PROJECT FINAL REPORT

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1.Final publishable summary report

1.1- executive summary

Battery reliability and safety are the key issue for the commercialization of x-EV vehicles, especially for High Energy applications, requiring a large amount of energy stored on board.

HELIOS is a 4 year project to carry out a comparative assessment of 4 types of lithium-ion battery technologies, selected as the most promising technologies being developed across the world: NCA, NMC, LMO & LFP/C. The assessments concern traction batteries for the automotive sector (EV, PHEV & HEV-APU). The work achieved from laboratory testing and other analysis deliver the comparative data covering performance, life, cost, recycling and safety/abuse characteristics.

NCA is the current mainstream manufacturing technology used by SAFT and is therefore the base case against which the other 3 technologies are compared using the same design, same electrolyte and same electrode material. In each case the evaluations are carried out on representative size high energy cells (with a capacity of approximately 40 Ah), produced industrially. In total, up to 220 cells have been employed across the various test activities (safety tests on new and pre-aged cells), cycling (EV and PHEV) and calendar tests (12-15 months).

Post-mortem analysis were also performed at 3 different ageing steps (0, 6 and 12/15 months). The main objective, and not the less, is to evaluate the impact of the cell characteristics on the ageing mechanisms.

The main conclusion under all the results is that no chemistry fulfil all the requirements on the performance, durability, economical and safety points of view. The alternative systems (to NCA commercial and reference one) provide a potential for further improvement and possible application.

It needs to be emphasized that the cells were not manufactured on an industrial scale. It’s expected that optimization of the design & the formulation will overcome the life duration problems and improve significantly the energy density.

However, all these results will give a stronger knowledge base to develop the future Electric and Hybrid / Plug-In Hybrid electric vehicles by the vehicle OEM’s and the supply industry. The end result will give, to decision makers, a clearer view of the potentially effective investments in research, development and manufacture. Furthermore they will contribute to the development of x-EV vehicles and so, too long term benefits for the environment, fuel security and European Union employment.

Lexical :
x-EV : Electric Vehicles, Hybrid Electric Vehicles, Plug-in Hybrid Electric Vehicles.
NCA : Lithium Nickel Cobalt Aluminium
NMC : Lithium Nickel Manganese Cobalt
LMO : Lithium Manganese oxide
LFP : Lithium Iron Phosphate

1.2- summary description of project context and objectives

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. Innovative, safe and with high performance energy storage solutions have to be studied and grow up.

Energy storage is an area of rapidly evolving technology. Lithium-ion has become the dominant rechargeable battery chemistry for consumer electronics devices and is going to become also the most competitive technology for industrial, transportation, and power-storage applications. From a technological point of view, this chemistry provides a high specific energy (Wh/kg) and high energy density (Wh/L) regarding previously popular rechargeable battery chemistries (nickel metal hydride, nickel cadmium, and lead acid battery).

Battery reliability and safety are the key issue for the commercialization of x-EV vehicles.

Objectives and presentation of Helios project :

HELIOS is a 4 year project to carry out a comparative assessment of 4 types of lithium-ion battery technologies, selected as the most promising technologies being developed across the world. The 4 types of positive electrode materials having been selected are :

Lithium Nickel Manganese Cobalt (NMC)
Lithium Manganese oxide - NCA blend (LMO-NCA or LMO-b)
Lithium Iron Phosphate (LFP)
Lithium Nickel Cobalt Aluminium (NCA)

NCA is the current mainstream manufacturing technology used by SAFT and regarded therefore as the base case against which the other 3 technologies are compared. In order to make the comparison easier (changing only one thing at a time: the positive electrode material), electrolyte and negative electrode were kept the same, only adjusting quantities (balancing electrodes capacities and electrolyte quantity) to optimize the cell operation.
The assessments concern traction batteries for the automotive sector (EV, PHEV & HEV-APU).
The work achieved from laboratory testing and other analysis of full sized battery to determine the performance, cycle life and storage life, safety under abuse conditions, volume cost, capability for recycling of material.

The majority of the work was performed at cell level, with some module abuse testing (typically 4 cells). In all cases, the comparative results have been extrapolated to full battery pack size units suitable for complete vehicle. From the results, a recommendation for the future work on electrochemical system was proposed.

Main Results :
The final goal of the investigation is to benchmark the properties of the four different electrochemical systems versus each other and to identify their advantages, disadvantages, risks, challenges.

In order to carry out the testing and analysis work it was necessary to develop procedures for each phase. These documents are available for future use in similar activities:

- Cell specifications applicable to both electric and hybrid electric vehicles (see table1)

	EV battery specification	PHEV & HEV-APU battery specification
Usable energy (kWh)	20	10-12
Peak power (kW)	75 kW (@45 s)	80 kW (@15 s)
Life	>10 y	10-15 y
Voltage (V)	250- 420	250-410
E throughput (kWh)	60 000	50 000
Mass (Kg)	200	120
Volume (L)	125	80

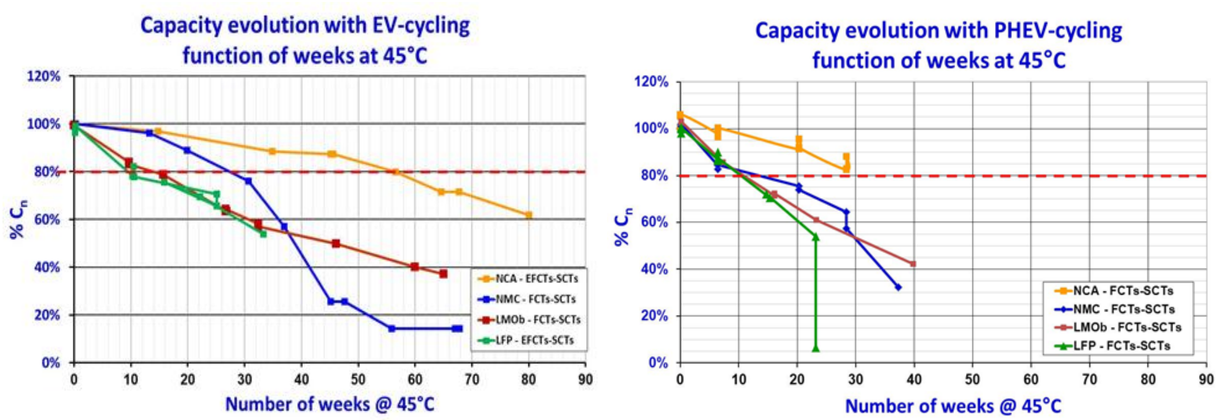
Table 1 : Battery specifications (HELIOS recommendation)

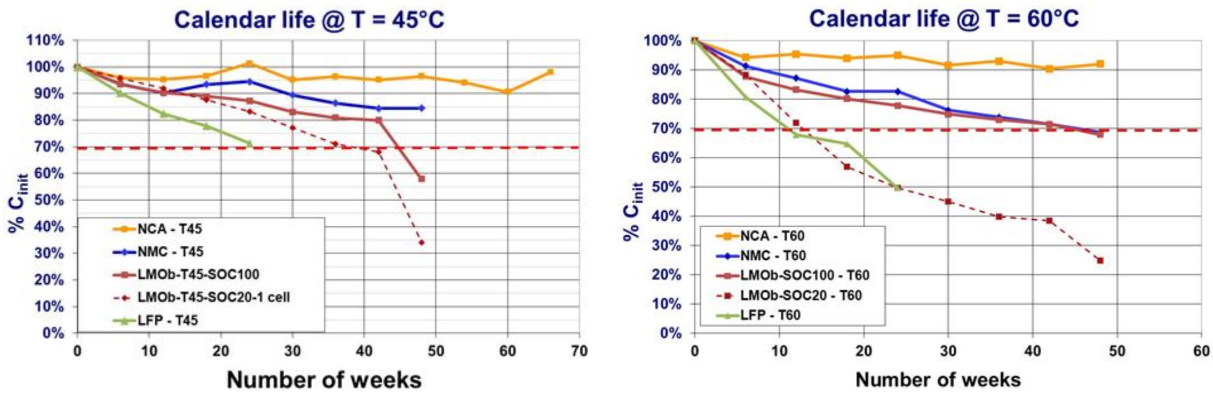
- Performance, cycle and ageing test procedures, with links to other existing procedures available world-wide (see public Deliverable 3.2)

- Safety test procedures for performance under electrical/thermal/mechanical accident or abuse for new and aged cells (see public Deliverable 3.3)

- Procedures and recommendation for handling of used cells and recovery of materials (see Deliverables 8.1 & 8.2).

- Electrical tests show that EV & PHEV cycles defined in the project are the most constraining parameter (concerning the cell capacity decrease, and cells power ability decrease in a less extent). Moreover, temperature seems to be a really predominant parameter influencing the cells ageing, though its influence turned out to be more and more important from storage to EV-Cycling and finally PHEV cycling (see figure 1)





<u>Figure 1</u> : Capacity decrease for the four chemistries tested in Helios project and for four cycling test conditions (PHEV, EV cycling @ 45°C and calendar life @ 45 and 60°C)

NCA and NMC cells show the best performances at 30 and 45°C.

- The safety tests have been performed on 40Ah cells produced by SAFT. Safety is the key point to allow lithium-ion batteries technology to be widely used for electric vehicles. According to the several types of positive active material dealing in the HELIOS project, each of them has not exactly the same performances in terms of specific energy, cycling life time and safety. A review on the chemical runaway mechanism under abuse conditions has been performed and disseminated (see the public deliverable 6.1).

Abusive tests were performed on 40 Ah cells (with new and pre-aged cells).

The three tested technologies could be ranked from the one with the safest behaviour to the lowest as below: **LFP (110Wh) ≥ NMC (140Wh) > NCA (150Wh)**

This ranking is rather close than the one obtained on small cell (NMC ≥ LFP > NCA) and the same obtained after Differential Scanning Calorimetry measurements on pristine and charged materials.

Regarding the abuse tests on 40 Ah module (without taking into account LMO-NCA blend of which capacity is about 28 Ah instead of 40 Ah), crush tests (radial position), nail penetration, short-circuit, thermal stability and overcharge seem to be the most constraining tests.

No technology has a satisfactory behaviour if we consider all the test results at cell level: without BMS (Battery Management System) or casing integration...

- Finally, post-mortem analysis on new, intermediate and final samples showed that :

- Adhesion is one of the main ageing mechanism (but electrode formulations except for NCA were done by labs with low optimisation)
- Dissolution issue with NMC and LFP is activated by the temperature
- Graphite is the limited electrode for the 4 technologies
- for LMO-NCA / Graphite cells, a Mn migration was observed from LMO to NCA particles.

Conclusion and perspectives :

The project is showing significant information on the differences between the 4 cell technologies. This will provide considerable assistance to future R&D and business decision making within the industry. The main results, conclusions obtained within Helios project can be summarized in the table 2:

material level	NCA (SAFT)	NMC	75%LMO-25%NCA	LFP
specific capacity (mAh/g @ C/2)	142	150	110	130
WP6 - thermal tests on small cells (0,5Ah)	3	1	3	1
WP7- economical assessment at material level	4	3	1	2
cell level	**NCA/Graphite (SAFT)**	**NMC/Graphite**	**LMO-NCA/Graphite**	**LFP/Graphite**
	commercial reference	formulation done in research labs with lack of optimisation		
Ah (real capacity)	41	38	28	35
WP2 - post mortem analysis	- adhesion is one of the main ageing mechanism but difficult to evaluate - graphite is the limited electrode			
			Mn migration from LMO to NCA	
WP5 – PHEV cycling (45°C)	1	2	3	4
WP5 – EV cycling (45°C)	1	2	3	3
WP5- calendar (45°C)	1	2	3	4
WP5- low temperature (-20°C@ C/5)	1	3	2	4
WP6 - abuse tests (average on cell tests)	3	2	N/A	1
WP6 - abuse tests (average on cell tests)	crush tests (radial position), nail penetration, short-circuit, thermal stability and overcharge seem to be the most constraining tests.			
WP6 - abuse tests with aged cells	no significant effect (in fact,lower SOH of the aged cells ~50-70% is masking the higher reactivity of aged components)			
WP7- economical assessment at cell level (EV or PHEV)	2	1	2	4
pack level	**NCA/G**	**NMC/G**	**LMO-NCA/G**	**LFP/G**
WP7- economical assessment at pack level in $/kWh(PHEV)	3	1	1	4
WP7- economical assessment at pack level in $/kWh(EV)	3	1	1	4
WP8- recycling	Optimisation depends on volume, battery chemistry, design, investment and labour cost …			

Table 2 : Overview and synthesis of Helios results

The NMC based cells showed a slightly lower capacity than the NCA based cells, but continued material improvement and further adaptations in the cell geometry may lead to an equivalent energy density to the current NCA product. LMO/NCA-blend cells are definitely significantly lower in their capacity. Future activities with respect to an optimization in the mass mixture and the recipe may lead to at least partly compensate this disadvantage. LFP based cells were rather disappointing, particularly with regard to life endurance, linked to water content of positive material electrode (water content of raw material, and many transportation steps). It needs to be emphasized that the cells were not manufactured on an industrial scale. It is expected that optimization with this chemistry will overcome the life problem. Also the capacity of these cells may be further increased without sacrificing their advantageous abuse tolerance. This makes them interesting especially for those PHEVs with a relatively small battery system.

1.3 Description of the main S&T results/foregrounds

conomic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results (not exceeding 10 pages).

The reduction of emissions (CO2, particles …) in the atmosphere is THE challenge of the next decades. The development of electric and Hybrid vehicles will deeply contribute to this objective and to fulfil the CAFE target (Corporate Average Fuel Economy) which is 95 g CO2/Km end 2020.
High level of knowledge and good collaboration between the main actors (car and batteries manufacturers, energy holders but also R&D laboratories) are the key of the success of this development.

By achieving and evaluating new, safer, more efficient and cheaper Li-ion cells, HELIOS will contribute to an enhanced use of low or zero emission vehicles, which will provides citizens better health and better quality of life.

Impact on European Research :

The main objective of Helios project is to gather European car manufacturers, battery manufacturers, research organisations and recyclers with their interdisciplinary skills in order to form a strong collaboration, to generate new knowledge and recommendations that will be implemented in future products.

Six European OEMs, who are the main end-users, were deeply involved in the consortium. Furthermore, there were a very good complementarity and fruitful interaction between partners (industrials, universities, R&D labs and technical Centers).

Scientific and technological impacts and reinforcing European competitiveness :

The comparisons covered in Helios project will be a good support to the automotive industry, research organisations and legislative bodies in their decision making for the future development of electric and hybrid electric vehicles :

- For the end users, having tests procedures for safety and electrical tests, robust and agreed
- Ageing model will give a helpful tool to define the ageing mechanisms

- Selection and evaluation of the most- promising positive electrode materials on safety, performance and economical points of view.

Finally, we can conclude that each of the four Li-ion chemistries have some advantages / disadvantages / risks and opportunities. A compromise has to be done according the technology and the application chosen.

Main Dissemination activities :

The Dissemination activities were conducted throughout the project, from the first year and will go on during the next months to disseminate all the results.

Within the EUCAR organisation, yearly presentation were explained and discussed during the EUCAR program board meetings. A poster was also established and presented during the four last EUCAR conferences. Furthermore, the test procedures developed in the WP3 were introduced and promoted in the Working Group EUCAR dedicated to Battery eVs, and fuel cells eV.

Throughout all the duration of the project, there was a large involvement of the coordinator in seminars & workshop organized by the Green Car Initiative (July, Nov 2012 and April 2013). It was an opportunity to present and share Helios's results and experience with industry, scientific community and the European commission. These meetings promote also widely the dissemination and the sharing between the European projects.

Several papers and talks were also presented in International conferences by Helios partners (batteries 2012, EVS 26 & 27, IWIS …)

The results of Helios will continue to be largely disseminated to a wide community via scientific presentations and dissemination via the public web site and via distribution of the twenty deliverables with Restricted dissemination to selected beneficiaries (scientific community, experts, other FP7 projects …).

-HELIOS provides tests procedures to carry out safety and electrical tests within the project but they can be widely used by similar testing activities. The deliverables are public reports, they are available on the Helios website and they were presented to EUCAR experts working group. The procedures have been also shared with other European projects (ELIBAMA, EUROLIION, AMELIE, EASYBAT …) :

- Cell specifications applicable to both electric and hybrid electric vehicles (see public Deliverable 3.1)

- Performance, cycle and ageing test procedures, with links to other existing procedures available world-wide and characterisation of the cells (see public Deliverable 3.2)
- Safety test procedures for performance under electrical/thermal/mechanical accident or abuse for new and aged cells (see public Deliverable 3.3)

- post-mortem analysis performed in the WP2 are confidential. But an abstract of the deliverable 2.5, resuming the interpretation of the ageing results measured on Helios cells (on electrodes, separators and electrolyte) will be uploaded on the Helios public website to benefit to the scientific community and R&D labs. Based on their experiences, some recommendations were also emphasized to select the right analysis methods and to prepare and handle the samples. In particular, for post-mortem analysis it is important to open the cell under protective atmosphere to avoid any contact with air and moisture and generate “parasite” reactions.

-Development of Procedures and recommendation for handling of used cells and recovery of materials during recycling process (see Deliverables 8.1, 8.2 & 8.3) taken into account economical, Life Cycle Assessment and safety points of view were established. They describe and compare the main process and the best practises. These deliverables have been sent to RECHARGE and EBRA (European Battery Recycling Association) and to EUROLIION project.

-Economical assessment at material, cell and pack level will be also shared with other FP7 projects (AMELIE, EUROLIION…). A specific report, resuming the main results described in the deliverables 7.1, 7.2 and 7.3 has been consolidated and will be sent to main suppliers and shared with other battery’s projects (EUROLIION, AMELIE, ELIBAMA …).

The address of the project public website, if applicable as well as relevant contact details.

http://www.helios-eu.org/

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HELIOS consortium : 18 partners are involved from 6 european countries

6 OEM	CRF
	Adam Opel AG
	Ford
	Volvo
	Renault
	PCA
4 Industries	EDF
	SAFT
	Umicore
	JCHaR
6 Research Institutes	AIT
	ZSW
	CNRS - LRCS
	INERIS
	CEA
	ENEA
2 Universities	RWTH-ISEA & IME
	UU