PROJECT FINAL REPORT

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ELIBAMA

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European Li-Ion Battery Advanced Manufacturing for Electric Vehicles

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1. Final publishable summary report (Public)

1.1. Executive summary

Electric Vehicles (EVs) symbolize the future of sustainable road transport. In this context, energy storage is an area of rapidly evolving technology. In some years, Lithium-ion has become the dominant rechargeable battery chemistry for consumer electronics devices as well as for x-EV vehicles.

Simultaneously to the researches for increasing batteries performances (capacity, safety, cost), a global race is underway for establishing an industry for large-scale, cost-effective, and environment-friendly production of lithium-ion (Li-ion) batteries.

ELIBAMA (European Li-Ion Batteries Advances Manufacturing) is a 3 years' project, aiming at enhancing and accelerating the creation of a strong European automotive battery industry structured around industrial companies already committed to mass production of Li-ion cells and batteries.

In order to achieve this target, innovative electrodes and cells manufacturing processes were developed up to a high TRL[1] to guarantee drastic cost reductions and significantly enhanced environment-friendliness across the value chain of the battery production.

During the course of the project, the manufacturing of LiTFSI[2] electrolyte's salt was strongly improved leading to a significant cost reduction. LTO[3] anode active material and eco-friendly aqueous based latex PVDF binders' uses were also studied.

Getting rid of the expensive and environmentally unfriendly solvent NMP[4] during the electrodes' coating is a must. Therefore, to achieve this target, the partners developed and demonstrated three beyond state of the art processes. The full elimination of the NMP was achieved for all of them, generating significant surfaces, costs and energy savings. In addition to two aqueous based processes (one for the anode and one for the cathode), a dry blend fully solvent free coating based on an powder's electro-deposition process was also studied up to a pilot level.

A 3D structured collector foils manufacturing process was also set up; the feasibility of such a process and the improvements generated on the product (increased coating adhesion as well as cells' wettability and performance improved) was demonstrated.

At cell level, the electrolyte filling process was modelled leading to an increased understanding of the wetting physics. In parallel, an experimental study was performed. At the end, the cell filling time has been divided by 2.

ELIBAMA also studied a new electrodes welding process enabling a less invasive joining process and increased quality.

A new concept of high speed stacking line was also developed using innovative gripping and depositing combined with high speed folding process management.

ELIBAMA also focused in improving the electrodes and cells' overall quality by working on a Non Destructive cells' Testing method and by developing clean manufacturing's methods: the diminution of the cells' end of line scrap rate by 2 was demonstrated.

At the end of the value chain, end-of-life battery management was also addressed. Used batteries logistic, dismantling, reuse and recycling were studied: innovative approaches were proposed and best-practices guides made available.

[1] *TRL: Technology Readiness Level*
[2] *LiTFSI: lithium bis-trifluoromethanesulfonimide*
[3] *LTO: lithium titanium oxide*
[4] *NMP: N-méthyl-2-pyrrolidone (organic solvent)*

After 3 years of work, most of the targets of the ELIBAMA project have been achieved. The expected cost reductions in the electrodes and cells' manufacturing are significant and the breakthroughs in the quality are obvious. The environmental impact of the batteries manufacturing processes, monitored by a LCA[5], has been deeply reduced.

Some of the foregrounds have already been transferred to mass-production; some are ready to be up scaled; finally, some others need additional research efforts already planned for most of them.

ELIBAMA opens the way to significantly improved manufacturing processes for the Electric Vehicles batteries' electrodes and cells, more eco-friendly and less expensive providing the involved partners durable competitive advantages for the future.

[5] *LCA: Life Cycle Assessment*

1.2. Description of project's context and objectives

1.2.1. Context

The automobile industry and urban transport operators must meet the required reduction of the environmental impact of vehicles and thereby contribute to the objectives fixed by the EU Climate and Energy package known as the "Grenelle de l'Environnement" 20-20-20 targets: 20 % renewables energies by 2020, 20% reduction of CO_2 emissions and fuel consumption from transport.

In this context, Electric Vehicles are key for the future of sustainable road transport. To support the development of EVs, innovative, safe and high performance Lithium-ion energy storage batteries are being studied. Simultaneously a global race is underway for establishing an industry for large-scale, cost-effective, and environment-friendly production of lithium-ion (Li-ion) batteries. The rewards for the winners are clear: the market for automotive Li-ion batteries in Europe, China, Japan, and USA alone is estimated to reach 25 billion € in the coming years.

Yet the path towards truly mass-scale production of large lithium-ion batteries as necessary for electric vehicles is faced with several serious challenges:

- Cost challenge: The battery of an EV accounts for roughly 40% of the overall cost of an EV and is clearly too high for broad acceptance in the market. Indeed, a persuasive point-of-view is that unless the cost of the battery is reduced drastically the price of an EV will exceed the price of a similar class gasoline-fueled car by several thousand Euros. Therefore, it is absolutely necessary to overcome this challenge.

- Environment challenge: The marketability of electric vehicles hinges on adopting clean manufacturing steps throughout the production of an EV, which leaves no ambiguity about the overall green credentials of the car. In this regard, the manufacture of the battery is a key focal point for an EV, and one where some clear challenges are present. It is estimated that about 15% of an EV's total environmental burden comes from manufacturing, maintaining, and disposing of the lithium-ion battery. When considering just the production phase, the Li-ion battery accounts for nearly 40% of an EV's impact on the environment, which is the principle reason for the extra burden on environment in producing an EV compared to a standard car of the same class.

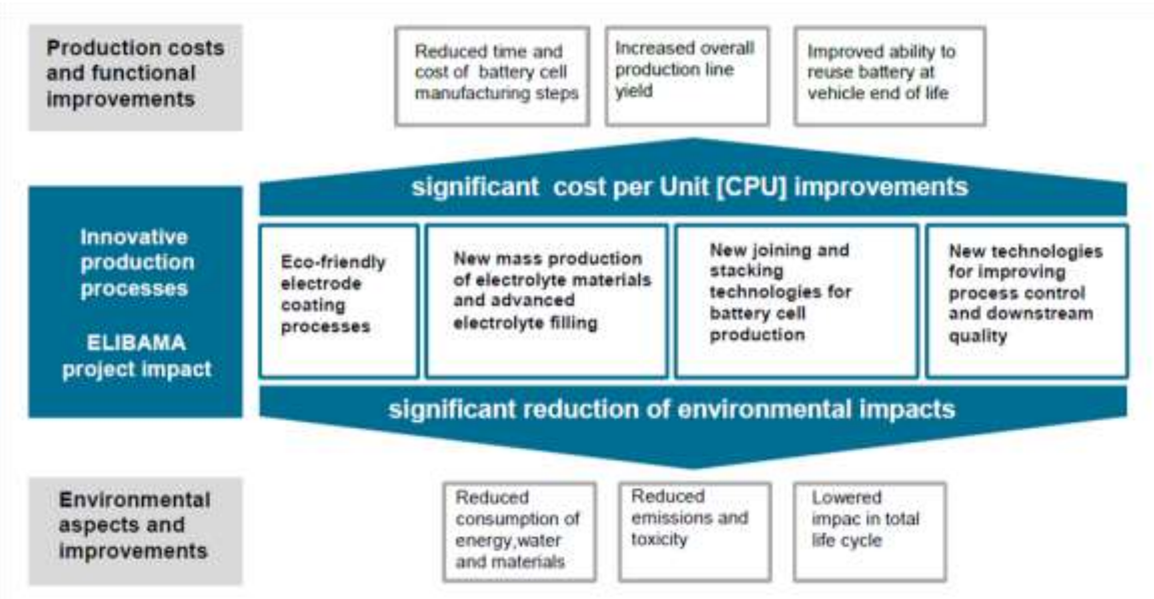
- Quality challenge: A key challenge for EVs being accepted in a broad consumer base is the quality and reliability of the vehicle. The battery, despite strong efforts on cost reduction, will remain an expensive part of the vehicle. Thus, it is a component that will be expected to have a long life and excellent reliability, the cost of replacement being unaffordable for the customer. Solutions through battery rentals have been proposed to remove this risk from the customer side, but this would shift the risk to the industry side, with the possible downside of creating a bad business case.

- Challenge for scale-up of production: Currently, the production of larger cells is still in the pilot- or low-volume manufacturing state. The technologies and manufacturing processes used for the production of small format of Li-Ion batteries for the consumer electronics market are of little avail to the producers of large batteries because of the much greater demands placed on HEV and EV batteries (e.g., higher power, wider temperature range, enhanced safety, etc.). Many aspects of production such as electrolyte filling techniques, online monitoring of electrode defects, improved cell stacking and joining technologies need to be up-scaled in order to meet the high throughput demands of the Li-ion battery industry for EVs.

1.2.2. The scientific and technological objectives

The targeted output of the ELIBAMA project is the production EV size cells and the feasibility demonstration of **cost-effective**, **environmentally reliable** and **high-yield** pilot industrial production units, scalable to about 100,000 EV packs per year.

The scientific and technological objectives are detailed in the figure below:



1.2.2.1. REDUCTION OF THE PRODUCTION COST

with a target of 10% thanks to process improvement through the project and 20% through volume effect

Cooperation along the value chain is required to enable supply of materials, cells and batteries to support the market growth. Market growth will depend on battery cost, especially for PHEV and EV. This will require cost reduction along the complete value chain. Within ELIBAMA project, the cost reduction targeted is of at least 30% along the manufacturing steps shown.

- Development of cost-effective processes for the manufacturing of electrodes

- Dry coating and solvent free coating processes for cathodes
- Aqueous-based coating process for anodes

Both processes have a direct cost benefit as they avoid the need of expensive equipment for drying and solvent recondensation, and associated running costs.

- Development and improvement of electrolyte materials production as well as electrolyte filling processes

- Cost-effective process for the mass production of new electrolyte materials offering improved safety and reliability properties.
- Faster and less expensive electrolyte filling of cells by using 3D-structured current collector foils for prismatic hard and soft case cells.

- Improvement of battery cell assembly processes, enabling to bring down the manufacturing cost and improve the overall safety and efficiency of battery pack in use:

- Development of improved stacking technologies for large format cells to achieve low cycle time and high reliability of the assembly process.
- Replacement of standard ultrasonic welding of electrodes by innovative joining technologies with ultra-low thermal und mechanical invasion to the electrode materials and battery cell to ensure a long- term low resistance connection regarding automotive requirements.

1.2.2.2. IMPROVEMENT OF THE PRODUCTION QUALITY

A specific challenge will be to achieve the level of quality and reliability necessary to meet this request for the cell manufacturing. Looking in the failure tree analysis of a single cell, many parameters depend on cell design and manufacturing process design. But in addition to this, the quality of the process control, and specifically the cleanliness of the manufacturing process is a key parameter to obtain the high product reliability expected. Therefore, the ELIBAMA project will target the development and implementation of clean room manufacturing processes with a high level monitoring and inspection system for the surfaces of the electrodes, as well as the development of an automated non-destructive cell test process.

- Development of new technologies and processes that will allow improving downstream quality and reducing the rate of defective products at the end of the manufacturing chain:

- Development of high cleanliness manufacturing processes (“clean room” manufacturing processes) covering the whole chain from the manufacturing of active materials (electrode, electrolyte) to the assembly of cells into modules in order to reduce the risk of contamination of the products by exogenous particles at each step of the manufacturing process: the appropriate environment and related processes will be researched so as to ensure that pollution by contaminants in air or in electrolyte or generated during the process will be brought down to a minimum.
- Development of online high resolution monitoring and inspection solution in order to catch and then evaluate defects during the tests of different manufacturing processes: online high resolution monitoring and inspection of 100% of the surface of electrodes and 3D-structured current collector foils will be installed on manufacturing processes in order to control both the surface quality and their assembly.
- Development of new Non Destructive Test (NDT) to reduce quality control testing time of each cell, improve downstream quality by increased defect detection and reduce cost of testing.

1.2.2.3. DECREASE THE ENVIRONMENTAL IMPACT

One key environment challenge addressed in the ELIBAMA project arises from the current state-of-the-art (SOA) in the production of electrodes. PVDF[6] is the state-of-the-art binder for electrodes in Li-ion cells while the solvent NMP is the preferred solvent because of the excellent solubility of PVDF in NMP. However, NMP has several adverse effects on the environment: it is volatile and combustible adsorbed by the skin and considered to cause reproductive and genetic damage. Additionally, the need for NMP recovery and the stringent production controls (e.g., to reduce humidity) carry an indirect burden on the environment.

[6] *PVDF: Polyvinylidene fluoride*

- Development of new eco-friendly processes for the manufacturing of electrodes and electrolyte enabling to lower the environmental impacts of the manufacturing stage:

- Less energy intensive processes with an overall reduction target of 25% net energy consumption, hence CO2 emission and up to 65% reduction of the energy consumption during the electrode manufacture
- Dry coating method for cathode manufacturing lines involving an electrostatic powder coating process of all the components of the electrode material in the form of a dry blend-mixture. This will reduce the environmental impact of using organic solvents and overall water consumption.
- Development of NMP free solvent for cathode manufacturing process using an adapted binder.
- Development of aqueous electrode manufacturing processes for titanate-based anodes.
- Reduced risk of HF[7] emission from new LiTSFI electrolyte

- Recycling, refurbishment and re-circulation of batteries:

- Defining schemes and tools for the safe take back and transportation of end of life batteries, especially in order to address safety issues for batteries in an undefined state (for example after a car crash or in case of defects).
- Developing diagnostic and testing methods for the monitoring of used commercial batteries to assess their second life potential (refurbishment, reuse in new applications out of the automotive field, recycling of components).
- Developing methods to discharge completely batteries before dismantling in order to insure the protection of workers against electrical risks during the recycling processes.
- Implementing standard for the easy dismantling of batteries in order to maximize their recycling.
- Improving recycling processes efficiency of end of life batteries as well as production scrap at the different stages of the battery manufacturing (raw material powders out of specifications, electrodes inks waste, substandard electrodes coated of metallic current collector tapes, cells).
- Developing new recycling processes at pilot / industrial scale to ensure the recyclability of the new technologies developed in ELIBAMA project (WP1-4).
- Defining best practices for the conception and clean manufacturing (eco-design) of batteries in order to lower the global environmental impacts and improve the overall recycling efficiency and possible second life of batteries and components.

- Life-cycle-assessment (LCA) studies to minimize environmental impact:

- All these technical improvements will be closely monitored and validated from the environmental point of view (by quantitative assessment) by providing an integrated environmental assessment of the different technologies developed in the course of the ELIBAMA project.
- Life Cycle Assessment will be run in parallel over the whole period in order to give early feedback on what has been already achieved and what still has to be improved, and will provide quantitative data to ensure that the technological improvement is accompanied by the overall environmental improvement.

1.3. Main scientific and technological results / foregrounds

[7] *HF: Hydrofluoric acid*

The ELIBAMA project worked on various topics from raw material manufacturing up to batteries and cells recycling. The entire foreground generated is described in the “Electrodes and Cells Manufacturing White Paper” available on the project’s website.

This part of the report will focus on some major findings of the project.

1.3.1. LiTFSI electrolyte

Rhodia (Solvay group) worked jointly with the CEA and SAFT on an alternative electrolyte salt, chemically and thermally stable, the LiTFSI.

- A benchmark of LiTFSI vs $LiPF_6$ was performed in order to establish comparative physical, chemical and cycling properties of the two salts; it showed significant life time improvements compared to the SOA:

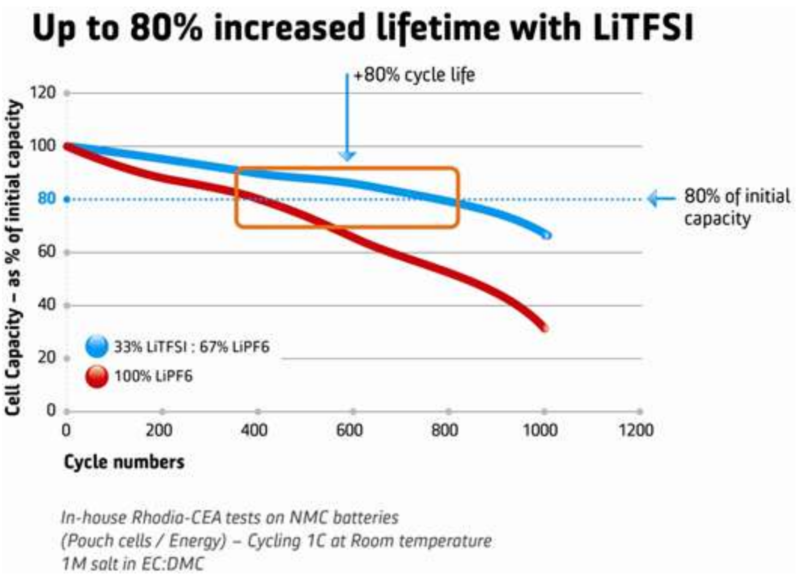


Figure 1 – Increased lifetime with LiTFSI-based electrolytes

Witnessing an up to ***+80% increased life time with LiTFSI***, these above results lead to an estimated benefit up to ***1000 € over a full EV*** (25kWh) battery life.

- The LiTFSI manufacturing process was also improved to reduce the salt’s costs: the focus has been put on the key step (TFAK Sulphination) of the global process.
A gain of more than 10% TFSK selectivity was obtained thanks to the work performed within the frame of the ELIBAMA project; this improvement was confirmed at a 250L scale.

Figure 2 – glass reactor used (P up to 10bar)

Over the whole LiTFSI manufacturing process, a ***7% Full Manufacturing Costs reduction*** is expected, in good agreement with the target proposed at the beginning of the project.

- At the end of the chain, the recycling process for the LiTFSI lithium salt in used battery cells was studied.
  A first draft of a LiTFSI recovery process from LiTFSI-containing electrolyte of used Li-ion batteries was defined on a LLE (Liquid-Liquid Extraction) with water and tested on real used cells. ***96% recycling rate*** with a single extraction stage was observed.

1.3.2. Structured collector foils

In the scope of ELIBAMA, Fraunhofer, jointly with Daimler and In-core system, developed a technology for the preparation and production of the structured copper collector foils aiming at reducing the battery filling time and increasing the adhesion between the active material and the collector.

During the project, a 2 step copper plating process was defined and a ***demonstrator*** was build; this batch process is already representative of a mass production roll to roll process.

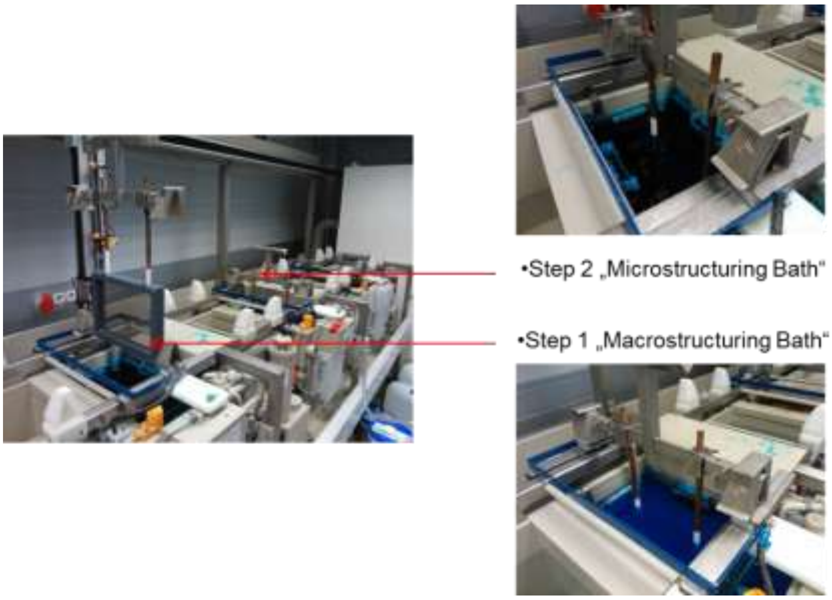


Figure 1 – 2 steps structured foils manufacturing

Using this equipment, different macro and micro-structures were tested.

At the end, more than 150 foils were manufactured enabling to assemble and test a number of 12 Ah cells.

Regarding the adhesion, the pull-out test and also the cross-cut test have shown that the ***adhesion*** between the battery active material and the copper foil can be ***increased*** by using structured copper foils.

The impact of the structuring on the filling was also demonstrated with ***a filling time reduction of 10%***.

Moreover, the wetting of the electrode with structured collector foils is also improved leading to a ***better cell capacity retention*** in cycling tests.

1.3.3. Dry blend electrodes Coating

ELIBAMA's partners worked on 3 innovative NMP free electrodes's coating process.

Fraunhofer developed with Daimler and Kroenert a solvent free electrostatic powder coating process which applies all components of the electrode material (e.g., LiFePO4, carbon black, binder, etc.) electrostatically as a powdery dry blend-mixture.

Due to the absence of solvents an energy-intensive flash-off zone and thermal combustion or recondensation of the evaporated solvent is not required. The energy-intensive long term process for solidifying the state-of-the art liquid or pasty electrode material in a convection oven was substituted by an energy- and floor space saving contact IR heating process.

The process was demonstrated up to a pilot level on a ***roll to toll machine specifically developed*** by the project's partners.

Figure 1: Start-up trials with aluminium current collector foil (left), application area and precompacting unit (middle), trials with carrier foil made from polyimide (right), monitoring system (In-Core technology) installed at demonstrator

Production-like dry-blend coating trials were carried out with large surfaces; the obtained electrodes, assembled as EV size cells, show **good electrochemical behaviour**.

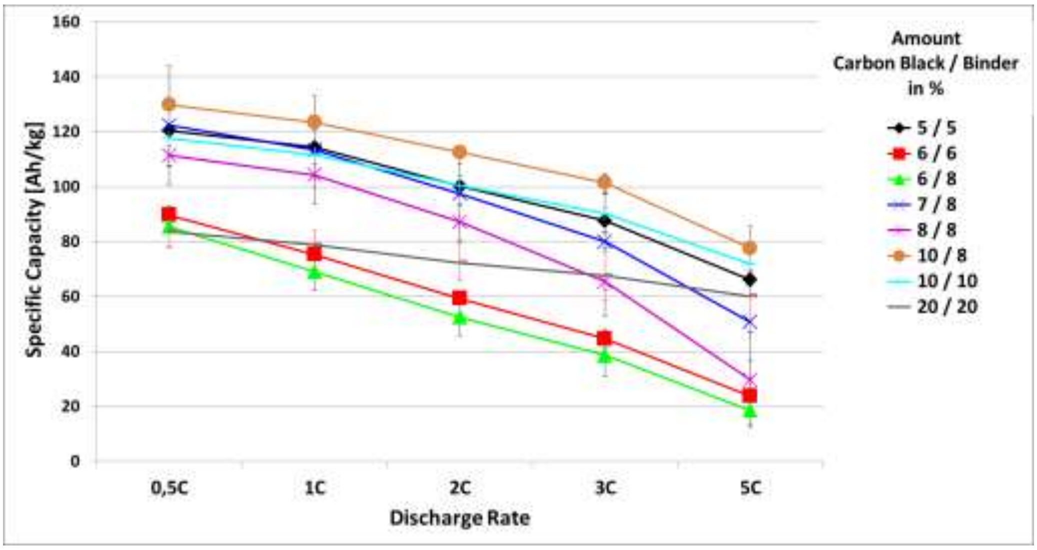


Figure 2: Discharge capacity of LFP/PVDF/CB dry blend coated electrodes in half cells, measured at different C-rates.

At the end, the viability of the dry blend electro deposition process was demonstrated.

1.3.4. Cathode NMP free coating

Switching to water-based formulations can have a negative impact at several steps of positive electrode manufacturing (Mixing, coating, drying). Saft worked on this issue in the scope of the ELIBAMA project, as illustrated in the figure 1:

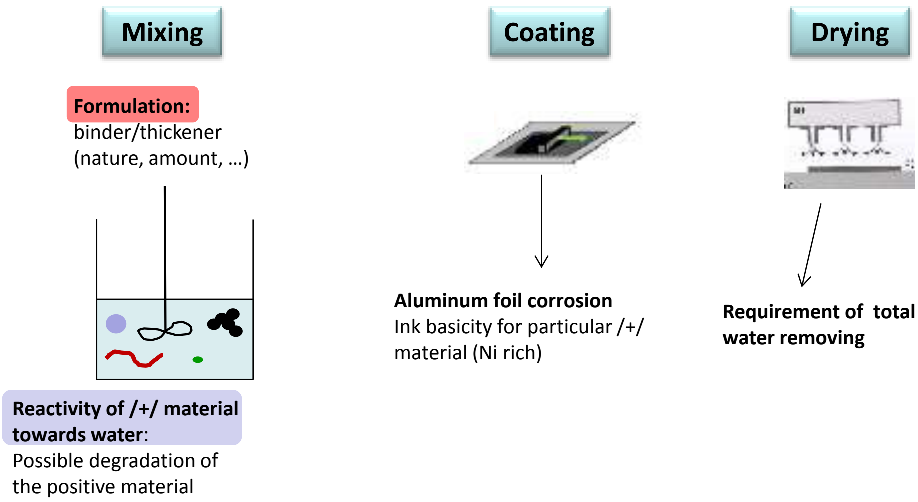


Figure 1: Electrode manufacturing steps impacted by switching to water-based process

After a first step of research at lab scale (test of different additives and selection of the most promising one, mixing, coating and drying parameters optimisation), the process have been transferred at pilot-scale, in order to build demonstrator cells.

Three different generations of water-based cells, with the objective on constant improvement in terms of process (dispersion of raw materials in water, residual water in electrode after drying, etc…) and electrochemical design (initial performances of cells, covering effect of the binders, etc..) have been manufactured.

At the end, NMP-free positive electrode process has been successfully demonstrated in 40Ah cylindrical cells, with ***initial performances as good as reference*** NMP-based electrodes. By a thorough investigation at lab-scale, ***Al foil corrosion*** issue has been ***solved*** by using a specific additive with a specific content.

The cathode water-process is controlled:

- Drastic reduction of residual water in the dried electrode

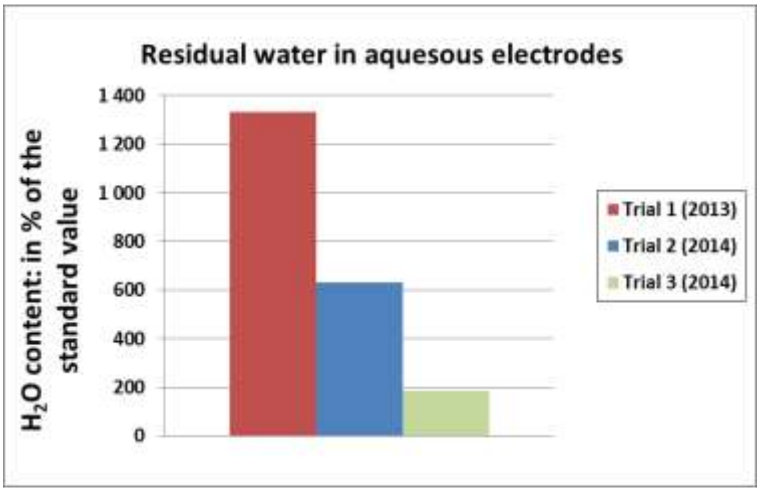


Figure 2: Evolution of the residual water

- Electrical resistivity of the electrode as low as the NMP-based reference

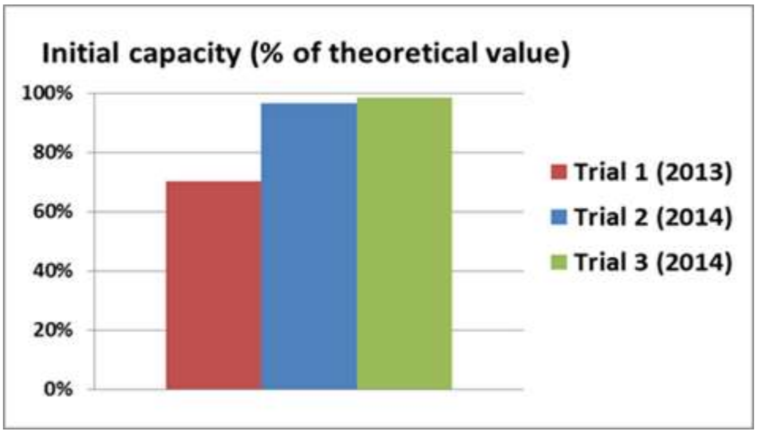


Figure 14: Evolution of initial Capacities for the 3 trials

- Increasing of the accessibility of the material by the electrolyte.

Cycling and calendar life show also promising results, when compared to NMP electrodes.

1.3.5. LTO anode Coating

Some titanium based materials shown significant promise as an alternative negative-electrode material to graphitic carbon for lithium-ion batteries application. In ELIBAMA Project, Renault, CEA, Solvay and Prayon joined their efforts to demonstrate a water based process to produce Titanate Li4Ti5O12 (LTO) electrode.

Different problems have been faced and solved to achieve these objectives:

- The water based slurry mixing parameters and products have been adjusted in order to obtain a good dispersion
- At the coating step, obtaining a sufficient coating adhesion has been the main challenge: different slurries viscosities and composition have been tested and the drying conditions have been optimized keeping the objective to reduce the energy consumption

At the end of the project, 10Ah cells were manufactured using the aqueous based pilot process and electrochemically tested.

More than 400 cycles (1C charge and 1C discharge) have been performed comparing NMC/LTO_Aq cells and NMC/LTO_NMP cells. Globally, no difference between new process (water based) and traditional one (NMP based) was showed. Especially, a very good results is obtained for the 55°C cycling with nearly no capacity loss after 400 cycles with the H2O based electrode.

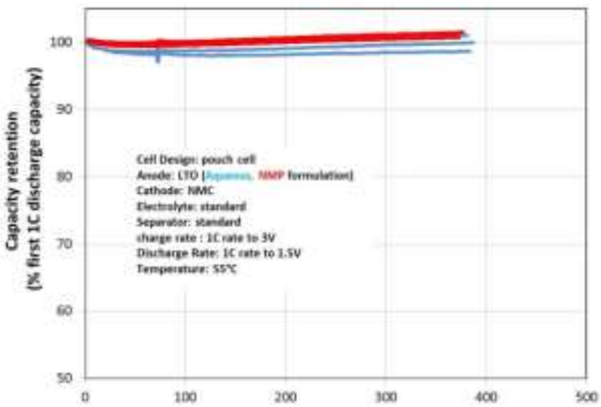


Figure 1: 1C/1D High temerature (55°C) cycling of LTO/NMC$_{NMP}$ and LTO/NMC$_{(aq)}$ cells

The savings in term of ***costs (-32%)*** and environmental impact (***Reduction of the Energy of -40%***) are very significant.

1.3.6. Electrodes Calendering

Reducing the electrodes' porosity is one potential way to increase the energy density (in Wh/L), and thus to reduce the global cell production costs.

Saft and Ingecal worked on this topic in the scope of the ELIBAMA project.

To achieve the objective, a specific apparatus has been added before the calendering operation on the production line:

In parallel, a more accurate thickness measuring system has been experimented.

Using these systems, ***electrode porosities*** have been successfully ***decreased to -22%*** for the positive one and ***-35%*** for the negative one. The use of new systems seems promising. From this initial work, two mains observations have been done.

The ***adhesion*** is ***improved*** at low porosity as far as the positive electrode is concerned. This observation is also promising because it could make possible the reduction of binder percentage in the positive formulation, and thus increase the active material percentage.

Electrical performances need to be continued but an ***initial capacity gain of +10%*** at cell level is already obtained.

1.3.7. Electrodes surface inspection

During the ELIBAMA project, the main objectives of IN-CORE Systèmes were to use the existing know-how in the field of Li-Ion battery inspection and to develop quality control systems for powder coated electrodes and for structured electrode collector foils.

- For the dry blend powder coated surfaces, the main challenges were to detect defects and inhomogeneities in the recycled electrode material by using high resolution imaging systems.

  Laboratory based studies of samples provided by partners lead to on-line installations on pilot equipment present at Fraunhofer and Kroenert. These installations used newest generation CMOS based line-scan cameras and permitted to statistically evaluate their capability.

  Results from both installations showed that the system is ***able to detect valuable defects*** in the powder electrode. Figure 1 shows from the left to the right side normal surface aspect variations, non-adhering coating, pin-holes, non-homogeneous coating (thickness variations) and a defect caused by wrinkles in the electrode foil.

Figure 1 Inspection results from powder coated electrode material on primer.

- For the structured current collector foils, specifications for an on-line quality control system to control the regularity of the holes and to detect defects on the copper anode surface had to be developed in co-operation with Fraunhofer.

  A laser triangulation based cameras system has been selected as the most suitable inspection means considering acquisition speed, resolution requirements and a 100% inspection over the full width.

  The capabilities of the system have been evaluated off-line. Considering the image acquisition conditions, the resulting theoretical height resolution was 0.25µm due to the ability of the camera to work with a higher precision than the optical resolution. This setting allowed ***detecting height defects*** present on the samples (see Figure 2).

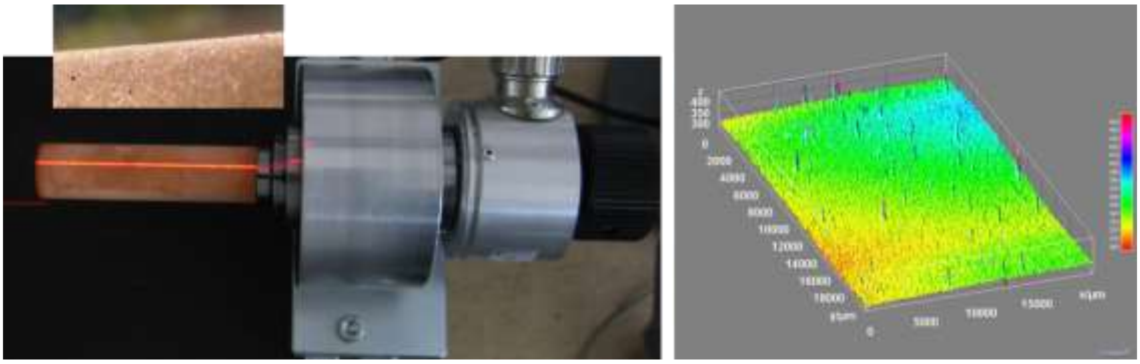


Figure 2 Height defect detection on micro-structured electrode.

- During the project, IN-CORE also worked on an ***automatic defect classification***. Figure 3 shows in the centre a defect distribution from an electrode wet coating process used as reference data and the resulting quality of classification for these defects on the right.

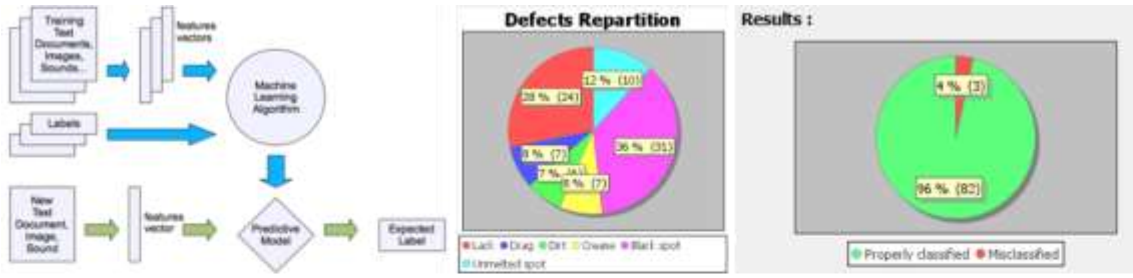


Figure 3 Principle of supervised computer learning (left), input data defect class distribution (centre) and the automatic classification result (right).

- A ***data management solution*** has also been developed which permits to merge inspection results of multiple inspection posts present in one process or of different production steps. Thereby, a full traceability of the product quality over the full production flow can be generated.

1.3.8. Electrode foils stacking and welding

At the cell' level, Daimler worked on the joining and assembly technologies with the target to improve the battery cell design and the joining and stacking process steps.

As far as collectors' joining is concerned, different solutions have were investigated:

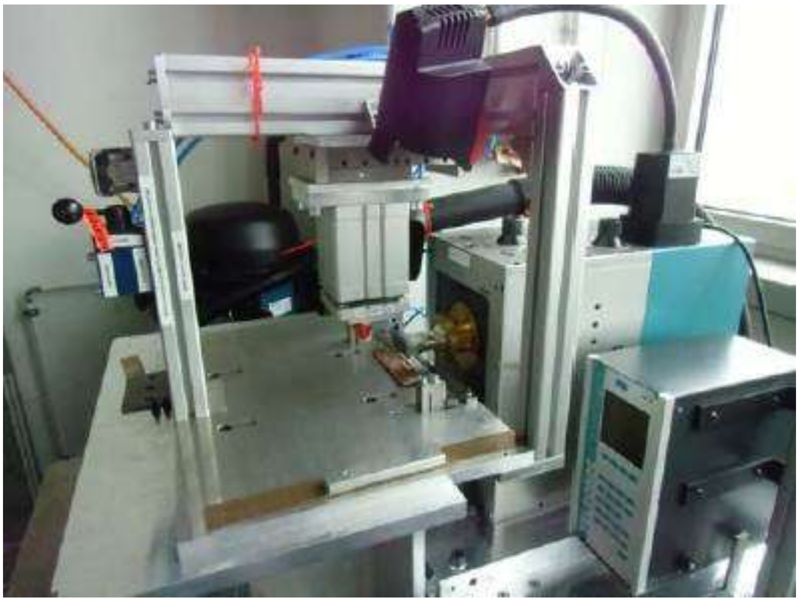
- Ultrasonic welding has been deeply studied:
    - Machine's parameters influence have been checked.
    - Sonotrode shape has been redefined.
    - Different welding quality inspection systems have been developed.
    - 

Figure 1: US Lab welding station

- An electrodes' clamping system has also been defined to warranty a good dimensional accuracy and the joining quality.

Figure 2: Work piece carrier

- The Resistance Projection Welding has also been proven to be a possible alternative joining technologies for foils.

At the end, a deep understanding on ultrasonic welding was acquired that enabled to define a weld process giving narrow weld seam. This improvements will permit to have a less intrusive welding zone and to ***extend the active part of the cell of +1,7%***.

More globally, a comprehensive cells' assembly plant scheme were defined integrating different innovative concepts. All aspects of production have been integrated into one overall concept. Based on a thorough analysis the proposed solution sets the basic setup for further advancements in production design:

- A collectors' foils' buffer has been developed and demonstrated using an ultrasonic levitation handling system.

Figure 3: Magazining demonstrator

- The management of the dry air condition constraints have been reviewed by the use of specific local encapsulation systems
- The designed stations were manufactured and assembled. By producing demonstrators the ***concept of an innovative cell's manufacturing line could be verified***.

1.3.9. Cells filling

The main objectives of the electrolyte filling activities performed by Daimler and Saft were to decrease the filling time and the filling costs of this specific and critical manufacturing step.

The wetting mechanisms of cathode, separator and anode on the one hand and the wetting mechanisms inside the cells in the multilayer system on the other hand had to be understood before being optimized.

Therefore, electrolyte flow modelling simulations have been performed using computational fluid dynamics (CFD) tools.

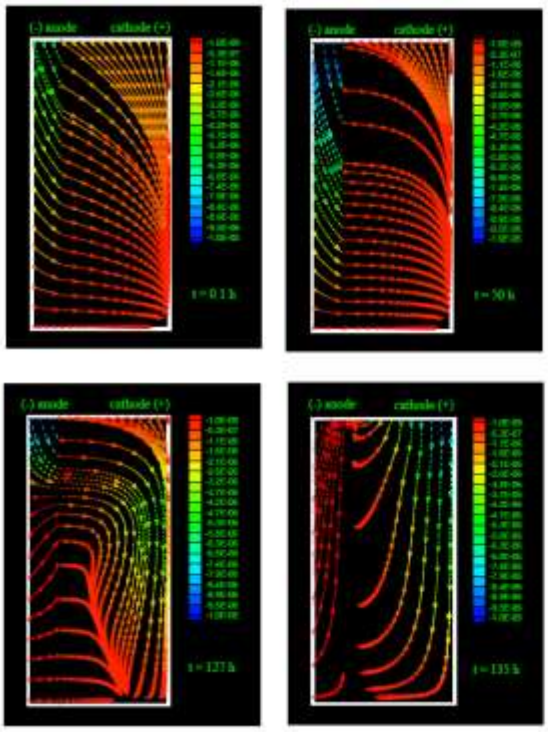


Figure 1: Example of Electrolyte flow within the cell ¾ streamline plot. The cell is discharged at -0 °C with a 50 W load and the end of discharge is 135.2 hours. The color bars on the side denote the vertical velocity component in cm s^{-1}.

This first principle modelling activity has been coupled with experimentation. In order to correlate the model, comparisons were made to the recent experimental data for a pouch-sized cell over a range of temperatures.

A <u>3D imaging</u> of the state of the electrolyte filling working with thermo sensitive IR camera has also been set up and tested under different conditions to help understand the wetting mechanism.

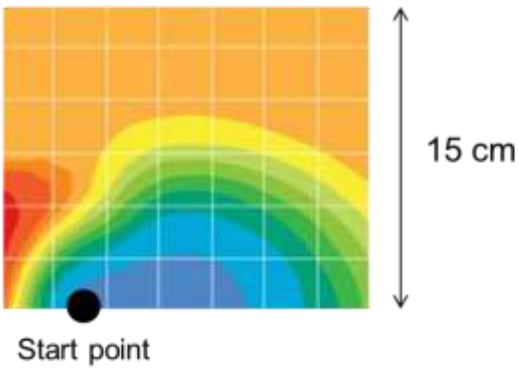


Figure 2: Time resolved 3D monitoring of a wetting experiment.

The most important <u>filling parameters</u> such as vacuum, pressure, temperature and time depending on the cell design and the cell composition have also been deeply investigated. Best sequences for filling and their combination to reduce the filling time with a complete deep filling of the pores was then defined.

Through each different step of the improvements of the electrolyte filling, the ***filling time*** can finally be globally ***reduced up to -61%.***

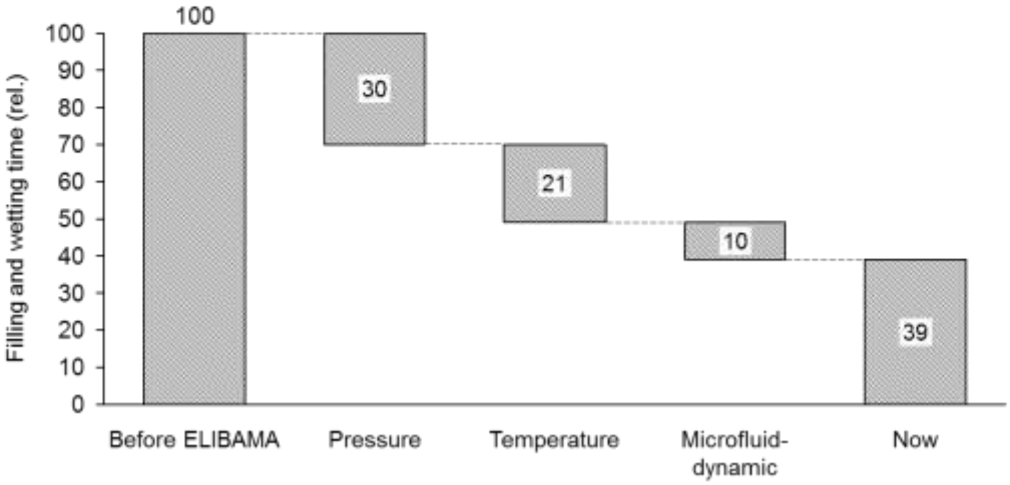


Figure 3: Reduction of the filling and wetting time with respect to the different procedures.

1.3.10. Electrodes and cells clean manufacturing

Through this task driven by Entégris with Saft and the CEA, the goal was to determine the main contaminants arising during the production of a Li-ion battery and find the adequate solutions to remove them in order to improve the product's quality and especially reduce the cells' final scrap rate.

To detect the contaminations, a methodology based on traditional quality system tools (Ishikawa diagram, FMEA, Pareto...) was developed.

The audits, performed on the manufacturing lines, enabled to classify the most important contaminants by steps in materials (raw materials, slurries, electrodes...), methods (methodology by process step), media (environment) and machine (equipment cleanliness).

Regarding the results of the audits, analytical techniques were used to evaluate and confirm the risks of the contaminants and solutions have been implemented accordingly and evaluated on 40Ah cells' batches.

For example, filters have been installed on the dispensing line conducting the solvents from the tank to the mixing vessel leading to a ***drastic reduction of the number of particles*** (figure 1):

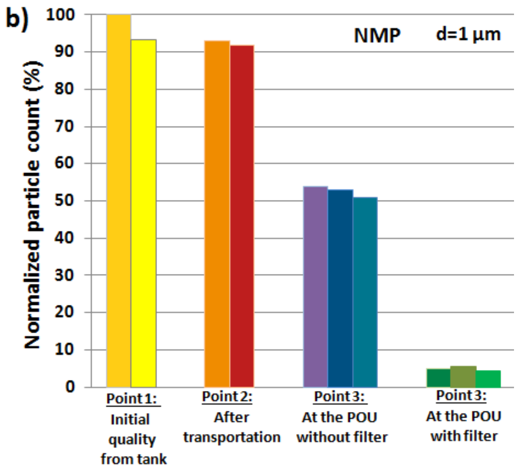


Figure 1: Normalized particle count evolution in NMP for 1 µm particle size at different locations.

The dry room air quality was also studied to reduce the particle number, i.e. the ISO Class. Different solutions have been successively implemented on the mass production line: modification of the sleeve mesh blowing the dry air in the room, modification of the air uptake filtration.

As shown in figure 2, the ***Iso 7 class was reached*** and validated by an external audit:

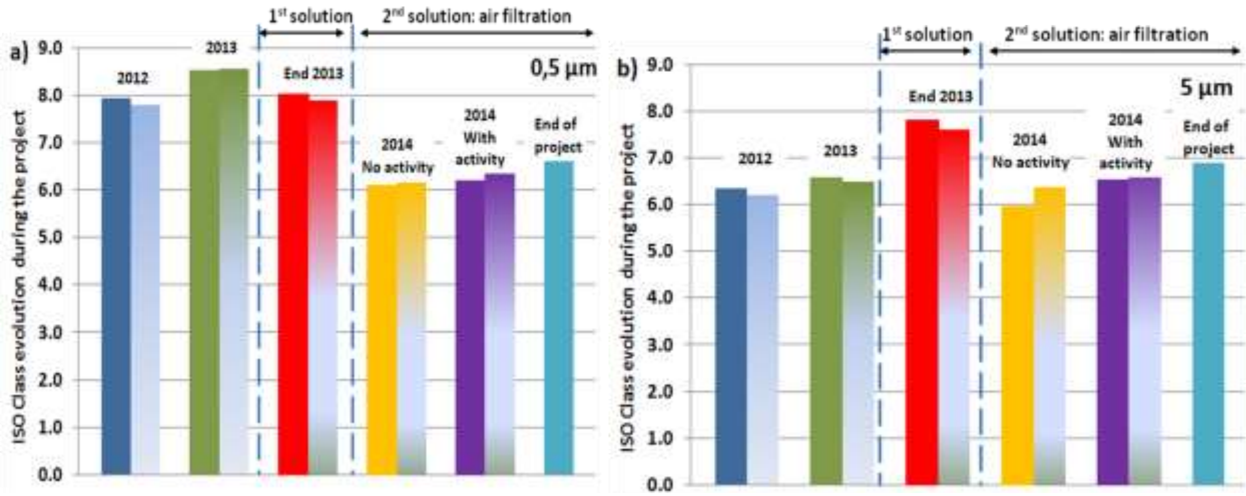


Figure 2: ISO Class evolution during the project with the different solutions implemented for 0.5 and 5 µm particles.

At the end of the project, the efficiency of the filtration tools installed for clean manufacturing steps on both materials and air of the dry room has been assessed by the results on electrical performance of 40 Ah batch cells. As illustrated in Figure 3, cleaning systems at electrode manufacturing steps (including calendaring) and dry room air quality have a strong impact on self-discharge values, leading to ***decrease of number of cells with high and medium self-discharge values up to -50%.***

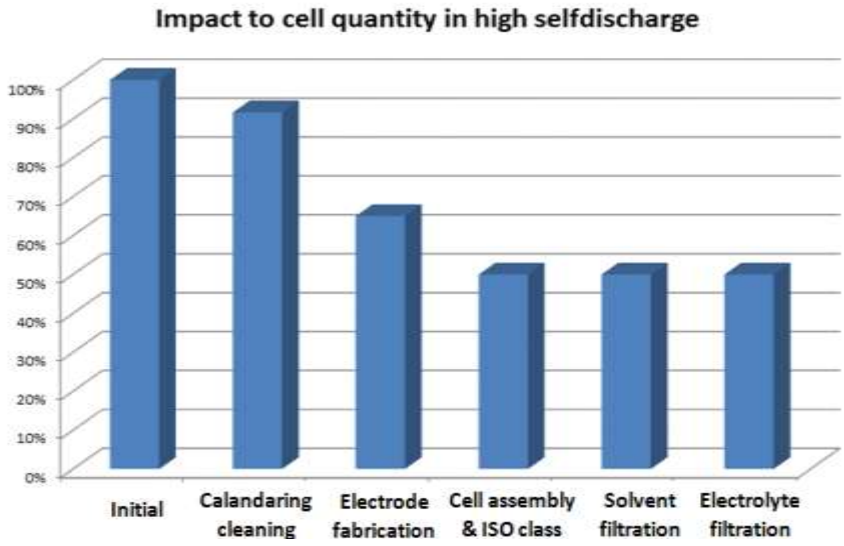


Figure 3: Impact of clean manufacturing step solutions implemented during ELIBAMA and their impact on self-discharge of 40 Ah cells.

1.3.11. Development of a Non-Destructive Testing (NDT) technique for Li-Ion battery manufacture

ELIBAMA partners **Newcastle University, Renault, SAFT,** and **Daimler** collaborated to develop a manufacturer non-specific Non Destructive Testing technique for the cells DT technique that is intended to be.

After a careful review of the different potential techniques, EIS methods were chosen to develop the proposed NDT.

The EIS cell's signal varies significantly with temperature and state of charge (SOC). To avoid this issue, the test cell's temperature and SOC must be known and a library of the target impedance spectrum must be available for the measured temperature and SOC.

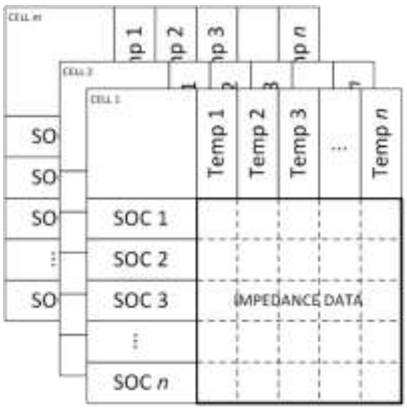


Figure 1: Target spectrum library

The EIS plots also have to be normalized to be exploitable (Subtraction of the real component from each response using the interpolated real-axis crossing point value).

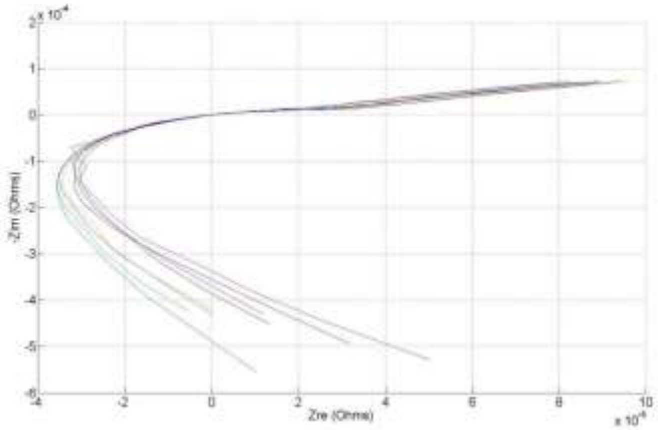


Figure 2 – Example of normalised and filtered responses

Based on this principle, a lab test device has been installed and a test procedure defined:

Figure 3 – NDT lab device

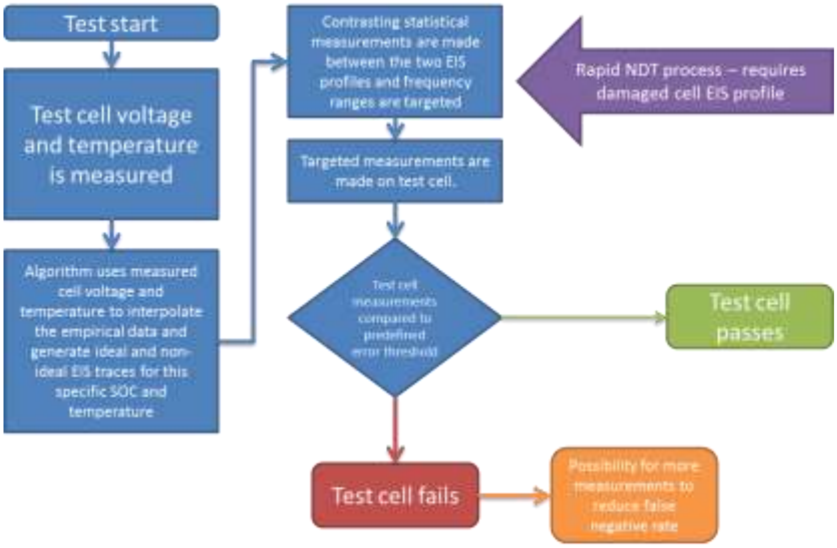


Figure 4 - NDT technique process steps

In summary, the developed technique has been shown to rapidly ***discern between cells with known electrochemical behaviour discrepancies***. The lab tool is shown to be accurate with all sample cells provided by different industrial partners ***in less than one minute***.

1.3.12. Batteries recycling

On European level the Battery directive 2006/66 EG is the legal framework for battery recycling. The battery directive defines different battery types and collection schemes and quotas, regulates the market participation, prohibitions of materials in batteries and recycling quotas for different battery types. Lithium-ion batteries from HEV & EV are considered as industrial batteries. Their minimum recycling rate is 50 %.

To overcome the technical or environmental issues shown through the state of the art which limit the recovery efficiency, several investigations have been done during the ELIBAMA project on in the work

- Electrolyte recovery by Solvay and CEA,

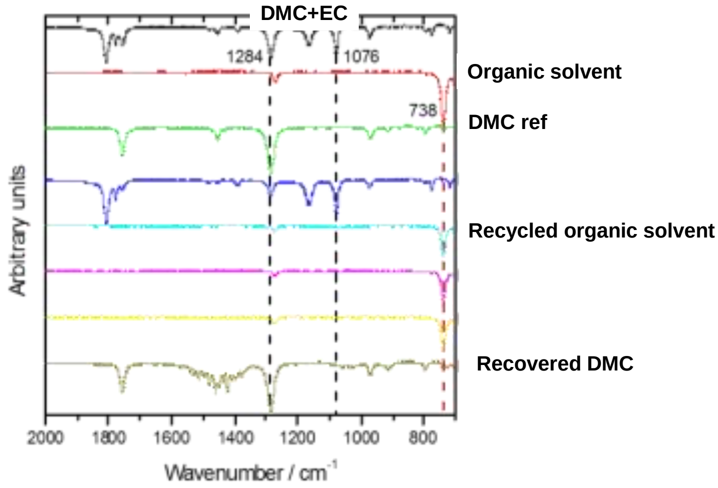


Figure 1: FTIR analysis of solutions used and obtained in the electrolyte extraction

- Dry sorting techniques by SNAM, FRAUNHOFER and CEA,

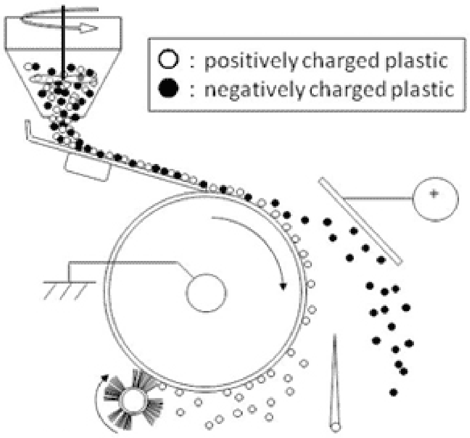


Figure 2: Principle of electrostatic separation

- Hydrometallurgical treatment for metal extraction and new active materials recycling by CEA.

At the end, a ***recycling efficiency up to 70%*** could be reach by using the techniques investigated during ELIBAMA project.

The energy consumption of the thermal process has also been reduced.

1.3.13. Eco-design of Lithium-Ion batteries

An integrated environmental assessment of the different technologies developed in the course of the project has been realized to support the technical developments.

The results of this analysis enable the environmental impacts of the baseline scenario to be compared to new technologies from a life-cycle assessment perspective. This allows identifying the best possibilities for eco-design, allowing the developers to design products and processes which take into consideration the environmental impacts of different components/processes of manufacturing.

The data for the different phases of the LCA were collected from the project partners. Based on this information, PE established an assessment methodology and modelled different scenarios for analysis using GaBi software for life-cycle assessment.

In general, the technologies developed or improved within the ELIBAMA project contribute to a ***significant reduction in the environmental impacts*** of lithium-ion batteries, either by providing improvements in the anode (replacing PVDF and NMP by latex and water) or by improving the cathode (dry blend process or aqueous based process).

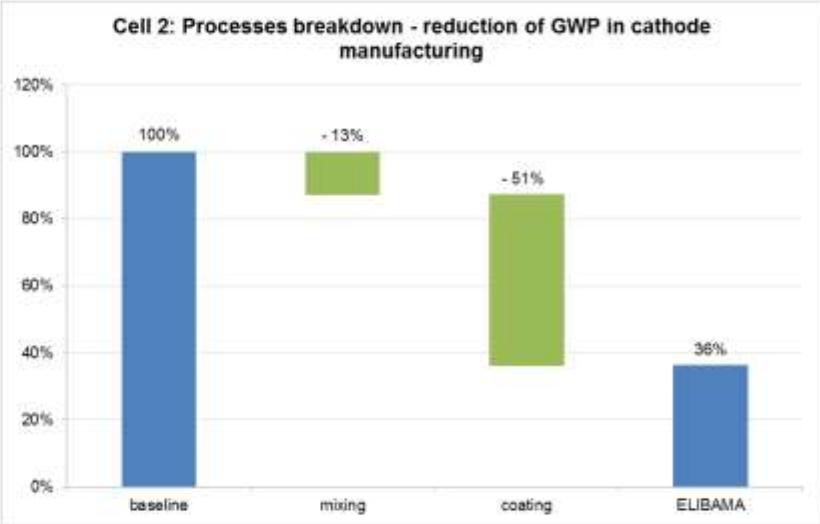


Figure 1: example of the Global Warming Potential reduction linked to the dry blend coating

1.4. Potential impacts of the project / Main dissemination activities and exploitation of results

1.4.1. Potential impacts of the project

1.4.1.1. Impact on advanced, eco-design processes of Li-Ion cell production

The first impact of the ELIBAMA project is of course the technical one.

The ELIBAMA project has applied a deliberate focus to the manufacturing of Li-Ion battery cells and their key components. This focus is critical as the production of the Li-Ion battery cell currently forms the single most significant cost element in the construction of competitively priced EVs.

Part of the foreground is already industrially implemented and has improved the economic competitiveness of the different partners (see §1.4.2 on exploitation). Some other findings are ready to be up-scaled.

Moreover, the work done in the scope of the ELIBAMA project significantly increased the partners' knowledge both on the global context of the Li-ion batteries' industry and on their own domain. It then gave them a competitive advantage for potential future use of the generated foregrounds.
This is especially the case for the SMEs[8] that generated directly marketable technics:

- Cleanliness tools for Entegris
- Better surface defects detection for InCore
- Improved calendaring process for Ingecal
- …

1.4.1.2. Impact on the coordination among major European automotive battery producers

SAFT (first European supplier of Li-ion batteries), the alliance RENAULT-NISSAN (4 EV launches due in the next 2 years), DAIMLER (through Deutsche Accumotive GmbH + Co KG for battery manufacturing and Li-Tec Battery GmbH for manufacturing of cells) and FRAUNHOFER (in cooperation with VOLKSWAGEN) are currently leading the way in the production of Li-Ion batteries for the automotive industry in Europe. In order to develop Europe's position at the heart of this industry it is important that the position of European based businesses are strengthened.

The ELIBAMA project has strengthen the coordination among involved industries by:

- Providing an R&D environment for a full synergetic cooperation among European partners that enabled the cross fertilisation of ideas among the companies involved and, via dissemination, to those outside the direct consortium.
- Providing cross contacts and collaborations in the frame of the contracts for establishing a more efficient network of SMEs supporting the battery industry (components manufacturers, equipment makers, etc.).
  New concrete business opportunities (of more than 200 k€) have been generated in the frame ELIBAMA between SME's and other partners and some others are already planned after the end of the project.
- Helping defining common process and product controls, production cleanliness, and product quality standards at European level to contribute to international standards.

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[8] *SME: Small and Medium Enterprise*

1.4.1.3. Cross industry focus on automotive Li-Ion battery recycling

Whilst the industry to recycle Li-Ion batteries for consumer applications is well established in Europe, a proven logistics process to manage the recycling of increasing numbers of automotive Li-Ion battery packs does not yet exist.

The size of battery packs increases the handling challenges as well as the safety risks, particularly due to the high voltages and energy densities of such packs. In addition automotive battery packs are expected to include some new chemistries in the future for which recycling processes may not yet be available.

The ELIBAMA project also addressed in a cross-approach the challenges of recycling by:

- Improving the logistic of end of life batteries including the safety risk management.
- Reducing of 20% the diagnostic and dismantling time.
- Identifying and evaluating future markets for re-use.
- Defining innovative way to reduce of 26% the recycling cost and to increase the material recovery up to 70%.

Two deliverables have been made public on the website giving the opportunity to deeply impact the future batteries design for a better recycling.

1.4.1.4. Contribution of ELIBAMA project towards expected impacts listed in the Climate and Renewable Energy Package of 2009

The wide range of innovative processes and technologies explored and developed through ELIBAMA project will contribute to achieving the new policy targets as set out in the Climate and Renewable Energy Package of 2009 through:

- Pollution reduction: ELIBAMA succeeded in fully get rid of the toxic solvent NMP during the electrodes' coating operation by using dry or water-based processes.
- Reduction of greenhouse gas emissions and maximization of energy conversion and rationalization of energy use, through the development and industrial demonstration of more efficient and eco-friendly processes. For example, the dry blend requires just an IR dryer with a hot-roll so that the energy consumption is divided by more than two compared to the SOA process.

1.4.2. Main exploitation of the results and dissemination activities

1.4.2.1. Organisation of the work

In order to ensure that the impacts are valorised at the maximum and that its objectives are met, the ELIBAMA project has undertook during the 3 years a series of key steps, centred on the LCA process:

Step 1: Consolidation of the experience of existing Li-Ion battery production and recycling

The consortium brings together major European players in the production and recycling of Li-Ion batteries. As a result the consortium has consolidated this experience into an LCA and cost baseline, suitable for measuring improvement throughout the course of the project.

Step 2: Evaluation and demonstration of solutions to current challenges

Once the baseline has been identified, the combination of industrial partners and research organisations have identified appropriate solutions, aimed squarely at the objectives to improve competitiveness by reducing cost and environmental impact as well as improving recycling. Effective demonstration of these technologies have been run and the potential effectiveness of these solutions have been confirmed by the independent LCA and cost assessment processes.

Step 3: Partners exploitation of results

Once these improved technologies have been demonstrated it is then essential that the partners apply them to their processes. Partners will provide an exploitation roadmap which will demonstrate how and when the LCA benefits will be realised (§ 1.4.2.2).

Step 4: Wider dissemination of results

Wider dissemination of project results is critical both to benefit the broader stakeholder community and also to publicise the results of the project. Effective dissemination has been achieved through the measures described in the § 1.4.2.3

1.4.2.2. Exploitation

The ELIBAMA partners have listed 61 exploitation plans that can be split into 4 different categories.

- ALREADY COMMERCIALLY EXPLOITED FINDINGS

Some of the ELIBAMA findings have already been exploited by the partners.
It's especially the case for:

  - Investments are in progress to improve the LiTFSI electrolyte manufacturing.
  - The improved cells' filling has already been applied and is to be generalized by the project's partners.
  - The cleanliness tools that have been implemented.
  - The improved calendaring system is operational.
  - …

- RESULTS COMMERCIALLY READY TO BE IMPLEMENTED

Some of the projects results are ready to be up scaled but are conditioned by the development of the EV industry. This is for example the case for:

  - The improved LTO manufacturing
  - The anode aqueous based process (that aimed at being used in the future batteries plant)
  - The cells NDT
  - …

- CONTRIBUTION TO STANDARDS

BEV is a brand new industry. Therefore, a strong standardization activity is needed, especially in the batteries field.

ELIBAMA focuses its effort in this domain on the "end of life" period and have proposed different standardization actions in three specific topics:

  - Batteries end of life logistic;
  - Recommendations for the easy dismantling/disassembly of batteries;
  - Standard batteries eco-design for an improved and more efficient recycling.

These actions led to public deliverables that have been made available on the project website (http://elibama.wordpress.com/public-deliverables) that will contribute to batteries design standardization

- IMPROVEMENT EXPERTISE AND KNOW HOW / RESULTS THAT NEEDS FURTHER RESEARCH ACTIVITIES

In addition to these concrete exploitation paths, the ELIBAMA activities also lead to a significant improvement in the partners expertise and know how that give them strong competitive advantages.

This is for example the case for:

  - The improved calendaring
  - The surface inspection tools
  - …

Some of these results also need to be confirmed or improved by additional research activities.

For example:

  - The dry blend coating development will be pursued in another German founded project;
  - The aqueous based cathode activities will be continued next year for a mass production starting from 2016;
  - The NDT basis are already integrated in the MAT4BAT FP7 projects;
  - …

- PATENTS

ELIBAMA activities have generated 7 patents during the scope of the project.

1.4.2.3. Dissemination

Different dissemination media were used during the course of the project:

- Project Website

A project website (**http://elibama.wordpress.com/**) was developed and published during the first months of the project: with more than 35 000 views since its launch, the website provides all the information on the project necessary to the general public and offers a good entrance door to ELIBAMA:

  - Base description of the activities;
  - Key contacts for the project and each partner;
  - News and events information;
  - Project public publications;
  - Stakeholders conference presentations;
  - White paper;
  - …

- Scientific publications

During the course of the project, different partners published 8 detailed technical papers (subject to peer review) presenting the results from this project.

- Partners' corporate publications and events

Partners also used their internal channels such as corporate newsletters to disseminate the project expected results and benefits that their organization could gain from being in ELIBAMA.

During the entire project, partners presented the outcomes of the project (including conceptual prototypes) to their own business clients and local or national stakeholders during commercial meetings and/or showcases organized by their own organization.

- Stakeholder conference

A stakeholders' conference have been organized by the project partners on the 14th of September 2014. It took place in Newcastle upon Tyne and gathered more than 50 attendees from the batteries community.

All the presentations are available on the project's website at the following address:

http://elibama.wordpress.com/stakeholders-conference/

- Participation in external conferences and events

Personal contacts and presentations through attendance at relevant workshops, trade shows, technical fairs and other conferences are ranking top of the list of most popular channels used for the dissemination of project results.

ELIBAMA has catched all the opportunities to attend this kind of events by presenting the project, organizing a booth or simply exposing a poster.

The ELIBAMA project activities have for example been highlighted during last EUCAR Reception and Conference.

- White paper

At the end of the project, the ELIBAMA partners have written and made available a white paper on battery manufacturing processes.

This document is the opportunity to make engineers and research students from Europe discover some of the innovative manufacturing processes technologies developed through the ELIBAMA project.

The white paper has been widely dispatched and is available on the project's website:

http://elibama.wordpress.com/electrodes-and-cells-manufacturing-white-paper/

- Workshops

Cross sharing information between the different projects dealing with BEV batteries is a continuous preoccupation of the ELIBAMA project.

During the course of the project, productive exchanges took place with the eLCAr and the GREENLION teams.

1.4.3. Contacts (website, partners' contacts)

The ELIBAMA public website contains all the useful information regarding the project. It can be accessed at the following address:

http://elibama.wordpress.com/

It especially hosts the **Stakeholders Conference** presentations and the full **Electrodes and cells' manufacturing White Paper** issued by the project

The consortium partners can also be directly contacted using the below information.

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