectives and outcome in short

The purpose here is to demonstrate, at a prototype level (representative to the application), that the cell chemistries developed in this project will have a significant gain in energy density compared to the current Li-ion technology and that it can be implemented into cylindrical cells which are thus possible candidates for electrical vehicle use. Active materials and electrolytes developed in the other tasks are integrated into full cell systems in order to manufacture cylindrical cells.

The actual manufacturing was done in 3 steps:

Step 1) Implementation of Si/C composite anode into cylindrical cell applying CEA cell chemistry for LiFePO4.

Step 2) Implementation of new electrolyte into cylindrical cell applying Si/C composite anode and the CEA LiFePO4 cell chemistry.

Step 3) Implementation of new cathode composite into cylindrical cell applying Si/C composite anode and the developed electrolyte.

The goal was to produce 20 working cylindrical cells per manufacturing step. Taking into account scrap rates resulting from the use of new materials, at least 40 cells per step are produced and scrap cells are disposed.

In the end the following objectives have been realised:

- several high power LFP cell have been delivered for testing;
- a formulation has been successfully optimised for use in a semi-industrial coating machine;
- coatings of the Si anode electrode based on “formulation 1 and 2”;
- manufacturing of reference 18650 cylindrical cells LFP/G;
- manufacturing of 18650 cylindrical cells LFP/Si;
- implementation of Si/C composite anode into cylindrical cell applying CEA cell chemistry for LiFePO4 (Step 1);
- implementation of new cathode composite into cylindrical cell applying Si/C (step 3).
- due to incompatibility of the electrolyte with the electrode, step 2 has not been carried out.

Important Notice

During the course of the project, the work for the fabrication of those cells has been taken over by CEA from GAIA. Therefore, for the description of the project results, only work done by CEA has been considered.

Negative electrode fabrication and testing

The work concerned the development of producing Si negative electrode according to formulations created within WP3, where the objective is to achieve an electrode with a capacity of >1500 mAh/g for 500 cycles measured at C/5.

As mentioned earlier at the system definitions, the formulations have been defined and then many trials were carried out at CEA to coat the Si material with a slot-die equipment. The use of high quantities of slurry creasted significant gas evolution that needed to be solved. Finally the pilot line using forward-roll technology was used showing the best compromise in electrode quality (adhesion and flexibility). In parallel, at CNRS-LRCS work on the Si stability in water was done showing that a thermal treatment increased the stability and avoid hydrogen gas formation.

In a next stage, “Formulation 2” was developed containing graphene as conductive additive.

During the trial, slurry rheological properties were optimized with increasing the solid content. The results obtained, show the necessity to incorporate latex to give suppleness to the electrode, as for Formulation 1. No major difficulties were observed during this trial concerning the process scale up of this formulation and good mechanical properties of the electrode were obtained, suggesting that it can be used in the winding step for cylindrical cells manufacturing..

Performances of this electrode versus LiFePO4 have shown a first irreversible capacity of 20% and a Coulombic efficiency stabilized at 99.4% for the best coin cells.

Positive electrode fabrication and testing

In the first period, the positive LFP electrode was produced at CEA with the industrial coating line and a surface capacity of 3 mAh/cm^2. In the following period, CEA focuses on the scale-up of LNMO formulation develop by IMN with the pilot coating line. First trials with the CEA pilot line have shown that there was too much NMP and drying of the electrode was not sufficient for the high target loading of active material on electrode. A new formulation with less PVDF and less NMP was applied while keeping the same viscosity for the slurry. Hence, the new formulation became: LNMO 92% PVDF 4% SP 2% VGCF 2% .Thus it was possible to reach the target of an electrode coated at high loading with a surface capacity of 3 mAh/cm^2. This electrode showed good adhesion and flexibility to consider for electrode winding and cell assembly.

Cell assembling

In the first period, the cell assembly was planned with both LFP and Si “formulation1” electrodes.

The selected cells size was 18650 standard casing.

The CEA cells are assembled with following steps:

- tabs connector welding on both anode and cathode;
- positive / separator / negative electrodes winding;
- wound “jelly roll” insertion in cylindrical cases;
- tabs connector welding;
- electrolyte filling and cell crimping in an Argon filled glove box;
- cell activation.

All these steps (except the last one) operate in dry clean room environment (dew point -40°C).

Standard electrolyte showing good performance with Si was applied: LP30 88% +2% VC +10% FEC

(LP30 is EC:DMC 1:1 + $LiPF_6$ 1M).

In the next step, CEA focuses on the scale-up of LNMO as cathode electrode and Si “Formulation2”. The new electrolyte was also tested with both electrodes, but CEA observed that this electrolyte did not fulfil the requirement mainly at cathode side. LNMO electrode has a low reversible capacity with LiTDI electrolyte probably due to decomposition at high voltage. The corresponding voltammetry curves showed that it was not possible to reach a voltage beyond 4.6V with this electrolyte while a higher voltage is required, i.e. about 4.9V versus Li, for LNMO. It was also observed that VC additive is not stable at high voltage, and thus the best compromise for both anode and cathode cycle life was the LP30 electrolyte with FEC as additive. This electrolyte was then selected for the third generation cells. Due to the poor results of the LiTDI based electrolyte, the realization of the cells LFP//new electrolyte//Si-C were not considered anymore. Even though LP30+FEC electrolyte was identified as the best electrolyte, degassing was identified, probably due to carbonate solvent decomposition at high voltage in the vicinity of EC and DMC. This degassing was observed with 53437 soft packaging cells equipped with a lateral pouch. The swelling of this pouch occurs after the first forming cycle. This degassing should apply equally in 18650 cells and a calculation based on electrode surface ratio and free volume in 18650 cells proofed that the pressure into these cells would be close to the maximum allowable pressure of 15 bar. Then these cells can’t be shipped for safety reasons and it was decided to manufacture the third generation cells with the soft 53437 packaging, including two lateral pouches: one to remove the generated gas after forming and the other one for collecting the gas during cycling. Thus, 20 cells were manufactured and send to the other partners for testing. The average discharge capacity of these cells at the first forming cycle was 450 mAh whereas the charge was 675 mAh. It correspond to 33% of irreversible capacity which is more than the 25% expected and calculated with the irreversible capacities of the electrodes measured in coin cells versus Lithium metal.

These cells correspond to an energy density of 140 Wh/kg, but then with two lateral pouches for gas collecting, which obviously increases the total weight of the cells. Remember, the first generation of LFP/Si cells showed an energy density of only 110 Wh/kg, however with another concept, but still it proofs a significant improvement of the capacity compared to existing chemistries.

Testing and benchmarking

Objectives and outcome in short

The purpose here was to develop a testing procedure for the new chemistry cells with the following objectives:

- lifecycle test of prototype cells;
- dynamic modelling of promising battery concepts;
- safety evaluation and safety tests of prototype cells;
- evaluation of new concepts from system level perspective: management of cells when integrated into system.

In the end the following objectives have been realised:

- selection of the commercially available $LiFePO_4$ (LFP) based Li-ion cell;
- definition of the test procedures for benchmarking & life cycle testing and validate;
- reporting benchmarking test results of the LFP cells;

- full vehicle simulation;
- tests for cell modelling to extract necessary model parameters;
- cycle life testing of the prototype cells;
- management development for novel battery prototype (algorithm for estimation of SOC);
- safety assessment and testing (test procedure).

Benchmarking of LiFePO4-cells and prototype cells from GAIA
Three different prototype cells, Graphite/Lithium Iron Phosphate (G/LFP), Si/Lithium Iron Phosphate (Si/LFP) and Si/Lithium Nickel Manganese Oxide (Si/LNMO) were tested and benchmarked the performance following the procedure developed within the EuroLiion consortium. It is stressed that the later prototype cells were manufactured by CEA instead of GAIA as GAIA left the consortium in the middle of the project. The tests concerned formation cycles, energy, power, capacity, efficiency and internal resistance under various operating temperatures.
At least two cells were tested in order to see the consistency of the obtained results. Little deviation from the manufacturer's specification was obtained in general.

Life cycle testing
With respect to the early stage commercial cells arriving from GAIA, the results covered life cycle testing, and the benchmarking tests of the GAIA cells was performed according to the test procedure developed here. Furthermore other commercial LFP-cell were analysed, and performance comparison between conventional LFP-cells and Li-ion batteries was done. Also, simulation and test results from dynamic load cycle efficiency test were verified. In a later stage, the life cycle test results for the prototype cells was the main outcome from this work. Here we evaluated the life cycle performance and reliability of Li-ion cells with Si as negative electrode which was manufactured and supplied by the project partner.
Three types of cells were delivered from the project partner (CEA). The cells consist of LFP and LNMO as cathode, Graphite or Si as anode material. The cycling tests with these prototype cells have been executed at three different temperatures: 0, 23 and 45 oC and two different state of charge (SOC) ranges: 0-100% and 20-80%.
The capacity fade of the LFP/Si cells over the cycle number (a) and energy throughput (b) was measured, and after running a comprehensive characterization of the cells the life cycle tests are carried out. Results indicate that both temperature and DOD have significant impact on battery aging for the cell chemistry. As expected, the irreversible capacity loss as a result of the volumetric change during charging and discharging is significant to Si cells. The capacity shows a rapid fade in the early stage of full cycling (~4% fade per cycle up to 8 cycles) and stabilizes at a rate of ~0.67% fade per full cycle at 23 °C and ~0.82% fade per cycle at 45 °C, respectively.

Possible mechanisms behind the capacity fade in Si anode batteries have been reported in recent years, which appear to be twofold. First, the expansion and contraction of the Si can cause a pulverization of the anode particle morphology, which reduces electrical contact within the material as well as with the current collector. Second, the low potential of Si lithiation (<0.5 V vs Li+/Li) causes the electrolytic decomposition at the anode-electrolyte interface, forming a layer of solid-electrolyte interphase (SEI) over the anode surface. Due to the electronically insulating of SEI, its formation during the first few cycles is normally self-inhibiting. In the case of Si anode, however, the continuous fracturing over cycling ruptures the SEI and exposes fresh surface area, resulting in thick, substantial SEI formation. This unrestrained growth not only hinders ionic transport and electronic conductivity, but also decreases the amount of cycleable Li-ions due to the consumption of Li. Thus the total capacity is being decreased.

In addition, the life cycle tests were run with the high voltage prototype cells. For this purpose cells with LNMO as cathode material and nano-sized Si as anode material are developed here. The charge terminal voltage of the cells is set to 4.85V. High cell voltages increase the energy density of the battery. It was observed that during the formation, the capacities of all cells slightly increased. After that, a rapid capacity fading as a function of cycle number is obtained. As mentioned, the volume change of Si during cycling may lead to rapid cell degradation. The reason for this capacity fading of LNMO is not completely clear yet. The usual assumptions include, among others, excessive surface passivation, which occurs especially at high voltages.

Cell Modelling

Both VOLVO and AIT developed a battery cell model in Matlab® Simulink® which is suitable for use in full vehicle simulation. The developed model in Matlab®/Simulink® is suited to reflect the characteristics of high energy cells. Due to a delay in cell manufacturing the work for this task was carried out along commercial high energy cells (Panasonic) for first modelling activities and planned to be used for comparison later on. Once the EuroLiion cells (Si/LFP) were manufactured it was used for extracting necessary model parameters. During parameterisation, the obtained values were not stable even though the obtained unstable values were used. It needs to be mentioned however, that unstable values from prototype cells are very common.

In a little more detail, the full model including the part for the input signal with a simple RC parallel combination, where current Profile can be simulated. Here then, the current depends on time as imposed in the model. It further required Rs(Soc, T), Rp1(Soc, T, i) and Cp1(Soc, T, i) as the values to mimic the RC parallel combination which are thus dependent on the SOC, the temperature and the current of the cell.

The developed model in Matlab®/Simulink® was suited to reflect the characteristics of high energy cells. By introducing an object oriented C code to Simulink the simulation speed was high and the risk of the solver facing close loop problems was minimized. An interface still guarantees full flexibility of the model.

Tests for Cell Modelling

According to the initial plan, VOLVO performed extensive testing at cell level to extract necessary model parameters. The model was developed based on both high energy Panasonic and EuroLiion Si/LFP cells. Heavy duty Plug-in hybrid electric vehicle (PHEV) dynamic cycle was used to validate the model. A simulation scheme of the PHEV cycle was used in that respect. The model then was created based on an equivalent electric circuit model, and worked under Matlab®/Simulink®.

The model can predict the cell behaviour quite well. The simulated voltage response has a similar ohmic and dynamic voltage response as the measured signal over time. The only difference that can be noted is a small offset in voltage profile between simulation and measurement. This offset of about 0.01V can be the result of deviation in cell parameters, small temperature difference, and measurement errors e.g. from current, voltage or SOC estimation.

For EuroLiion Si/LFP two RC circuits were used to develop the model. The first result from the simulation shows that the impedance of the cell is significantly underestimated in the model of the Si based cell.

However, after careful investigation an adjustment of factor 4 on Equivalent Series Resistance (ESR) was performed. After adjustment in ESR value the simulation showed good dynamic response for Si/LFP cell.

Management developments for novel battery prototype

A comprehensive literature review was carried out to investigate algorithms for estimation of the internal battery states and performance. It concentrated on various methods for state prediction of batteries (SOX). While special focus was put on state of charge (SOC) prediction also state of health (SOH), voltage and power prediction and other strategies were investigated. Actually, it became clear that a reproducible method for evaluation of such methods was missing. This is why an approach for simulative validation of such algorithms was developed - a publication in an IEEE or related journal is under preparation.
With this information in mind, different SOC algorithms were selected for evaluation with the new EuroLiion test cells. The selection was done balancing needs for computational power, practicability and accuracy. The final strategies for evaluation then were:

- coloumb counting (easy parameterization, low accuracy, low computational power);
- enhanced coloumb counting (trade-off between accuracy, parameterization and computational power);
- extended Kalman Filter (high accuracy, complex parameterization and highest demands on computational power)

All methods were implemented in the developed Matlab®/Simulink® simulation environment. They were connected with the battery model developed in EuroLiion and parametrised with the cell data of the developed EuroLiion Si/LFP cell. This allows access to the internal states of the model in this case SOC. The measurements for the SOC estimators where distorted like it would be found in real world application. This allows for a direct comparison of the performance of each estimator in comparison to the real value.

It shows the response of the different estimators based on the distorted signals compared to the simulated SOC. While with constant charge and discharge pulses the coulomb counting drifts of because of not considering the coulombic efficiency of the cell and not resetting its states from time to time the enhanced coulomb counting is more accurate. After an initial learning phase the Extended Kalman Filter follows the real SOC closely. So this filter is also suited for the modern LNMO/Si technology developed in EuroLiion.

Safety Assessment & Testing

All the tests were performed according to the developed “Safety Test Procedure”. As additional cells were available for testing one further test was added. In the end, the tests conducted were:

- overcharge;
- short Circuit;
- thermal Stability;
- internal Short Circuit (additional).

Covering a broad spectrum of possible hazards to the cell as it is tested for electrical, thermal and mechanical abusive conditions. The entire test results, classification and interpretation were published via posters at various locations.
The results of the Si/LNMO cells gained through the internal short circuit test, showed that the voltage drops immediately, indicating a full short circuit. The temperature then in this case goes to 500 °C and the cells starts to burn. As this is one of the most destructive tests available this is not a bad result for cells still in prototype stadium.

A classification according to EUCAR hazard levels – level 1-5, with 5 being the worst – of the responses of the EuroLiion LMNO/Si cells to the safety tests is gathered below. The external short circuit tests show level 2, the overcharge shows 2-3, thermal stability as well as the internal short circuit up to level 5. However, in general it can be stated that the response of cell ranges from good to acceptable. For a prototype cell this is satisfying behaviour. The results might be positively compromised by the high internal resistance (lower short circuit currents), the high ratio of surface to volume (helps on heat dissipation) and the additional bag for gas (keeps cell pressure low). Homogeneous design, controlled production and fully balanced cell design in series production could positively affect the cell though.

Potential Impact:
Socio-economic issues - Eco-design, costs assessment and dissemination

For this part of the work, a collection of assessment activities took place, such as the “life cycles” of materials and devices, including recyclability and Eco-design. Clearly, the economic impact also plays a role in this, and therefore, costs evaluation and assessment was an inherent task here. In summary the work concerned:

- life Cycle assessment;
- recyclability assessment;
- eco-design assessment;
- cost evaluation;
- dissemination issues;
- collected forecast and future plans for the EuroLiion partners.

In the end the following objectives have been realised:

- finalized LCA (comparison of LNMO/Si to LFP/G battery);
- finalized Cost evaluation of LMNO/Si to various other battery types;
- conclusions on methods for recycling new materials and material mixtures.

LCA and Sustainability

This LCA study is a comparative assertion of the overall life-cycle environmental impacts associated with a Li-ion battery, used to propel a battery electric vehicle during its assumed life time distance of 200 000 km, containing:

- LNMO-Si cells (the chemistry of the prototype cells developed within the EuroLiion project, 204.1 Wh/kg cell energy density)
- conventional LFP-Gr cells (149.1 Wh/kg cell energy density)

As stated in the EuroLiion project description, this LCA study was carried out according to the International Reference LifeCycle Data System (ILCD) Handbook. The basic assumptions for the packs were based on energy storage capacity (kWh), Weight (kg), energy density (Wh/kg), number of cells, number of modules and lifetime cycles. The selection was then for the LNMO/Si cells and LFP/Carbon(graphite) cells (36.8; 245.2; 149.9; 168; 12; 2500) and (37.2; 342.6; 108.6; 224; 16; 2500), respectively.

A summary was shown for the results by impact category for both cell types compared. For six of the impact categories analysed, the LNMO-Si battery shows a significantly lower impact (<5%) than the LFP-Gr battery. Only for the category Human toxicity, cancer effects the impact is significantly higher (>5%) for the LNMO-Si battery. Based on this result the LNMO-Si battery is likely to be a slightly better alternative from an environmental perspective, and especially if the Human toxicity, cancer effects impact could be lowered.

For the impact categories where the use phase is the dominant phase, there is no significant difference in total impact between the two batteries. The production phase is small compared to the use phase, and the difference here does not affect the total impact. There is a significant difference in total impact for the categories where the production phase is the dominant phase. In several cases where the impact for the LFP-Graphite battery is larger, this is due to the higher amount of material used (39% more cell material is used, 16 modules needed instead of 12). In other cases the difference is more related to specific production processes used.

The Human toxicity, cancer effects category shows a much higher impact for the LNMO-Si battery due to the production of chromium oxide. This should be further investigated with up-to-date LCI data for chromium oxide production. If the result still holds, a recommendation for the future it could be tried to minimize or completely avoid chromium oxide when producing the LNMO active material.

Eco-design and Recycling

A potential eco-design process is the production of the Si-based electrode, as this can be processed under a much less controlled environment compared to the current electrodes based on carbons. This reduces the energy consumption usually required for maintaining a moisture free atmosphere. Furthermore, the electrode processing of the cathode material could be done also under ambient atmosphere, rather than in a dry room. However, the electrodes then still needs to be dried for further processing. Nevertheless this could then take place in a much smaller environment and thereby reducing the energy and the energy costs. It is stressed that this is not fully taken into account as the CEA production is also still in its infantile state.

With respect to recycling, each material producer within this consortium had to identify their own possible/potential recycling methods taking into account the LCA and existing processes.

- The company that was identified initially was Umicore using a pyrometallurgical route by heating / burning the cells or batteries to temperatures up to 1200 °C.
- TUDelft analysed experimentally novel recycling methods based on electrochemical means.
- During the course of the project, other groups working on recycling were identified and their methods are being described in detail in this deliverable.

New parts concerns the identification of several relevant documents that were released. These documents are:

- Battery to Battery – closing the battery loop: a brochure from UMICORE;
- EPA report: a report from EPA, USA;
- EU Commission regulations.

Furthermore for this work, three relevant documents have been identified:

- enabling Future Li-Ion Battery Recycling;

- European Lead Battery Conference, September 10-12, 2014;
- Linda Gaines - Center for Transportation Research Argonne National Laboratory

In the following part an additional section has been added to show the importance of the interplay of the LCA, costs and recycling before stepping in into the recycling processes as known so far. To identify the potential impacts of the growing market for automotive lithium-ion batteries, Argonne researchers are examining the material demand and recycling issues related to Li-ion batteries. It includes:
- conducting studies to identify the greenest, most economical recycling processes,
- investigating recycling practices to determine how much of which materials could be recovered with current or improved methods, and;
- quantifying the environmental impacts of both battery production and recycling processes through life-cycle analyses using Argonne's GREET model;
- researchers leverage Argonne's BatPaC model to determine the material compositions needed to perform LCAs on different Li-ion battery chemistries;
- funding from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program.

The information has been gathered in “Fact Sheets” such as:

- Closing the Lithium-ion Battery Life Cycle (fact sheet; January 2014);
- Energy and Materials Issues That Affect Electric Vehicle Batteries (fact sheet; May 2013);
- How Green is Battery Recycling (fact sheet; October 26, 2012);
- LCA: https://greet.es.anl.gov/greet/index.htm

For all those three items – costs, LCA, and ECO-design & recycling – the production process plays a major role. Since the items are so interrelated, it is clear that recycling helps economics. It that regard it is a start that in Europe, 50% of cell materials must be recycled as of ~2025, taking into account that the rest of the battery is included in the EU 95% auto recycling requirement. This may include enough valuable materials to make recycling paying off even if LiFePO4 cathodes are used. It is further stressed that the responsibility for EU recycling belongs to the company that makes the consumer product. Recycling, therefore can also drastically reduce virgin Li demand, considering those parts of the production to be ready for recycling.

Many processes for battery-recycling are known and in the below sections several are then being described in more detail. These concern a pyrometallurgical process, a hydrometallurgical process, and a physical process.

The pyrometallurgical process concerns a commercial smelting process recovering some metals. The basics of the process are shown in Fig. 8.7. The (dis)advantages of the methods are:
- allows about any input, therefore is gives high volume (throughput);
- high-temperature required (Organics are burned for process energy);
- valuable metals (Co, Ni, Cu) recovered and sent to refining ;
- suitable for any use;
- 70% of cobalt production energy saved; sulfur emissions avoided;

- fabrication still needed;
- less Co → less value;
- off-gas treated at high-T;
- Li, Al go to slag;
- Could be recovered;
- High costs;
- Mn and Ti also to slag.

Due to the above disadvantages, often the pyrometallurgical process is merely seen as down-cycling rather than recycling.

This type of process is used by Umicore, Hoboken, Belgium. Here, end-of-life batteries and cells are brought into a smelter practically as received – thus, no dismantling, cooling or crushing. The smelter is constructed such that separation occurs for the precious metals such as Co, Ni, Cu and eventually iron. The remains of the process is accommodated into a ceramic material forming a slag that will be further used in construction materials – here the lithium will be end up as well. The precious metals are further separated by various steps leaving in the end Fe, Cu and $LiCoO2$ and $Ni(OH)2$ as sellable products. This process has been widely used by Umicore for quite some time with the recovery of other precious materials from e-scrap (electronic waste). It is stressed that the processes do not take lithium recovery into account. Actually, Umicore has found that when the lithium stays in the slag, it improves the quality of the construction material derived from it.

The hydrometallurgical method is a key technology in metal recycling and recovery, since it allows separation between chemically alike metals. The method employs obtaining metals involving the use of aqueous, or other solvents, chemistry for the recovery of metals from ores, concentrates, and recycled or residual materials. The process is being used by Recupyl (FR). Hydrometallurgy is typically divided into three general areas:
- leaching;
- solution concentration and purification;
- metal recovery.

In principle, the hydrometallurgical leaching step consists of acid or basic leaching of scrap, to solvate the desired metals. After proper solvating, the metals are recovered by selective precipitation typically via:
- altering the pH of the solution;
- adding some reaction agent;
- using electrolysis;
- solvent extraction.

The process is currently adopted in the Chinese hydrometallurgical process where leaching occurs with organic acids. The process is being described in summary as follows:
- bench-scale process;
- no toxic gases (e.g. HCl) released;
- carbon burned off in calcination;
- lithium and metals recovered;

- lab work complete for Co cathodes.

The intermediate physical recycling process uses a mechanical treatment – shredding, hammering, shaking, etc, before to start with a chemical treatment. It then allows to recover lithium carbonate and all metals by dissolution and precipitation methods. This method has been implemented by Toxco in the US.

The direct physical recycling process utilize separation of all components before any chemical treatment. It then allows to recover all relevant materials by proper selection of the recovery process.
The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and the collaboration between industry partners* carried out a project for a recycling method based on this direct physical process with a project called LithoRec. The main goal of the project (8,4 Mio. €) was to recover the materials of batteries used for traction purposes.

* AUDI, Chemetall, Electrocycling, Evonik Litarion, Lars Walch, H.C. Starck, I*ME ACTIA, Recyclex, Süd-Chemie, Volkswagen, as well as six institutes of the TU Braunschweig (NFF, iPAT, IWF, elenia, IKT, AIP) and the Institute of Physical Chemistry of the WWU Münster

Recycling is of particular interest, but clearly some issues are obstructing the actual implementation. In that regard, looking at the existing Lead-acid systems, the recycling there works so well, mainly because it is profitable, is illegal to dispose the batteries, and the cells, chemistry and recycling processes are simple. Thus, in order to make Li-ion recycling viable, we need to find solution for those issues. Among these are the various existing chemistries. Nevertheless it is stressed that cathode recovery could enable economical recycling, particularly when materials have high market value. Therefore it is clear that due to the economic aspects, the Li-ion recycling work involves many challenges. It is nevertheless stressed that Long-term performance of some recycled materials is not proven yet, hence, battery makers may be reluctant to purchase recovered compounds. Still there can be many positive factors identified such as e.g. labelling cells, second-life use, and the time that we have to further implement a decent system.
Hence, the design for recycling can reduce recycling costs, by introducing e.g. labels. With respect to the chemistry, with so many different producers this will be a difficult factor. In the same line, standardized formats and materials would help.

Cost evaluation

Here the final cost assessment of advanced Li-ion battery combining high voltage cathode (LiNi0.5Mn1.5O4 - LNMO) and high capacity anode (nano-Si) developed within the EuroLiion project was concluded. The price of this new technology, which was still at a research level, has been estimated using BatPaC tool, an open source calculator which was developed by Argonne laboratory. The results were compared with other technologies such as LiFePO4 (LFP)/Graphite chosen as reference in WP7 (Testing and benchmarking) as well as LiNi0.3Mn0.3Co0.3O2 (NMC)/Graphite which is more widely used, especially for the automotive market. For cost calculation, mass production was assumed, meaning battery pack production from 10,000 packs/year to 200,000 packs/year.
Costs was estimated by considering a hypothetic electric vehicle (EV) with a battery of 36-37 kWh and ~350V as nominal voltage. When considering a pack with 2 cells in parallel (2P configuration), this requires 176 cells, 192 cells and 108 cells of 50-53Ah for LNMO/Si, NMC/Gr and LFP/Gr respectively.

A comparison of cell and pack cost was shown for the three technologies. At cell level LNMO/Si shows the higher cost: 190 €/kWh versus 157 €/kWh for NMC/Gr and 180 €/kWh LFP/Gr. Interestingly, at battery pack level, LFP/Gr battery become slightly more expensive (due to bigger size of casing and the number of interconnects) than LNMO/Gr while NMC/Gr remains the most interesting technology cost-wise.

Cost assessment of LNMO/Si technology was provided using the same cell features as those used for the fabrication of prototype in WP6 but by considering prismatic format instead of cylindrical geometry. We showed that LNMO/Si based cells, which combines two “immature chemistries” market-wise, are expected to be significantly more expensive as compared to state of the art chemistries: This is explained by the high cost expected for nano-Si when synthesized by CVD process (>200 €/kg). By decreasing the cost of Si down to the cost of Graphite (~15 €/kg), EuroLiion target (< 150 €/kWh at cell level) can be reached with a LNMO/Si cell price significantly below state of the art technologies. One may note that such decrease of Si material cost is realistic in the medium term having in mind recent progress with micro-Si, synthesized by low cost milling process.

Besides Si material cost, other opportunities can help to further decrease the price of LNMO/Si technology as listed here below:
- LNMO specific capacity could be improved up to its theoretical capacity of 138 mAh/g;
- Si specific capacity is here artificially limited to 1500 mAh/g. By improving the cyclability of the material, one could expect an increase of Si capacity at least up to 2000 mAh/g;
- N/P ratio is set at 1.2 for EuroLiion prototype. Taking advantage that only partial capacity is used for Si, one could imagine to reduce N/P down to 1 without increasing the risk of Li-plating over charging step.

From the results obtained above, the question arises about the potential of LNMO and Si taken alone, and combined with state of the art chemistry, namely, graphite and NMC. In summary it can be stated that:
- LNMO can provide a marginal increase of energy density only as compared to NMC333 (< +2 %) but a substantial decrease of cell cost (down to ~-15%);
- Si leads to a strong increase of cell cost (when assuming nano-Si price of 200 €/kg).

Moreover, the gain for Si in terms of energy density is slight (< +5%) when associated with both LNMO and NMC. One may note that higher energy density gain by replacing graphite by Si could be expected by decreasing the part of inactive material in the cell together with increasing the loading (capacity per unit of surface mAh/cm^2).

Dissemination

The dissemination was done along various lines:
- improve public awareness:
- several public meetings were held, including radio interviews
- the public website was updated, where the consortium information can be downloaded via posters and a outlook documents;
- inform policy makers for making their own decisions:
- the coordinator or his alternate visited the regular meetings of EUCar in Brussels and discussed the project with the Director-General of DG Research and Innovation (RTD) at the European Commision

Robert-Jan Smits. This was an important visit as Robert-Jan Smits is responsible for defining and implementing the EU policy and programmes in the field of research and innovation.
- national programmes have been defined, e.g. the work has found follow up in the Netherlands under the ADEM programme (A green Deal project on advanced Energy Materials);
- Suppling end users with relevant documents and hardware:
  - documents are delivered within EuroLiion, and were made public after the steering committee decision.
- delivering to the OEMs in the field, information for their own strategy, while keeping track of the consortium's intellectual properties: the cathode material LNMO has found a first pilot production by EuroSupport, Uden, NL;
- publications to the scientific community and in trade journals. We have published about 15 refereed papers during this period;
- organising symposia during the Materials Research Society (E-MRS) Spring Meeting 2012 and 2014, Symposium C, "Solid State Ionics"
- sharing information with other EU-funded projects, often via EUCar, such as:
  - SuperLIB and ESTRELLA: attended their shared workshop
  - HELiOS.
  - The coordinator visited the EUCAR Reception and Conference (EUCAR = European Council for Automotive R&D). The event took place at Autoworld Brussels, Parc du Cinquantenaire 11 from 4 till 5th November 2014. The consortium had a booth with their latest results, such as samples of the novel cathode material as produced by EuroSupport (see below), electrode coatings as manufactured by CEA, and the first generation demonstrator cell.

Exploitation of project results was started on the fabrication of several kilogrammes of cathode powder necessary for the manufacture of the positive electrode. In this regard a EuroSupport, Uden. NL, was contacted, and they prepared 4 kg of material that has found application in our 3rd generation demonstrator cells.
http://www.eurosupport.nl/pdf/ESM_custom_catalysts_2010.pdf)

Collected forecast and future plans for the EuroLiion partners

TUDelft - We would be happy to continue this work under a similar sort of consortium, taking the outcome of the project into account, such as costs for certain materials and then to find adequate materials suppliers as partners. With respect to the LNMO, we are in discussion with EuroSupport to further develop this material within a Dutch research programme called ADEM. Finishing the shared and unfinished scientific papers.

CNRS – LRCS/IMN - The outcome of the results has given us the possibility to strengthen our scientific and technological knowledge that we shall be able to invest in future cooperation with academic and industrial partners in the field.

UU - The outcome of the results has given us the possibility to strengthen our scientific and technological knowledge that we shall be able to invest in future cooperation with academic and industrial partners in the field. We will also further published project results that were not reported during the course of the project.

NIC - As regards the work on Si, the results have opened various new aspect that are worth pursuing in the future. In particular, systematic rheological studies combined with microscopy and electro-chemical testing could produce numerous recipes leading to further significant improvement of properties of Si electrodes (including those prepared with LaCVP). In the field of modelling and designing positive electrodes, various unusual (but important) phenomena still need to be explained and optimised. Examples are: i) the non-linear characteristic of current voltage curves; ii) the so-called memory effect, iii) the apparent enhancement of kinetic when nanomaterials are decorated with glassy surface films, iv) the variable slope of the Warburg diffusion tail during charge and discharge etc. It would be highly exciting if we could address this challenges within a similar project and similar consortium in the near future.

UCAM - Like the other Universities, the outcome of the results has given us the possibility to strengthen our scientific and technological knowledge that we shall be able to invest in future cooperation with academic and industrial partners in the field. We will also further published project results that were not reported during the course of the project.

WUT - Commercialisation of the developed Lithium salt and implementing the work into other cell designs

VOLVO - The outcome of the results has given us the possibility to extent our knowledge on new cell chemistry. This new knowledge will be useful in defining the specification to cell suppliers as well as in controlling strategy for best use of the cells in practical applications.

Renault - We would be open to continue such kind of upstream research on battery technology within similar consortium, keeping in mind targets should continue to include prototype definition in par with a higher technology readiness level than what is usually assumed at laboratory scale.

Spijkstaal - The outcome of the results has given us the possibility to extent our knowledge on new potential cell chemistry. This new knowledge will be useful in defining the specification to cell suppliers as well as in controlling strategy for best use of the cells in our practical applications, and vice versa to the further development of our vehicles (the pro and cons).
It is however still to be seen internally, whether we will be open to continue such kind of upstream research on battery technology within such similar consortium. Nevertheless, we hope that this effort/project gets a continuation (new/second project).

CEA - The outcome of the results has given us the possibility to extent our knowledge on new chemistries for Li-ion cells and on industry-relevant cells manufacturing, and we would be happy to continue this work under a similar sort of consortium.

ZSW - Performance tests with the demonstrator cells in the early stages enable us to characterize and understand the cells and to compare the cell performance with state of the art technologies.
These results help us to develop operational strategy for Si-based composite cells, i.e. to derive operating limits, to develop algorithms for cell monitoring, state estimation, and power prediction.
Future work will take the battery module design and development of battery management systems into account to ensure long and safe operation with this high energy battery.

AIT - The results from electrical and abusive testing will be shared within normative consortium TC / TMG 21 where AIT is participant. Findings of EuroLiion are and will be used in several national and international cofounded projects. More publications are planned, especially combined ones with the EuroLiion consortium. Future collaboration with the consortium is of high interest.

Expected final results and potential impacts

Electrification of transport is a priority in the Community Research Programme. It also figures prominently in the European Economic Recovery Plan presented in November 2008, within the framework of the Green Car Initiative. Besides that the policy related to battery-powered vehicles is mainly focused on technological optimisation and market development, future challenges in this field include reliability and durability of batteries and super-capacitors, reducing battery weight and volume, safety, cost reduction, improved hybrid electric power-trains, charging infrastructure and plug-in solutions.
A successful introduction of electric cars in the market requires the development of cheap, safe, reliable, light, small, highly efficient, and high power electrochemical storage devices – batteries.
The introduction of electric cars will have an enormous impact on the production volume of rechargeable batteries, as this has never been achieved before. Clearly this put a strain on the availability of some raw materials, and therefore, attention has been paid toward selection of materials that are abundantly available.

Outcome
The outcome will be a newly developed cell, manufactured and tested by end-users. The new cell consists of:
- a newly formulated Si-negative electrode;
- newly designed low cost salts;
- modified positive electrodes.

With regard to the battery producer CEA, due to this collaboration, the outcome could lead to establishing the basis for a world level European automotive battery industry. Besides, with these significant contributions it may also lead to large market shares in the area of electric cars on a global level.
Also, it opens up the possibility to manufacture custom-made electric vehicles within the area of for instance in-house transportation. This is particularly of interest for Spijkstaal, a Dutch SME. Hence, by fostering the partners, this interdisciplinary consortium will bring about a battery with technical specifications of 200 kW/kg and a power density of 1000 W/kg, which is at the same time cost-effective, and has materials with a low environmental impact. Besides, all the end users are involved in the life cycle analysis so as to review the recyclability and life-cycle sustainability, and take actions based on the outcome.

The strategic impact can be broken down by hardware and “software”:
- the battery producer CEA could well benefit from the outcome of the project so as to produce a battery that fulfils the requirement for electric vehicles;
- the knowledge gained from the project can be used for batteries for other applications as well;
- once the batteries are accepted the automotive industry can implement them into the cars;

- the ALISTORE-ERI will receive additional resources to sustain and therefore attains durability;
- the various academic research groups will gain knowledge that are been published in international journals.

List of Websites:
http://www.euroliion.eu/

Verwandte Dokumente

final1-euroliion_publishable-document_final-report.pdf

Letzte Aktualisierung: 12 Februar 2016

Permalink: https://cordis.europa.eu/project/id/265368/reporting/de