PROJECT FINAL REPORT

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Project acronym: AUTOSUPERCAP

Project title: DEVELOPMENT OF HIGH ENERGY / HIGH POWER DENSITY SUPERCAPACITORS FOR AUTOMOTIVE APPLICATIONS

Funding Scheme: Collaborative Project (CP) – STREP

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4.1 Final publishable summary report

Executive summary

The aim of AUTOSUPERCAP was to develop supercapacitors of both high power and high energy density at affordable levels by the automotive industry, and of higher sustainability than many current electrochemical storage devices. Supercapacitors are essential in electric vehicles for delivering power in the acceleration phase, which is a considerable proportion of a driving cycle, as well as to recover energy during braking which is also recommended for a sustainable energy and power system of a modern vehicle. A Consortium of nine partners was assembled across the research and value chain of materials, processing, battery fabrication and automotive industries, as well as cost and life cycle analysis. The project objectives in the development of the innovative supercapacitors were fully met covering tested supercapacitor performance levels, estimated cost, sustainability and materials recycling protocols.

Summary description of project context and objectives

The aim of AUTOSUPERCAP was to develop supercapacitors of both high power and high energy density at affordable levels by the automotive industry, and of higher sustainability than many current electrochemical storage devices. There are several issues to achieve a high performance/low weight power system that not only need to be addressed by various groups of scientists and engineers but those issues need to be analysed and processed in an integrated framework. In this project, we have assembled a multidisciplinary Consortium of leading researchers, research organisations, highly experienced industrialists, and highly active SMEs to tackle the problems. Supercapacitors are essential in electric vehicles for delivering power in the acceleration phase, which is a considerable proportion of a driving cycle, as well as to recover energy during braking which is also recommended for a sustainable energy and power system of a modern vehicle. High power and sufficient energy density (per kilogram) are required for both the performance of the power system but also to reduce the requested weight of supercapacitors. Some target performance levels were given in the FP7-GC Workprogramme including 20 kW/kg power density and 10 Wh/kg energy density for supercapacitors while there is also a cost target of 10 €/kW.

The **objectives** of this project were:

(a) To develop different types of carbon materials and structures as electrodes for supercapacitors in combination with different electrolytes and separating membranes, with the aim of a tenfold increase of current maximum energy density while maintaining high power density at least at 25 kW/kg. More specifically, binary carbon structure electrodes were targeted to have an energy density of more than 25 Wh/hr and a power density of 25 kW/kg.

(b) In selecting the best supercapacitor cells for further scale up and fabrication of one or more supercapacitor banks, the selection criteria would be apart from the power and energy density performance, also a cost level of 10 €/kW for large scale commercial production. The objective was to achieve all three criteria.

(c) To perform power system simulations and parametric studies to investigate the effects of a high energy density/high power density supercapacitor on an efficient and sustainable automotive power system, and design a supercapacitor bank to optimise the performance of the power system.

(d) To perform a cost and life-cycle-analysis of the proposed supercapacitors for their applications in electric vehicles to assess the business case, economic and environmental sustainability.

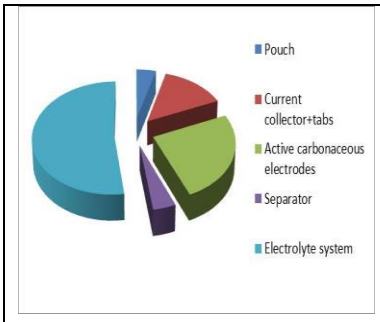
(e) To identify supercapacitor and materials technologies for future exploitation within the chain of materials suppliers, components suppliers, system suppliers and automobile manufacturers.

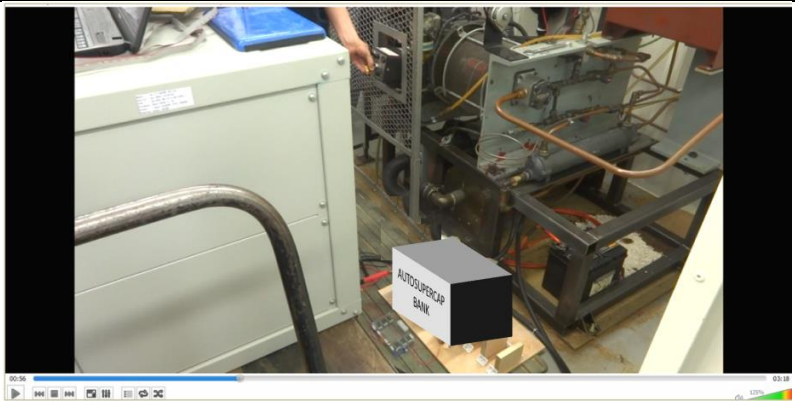
(f) To investigate and develop recycling methodologies and routes for all carbon materials of the proposed supercapacitors.

Project AUTOSUPERCAP was funded at the Call: Sustainable automotive electrochemical storage with Call identifier: FP7-2010-GC-ELECTROCHEMICAL-STORAGE. This Call covered the topics Materials, technologies and processes for sustainable automotive electrochemical storage applications and it was sponsored by Themes 4, 5, 6, 7 and corresponding Green Cars (GC)

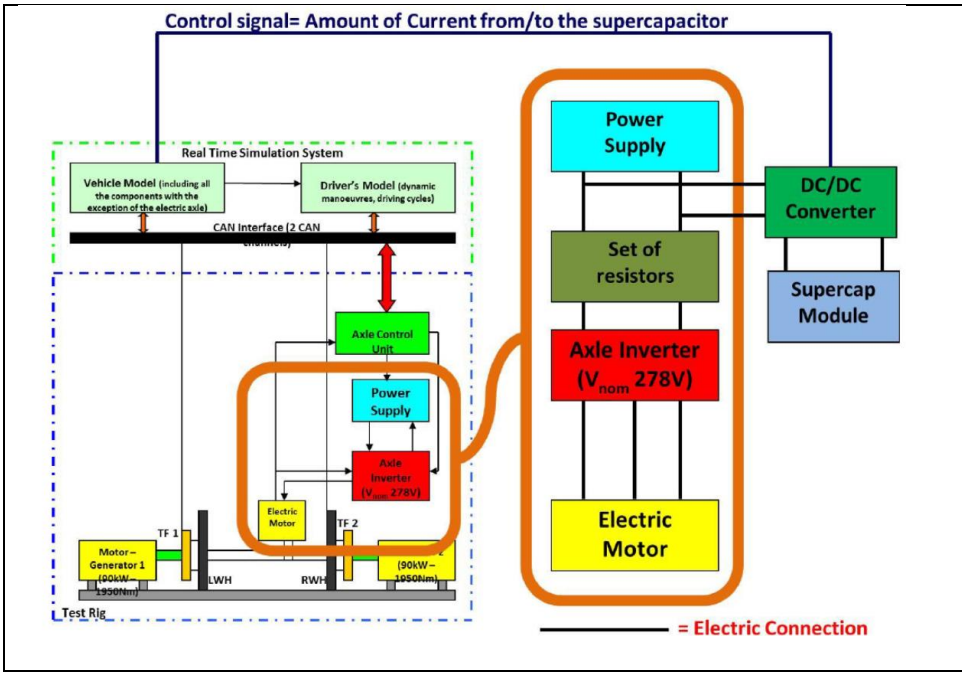
activities/areas: GC.NMP.2010-1, GC.ENERGY.2010.10.2-2, GC.ENV.2010.3.1.3-3, and GC.SST.2010.7-9.

Intensive research was carried out in the area of different electrode materials and their combinations, including novel activated carbon (AC) coatings and activated carbon (AC) fabrics, multiwall carbon nanotubes and graphene, in the area of cellulose-based and synthetic polymeric separators, electrolytes and current collectors. Small cells were fabricated in which our novel electrodes well reached and exceeded some of our project goals, where depending on material and electrolyte, they reached maximum energy density of 25-70 Wh/kg and maximum power density of 60-10 kW/kg, respectively. The proposed various carbon type electrodes were of much lower cost than nickel and cobalt oxides, making our supercapacitors of much lower cost than other energy storage devices.

	On the basis of high performance and low cost criteria, electrode materials combined with organic electrolytes were selected for scaling up of electrode coating and cell fabrication to a pouch cell of pouch face of 12cmx12cm. Such scaled up pouch cells of different mass and size were fabricated and tested successfully at 10A, 50A, 300A, respectively. After intensive and extensive fabrication fine-tuning, the stated energy and power density per electrode mass of the small cells was replicated successfully in the scaled up cells. It is notable that the electrolyte system accounted for about half of the total cell mass in our large pouch cells.

	Subsequently, a supercapacitor bank was constructed using our AUTOSUPERCAP large pouch cells (>300 A) and was tested successfully for consecutive start ups (without recharging) of a 12 V starter motor for a diesel engine. A supercapacitor bank was designed and validated for the specified 12 V TSS (transient start stop) application for a vehicle.

Cost analyses were carried out for the supercapacitor cells at different stages of their scaling up and it was found out that for each of the large AUTOSUPERCAP pouch cells, the estimated cost was in the range of 9.7-43 €/kW where the lower limit is within the project target of 10 €/kW, labour (range in Europe) being the prominent cost component amounting to 35% of the total cost and defining the cost range according to labour rate variations in Europe. Furthermore, the estimated material cost for the AC powder produced by MAST Carbon, using a batch process, are expected to be further reduced when the AC powder production process becomes continuous at large-scale production.

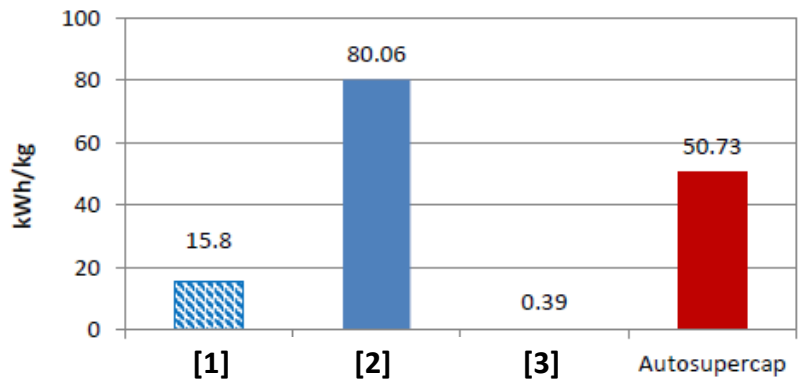


A commercial supercapacitor bank/DC-DC converter was installed in the hardware-in-the-loop EV test rig at the University of Surrey, connected in parallel with the simulated battery power supply, as in the diagram on the left. The system was tested successfully.

Parametric studies concluded that one of the main advantages ***derived from the coupling of a battery and a supercapacitor is the possibility of significantly reducing battery aging, in addition to marginal energy efficiency improvements when the system operates in critical climate conditions.*** The novel controllers comprised a novel Model Predictive Controller and a Dynamic Programming algorithm including a simplified battery aging model in their formulations. The simulation results of the Model Predictive Controller (MPC) and Dynamic Programming (DP) algorithm were compared with the results derived from a rule-based strategy. The rule-based (RB) controller achieved a 67% reduction of the root mean square values of battery current in the presence of supercapacitor across a selection of driving cycles in comparison with the same vehicle equipped with battery only. In the same conditions the battery peak current was reduced by 38% coupled with supercapacitor under the rule-based controller. The model predictive controller and the dynamic programming algorithm further reduced the root mean square value of battery current by a further 6% and 10% respectively in the presence of supercapacitor, whilst the peak values were additionally decreased by a further 17% and 45% respectively. Hence, it was also estimated that the presence of supercapacitor increases battery life by 400-2100%, depending on control strategy and driving cycle.

Hence, we have identified our novel supercapacitor and materials technologies for future exploitation within the chain of material suppliers, component suppliers, system suppliers and automobile manufacturers.

A life cycle analysis of supercapacitors and power systems in automotive applications was also carried out. Recycling protocols for the supercapacitor parts and materials were assembled in a process flow diagram and were tested.



Comparison of energy consumption rates for the production of a Li-ion cell reported in literature and rates used for this study. Dashed blue bars indicate electricity consumption only, whereas solid coloured bars indicate electricity and heat consumption [1]–[3].

References

[1] G. Majeau-Bettez, T. R. Hawkins, and A. H. Strømman, "Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles," *Environ. Sci. Technol.*, vol. 45, no. 10, pp. 4548–4554, 2011.

[2] R. Hischier, M. Classen, M. Lehmann, and W. Scharnhorst, "Life Cycle Inventories of Electric and Electronic Equipment: Production, Use and Disposal," Swiss Centre for Life Cycle Inventories, St. Gallen/Dübendorf, Database documentation 18, Dec. 2007.

[3] D. A. Notter, M. Gauch, R. Widmer, P. Wäger, A. Stamp, R. Zah, and H. J. Althaus, "Contribution of Li-ion batteries to the environmental impact of electric vehicles," *Environmental Science & Technology*, vol.44, no. 17, pp. 6550-6556, 2010.

Description of the main S&T results/foregrounds

First of all the specifications for start-stop applications of supercapacitors were assembled (Table 1) as well as a set of standard tests for automotive applications. The 12 V TSS application was used as the target application for the final AUTOSUPERCAP supercapacitor bank.

Table 1. Requirements based on FreedomCar UC [Deliverable D2.1], also [http://avt.inel.gov/battery/pdf/FreedomCAR_Capacitor_Test_Manual_Sept_2004.pdf]

System Attributes	12V Start-Stop (TSS)		42V Start-Stop (FSS)		42V Transient Power Assist (TPA)	
Discharge Pulse	4.2 kW	2s	6 kW	2s	13 kW	2s
Regenerative Pulse	N/A		N/A		8 kW	2s
Cold Cranking Pulse @ -30°C	4.2 kW	7 V Min.	8 kW	21 V Min.	8 kW	21 V Min.
Available Energy (CP @1kW)	15 Wh		30 Wh		60 Wh	
Recharge Rate (kW)	0.4 kW		2.4 kW		2.6 kW	
Cycle Life / Equiv. Road Miles	750k / 150,000 miles		750k / 150,000 miles		750k / 150,000 miles	
Cycle Life and Efficiency Load Profile	UC10		UC10		UC10	
Calendar Life (Yrs.)	15		15		15	
Energy Efficiency on UC10 Load Profile (%)	95		95%		95%	
Self Discharge (72hr from Max. V)	<4%		<4%		<4%	
Maximum Operating Voltage (Vdc)	17		48		48	
Minimum Operating Voltage (Vdc)	9		27		27	
Operating Temperature Range (°C)	- 30 to +52		- 30 to +52		- 30 to +52	
Survival Temperature Range (°C)	- 46 to +66		- 46 to +66		- 46 to +66	
Maximum System Weight (kg)	5		10		20	
Maximum System Volume (Liters)	4		8		16	
Selling Price ($/system @ 100k/yr)	40		80		130	

In the first phase of the AUTOSUPERCAP project, the development of new materials, and design and manufacturing of new electrodes were tested in laboratory-scale cells of 2-4 cm^2 which were fabricated and tested. Symmetric EDLC cells were fabricated comprising the following components: an outer current collector on each side of the cell, usually aluminium foil; active electrode carbon material; a porous separator sandwiched in the middle. The cells included in this paper were impregnated with an organic electrolyte, e.g. $TEABF_4$/PC or $TEABF_4$/AN solution. The following carbonaceous materials have been tested as active electrode materials: activated carbon (AC) powder (Fig. 1(a) on its own or mixed with conductive additives, such as carbon black or multiwall carbon nanotubes; multiwall carbon nanotubes (MWNTs) on their own or in blends with AC powder at different compositions (Fig. 1(b)); graphene (Fig. 1(c)); activated carbon (AC) fabrics (Fig. 1(d)); sintered activated carbon electrodes on external foil current collectors (Fig. 1(e)).

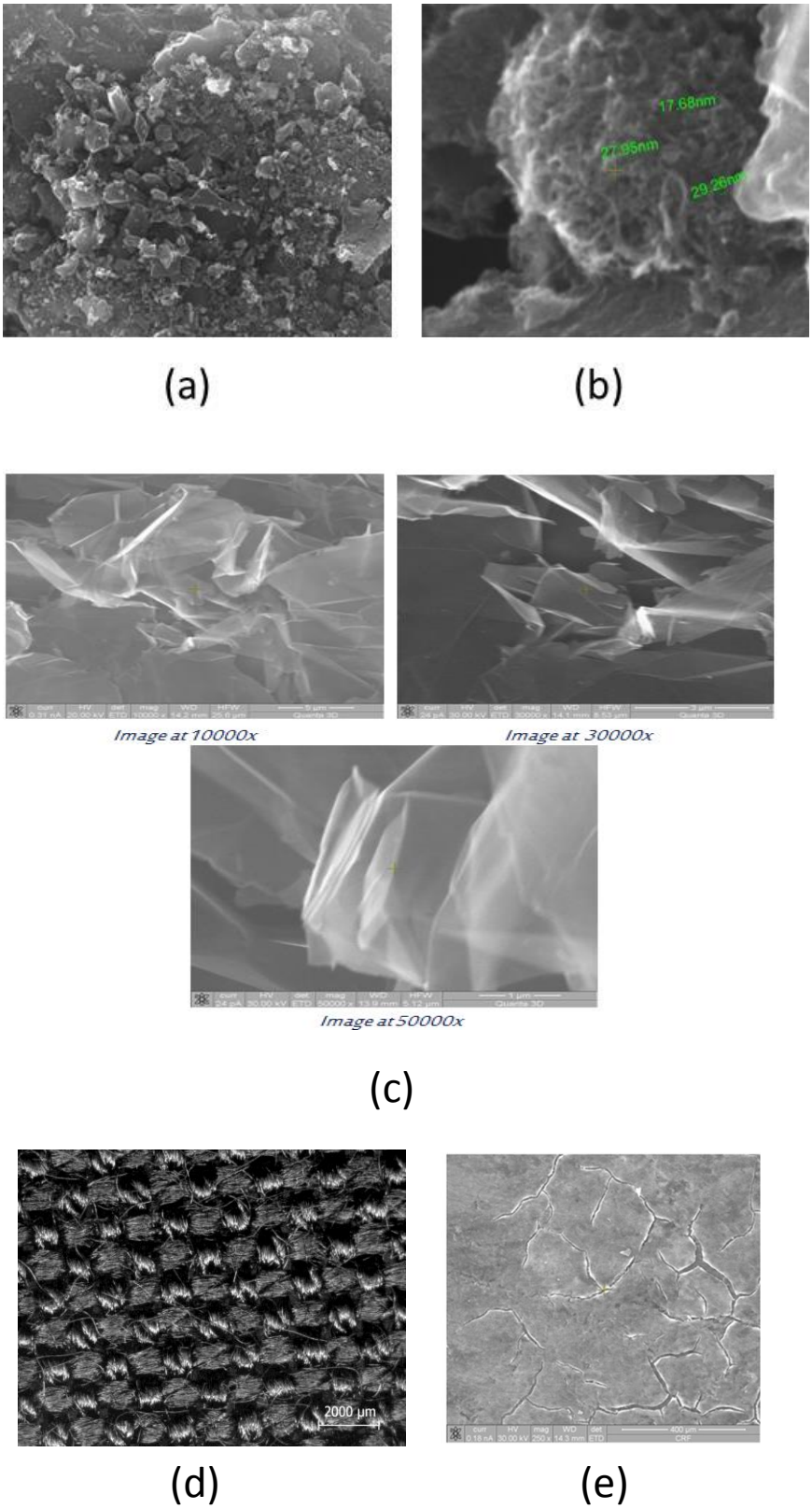


Fig. 1. Examples of active electrode materials: (a) AC powder; (b) AC and MWNT coating with 5 wt% PVDF binder, MWNTs produced by BTS, coating fabricated by University of Surrey and SEM photograph by CRF; (c) graphene from NCSR-Demokritos (d) AC fabric by MAST Carbon; (e) sintered phenolic-derived activated carbon electrodes by MAST Carbon.

A paste was formed from that mixture which was coated to aluminium foil, used as current collector, via a doctor-blade coating technique (Fig. 2).

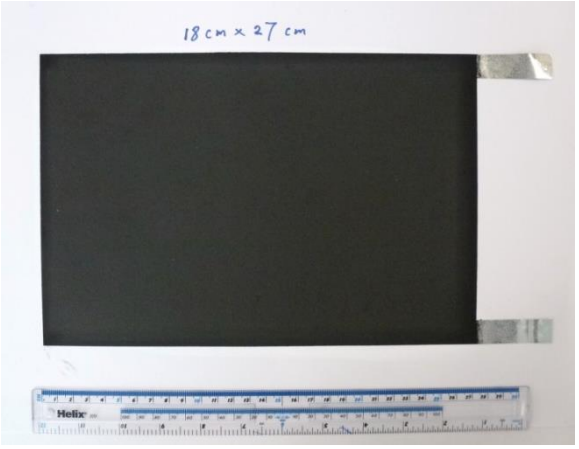


Fig. 2. Active electrode coating on aluminium foil used as current collector, as produced by the University of Surrey.

In the first phase of AUTOSUPERCAP project, small symmetric EDLC cells were fabricated and tested of dimensions of 2 cm^2 or 4 cm^2 for the AC-fabric based cells (Fig. 3).

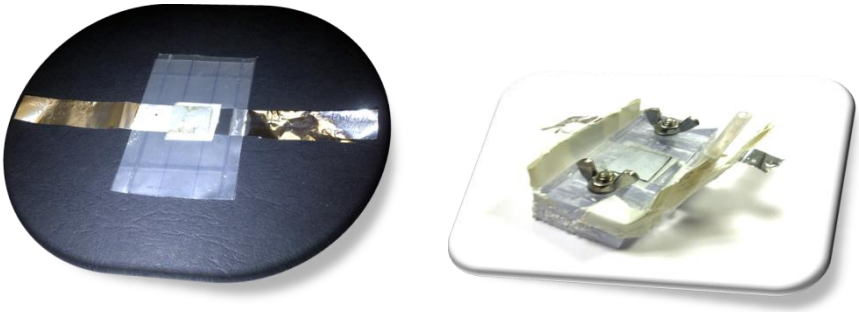


Fig. 3. Small supercapacitor cell testing at the University of Surrey.

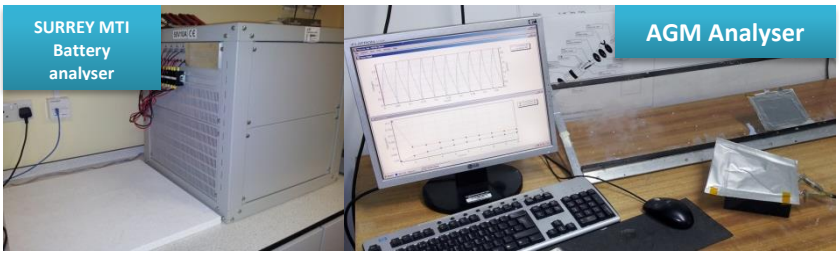


Fig. 4. Some of the supercapacitor testing equipment at the University of Surrey and at AGM Batteries Ltd.

The cells were tested (Fig. 4) in impedance spectroscopy tests (Nyquist impedance plots) in the frequency range of 1 MHz to 10 mHz, cyclic voltammetry in the range of 0-3 V, and galvanostatic

charge-discharge tests at different current densities. From the latter charge-discharge test data, Ragone plots were derived from which the energy density and power density of each type of cell were determined.

Particular efforts were made to produce high quality graphene, fabricate and test graphene-based supercapacitors. Graphene nanoplatelets were produced in different forms and were also functionalised . Although their production and treatment did not always yield graphene of the same consistent quality and BET (specific surface area according to the Brunauer–Emmett–Teller theory**)**, some samples resulted in higher performance supercapacitor cells with organic electrolyte as is shown in Fig. 5.

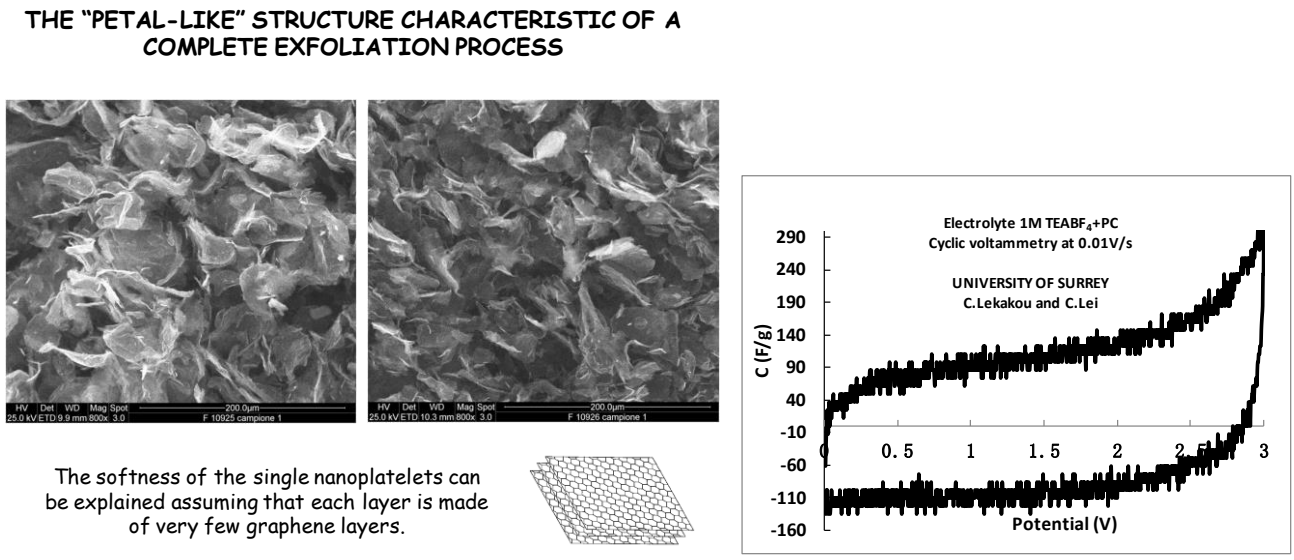


Fig. 5. Cyclic voltammetry test data of graphene-based supercapacitor cells, produced by IMCB-CNR and NCSR-Demokritos, and used by the University of Surrey for further coating processing and cell fabrication and testing.

In general, the small cells fabricated with our novel electrodes well reached and exceeded some of our project goals, where depending on material and electrolyte, they reached maximum energy density of 25-70 Wh/kg and maximum power density of 60-10 kW/kg, respectively. One of the main electrode materials crucial to the high performance of our best supercapacitors was the novel activated carbon (AC) powder developed by MAST Carbon International Ltd. Of course, its combination with other electrode constituents and other components of the cell as well as cell assembly and packaging were also key factors that influenced the cell performance.

The next step was to scale up, fine-tune and optimise the coating process using the pilot-scale coater constructed by the University of Surrey, presented in Fig.6. Pouch cells (Fig.7) were then fabricated of pouch face of 12cm x 12cm where each process in the whole manufacturing and fabrication line was optimised for the tested scaled up cells to successfully duplicate the energy density and power density performance of the small cells.

Fig.6. Pilot-scale coating system at University of Surrey

Fig.7. Coating and example of pouch cell

Pouch cells of different sizes and power were made and tested at 10, 50, and 300 A, respectively. Then a supercapacitor bank was made from the large AUTOSUPERCAP cells and was tested successfully for the 12 V TSS application in successful start-ups connected to the starter motor of a diesel engine. With regards to the specifications of the 12 V TSS application in Table 1, all power and energy specifications limits were achieved and exceeded with 20% mass reduction compared to the weight specification in Table 1. A bank from similar commercial supercapacitor cells would achieve less than half of the required energy of 15 Wh within the specified operating discharge

voltage range of 17 to 9 V, whereas the AUTOSUPERCAP bank achieved the full 15 Wh for this discharge voltage range.

University of Surrey developed their Hardware-in-the-Loop (HIL) test rig (Fig.8) with contributions from Oerlikon Graziano, whose main activity were these modifications in the HIL test rig and the testing activity. The HIL test rig allowed to evaluate the efficiency of the gearbox under load and imposed speed (mission profile) and to characterize the supercapacitors and models developed in the project through a complete electric chain (from wheels to battery / DCDC /supercapacitor) as physical (hardware) and simulated components, without the real complete vehicle. The test rig has a power supply that simulates the battery. A NESSCAP commercial supercapacitor bank (each cell is rated at 4.1 Wh/kg of total mass and 2 kW/kg of total mass, and life of 1 million cycles) and a DC/DC converter system was assembled with the components purchased within AUTOSUPERCAP to simulate the battery-DC/DC-supercapacitor system (Fig.9) for an electric vehicle (EV). The system was tested successfully.

In terms of modelling simulation models of the battery, supercapacitor and controllers were developed by Alberto Santucci (Surrey University) onto the dSPACE MicroAutobox system of the electric drivetrain test rig of the University of Surrey. The battery and supercapacitor models and the hybrid energy storage controller have been uploaded onto the real-time platform dSPACE and have been tested on the electric drivetrain rig during various examples of driving cycles. The results (Tables 2,3) show a reduction of the peak and RMS values of battery current during driving cycles executed with the experimental drivetrain, in case of adoption of the dual-mode energy storage. This confirms the validity of the power split controllers previously implemented by the vehicle system team (in particular, University of Surrey and Oerlikon Graziano) of AUTOSUPERCAP, and the potential benefit of supercapacitors for fully electric and hybrid electric vehicle applications, with existing battery technology.

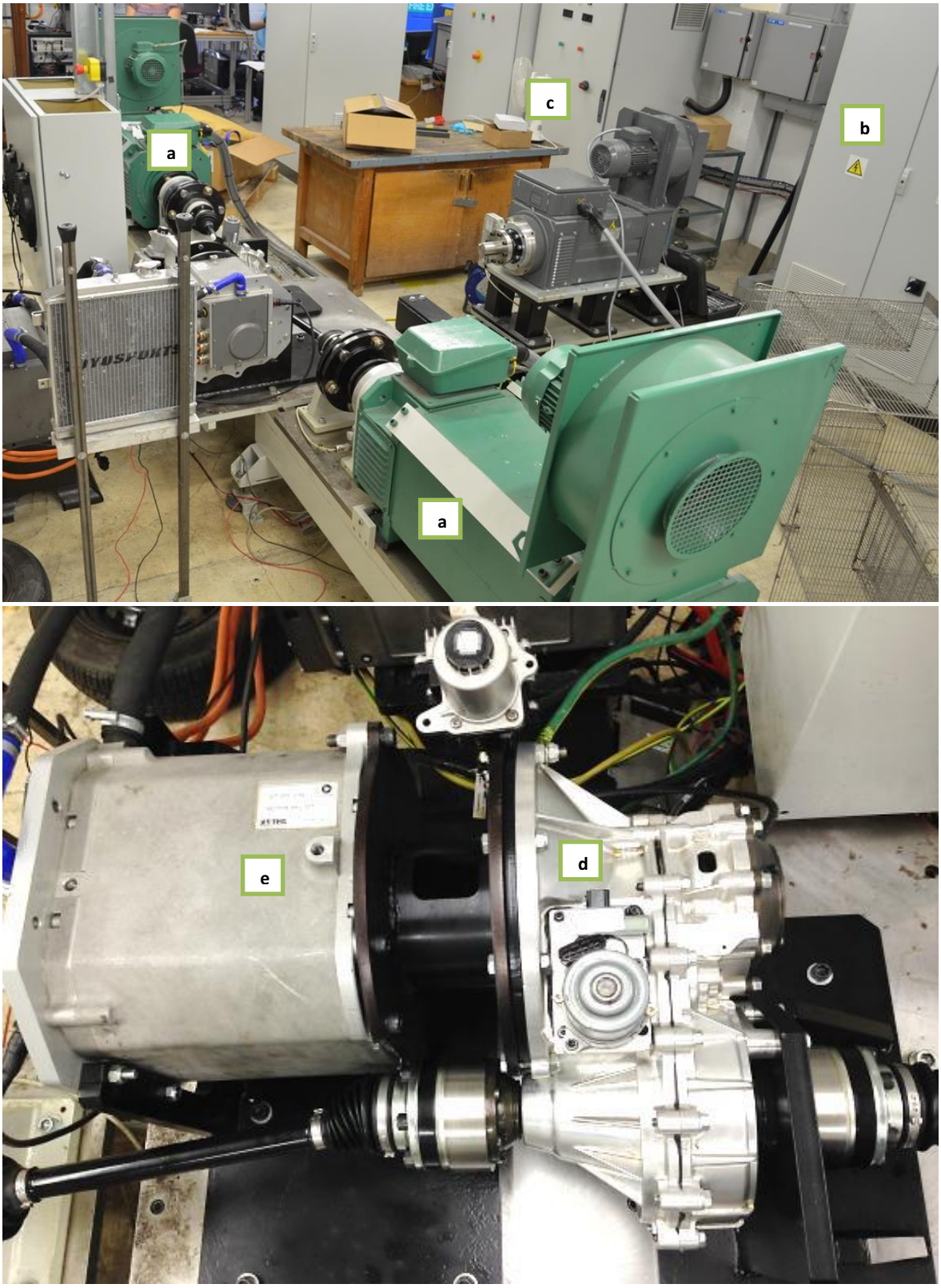


Fig.8. (Top) view of the overall test rig; (bottom) electric motor and Oerlikon Graziano 2–-speeds gear transmission.

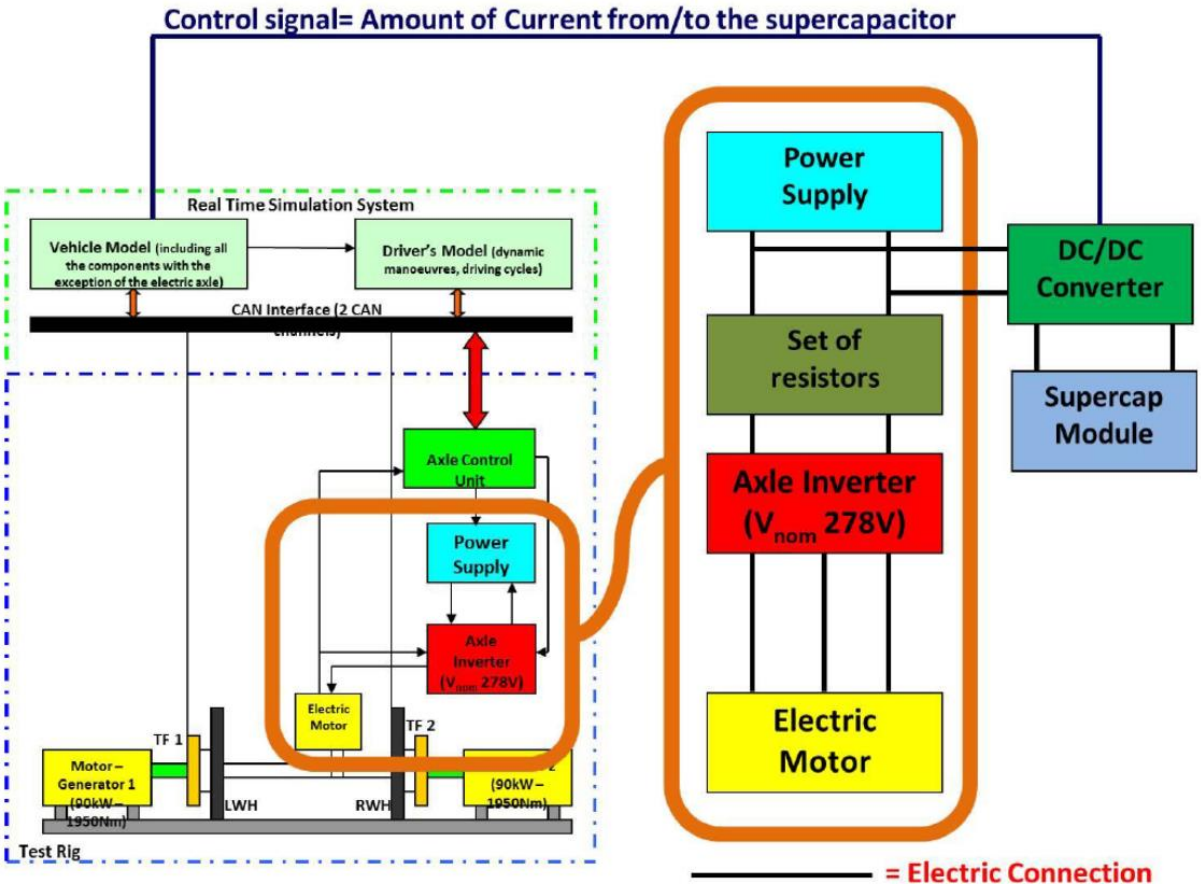


Fig.9. Extended test rig layout

Table 2. Battery stress comparison between NEDC Urban driving cycle with the supercapacitor and without the supercapacitor dur during the experimental driving cycle on the test rig.

HESS systems	RMSIbatt [A]	MINIbatt [A]	MAXIbatt [A]
battery + supercapacitor	13.7	-1.4	35.4
battery	22.5	-36.5	89.3

Table 3. Battery stress comparison between FTP driving cycle with the supercapacitor and without the supercapacitor.

HESS systems	RMSIbatt [A]	MINIbatt [A]	MAXIbatt [A]
battery + supercapacitor	34.6	-14.1	327.4
battery	48.6	-80.5	361.5

Innovative control systems were developed for a hybrid energy storage system, consisting of a battery and a supercapacitor for a through-the-road-parallel hybrid electric vehicle. Parametric studies concluded that one of the main advantages ***deriving from the coupling of a battery and a supercapacitor is the possibility of significantly reducing battery aging, in addition to marginal energy efficiency improvements when the system operates in critical climate conditions.*** The novel controllers comprised a novel Model Predictive Controller and a Dynamic Programming algorithm including a simplified battery aging model in their formulations. The simulation results of the Model Predictive Controller (MPC) and Dynamic Programming (DP) algorithm were compared in deliverable D3.3(b) with the results deriving from a rule-based strategy (presented in previously submitted deliverable D3.3(a)). The rule-based (RB) controller achieves a 67% reduction of the root mean square values of battery current in the presence of supercapacitor across a selection of driving cycles in comparison with the same vehicle equipped with battery only. In the same conditions the battery peak current is reduced by 38% coupled with supercapacitor under the rule-based controller. The model predictive controller and the dynamic programming algorithm further reduce the root mean square value of battery current by a further 6% and 10% respectively in the presence of supercapacitor, whilst the peak values are additionally decreased by a further 17% and 45% respectively. It was also found (Fig.10) that the presence of supercapacitor increases battery life by 400-2100%, depending on control strategy and driving cycle.

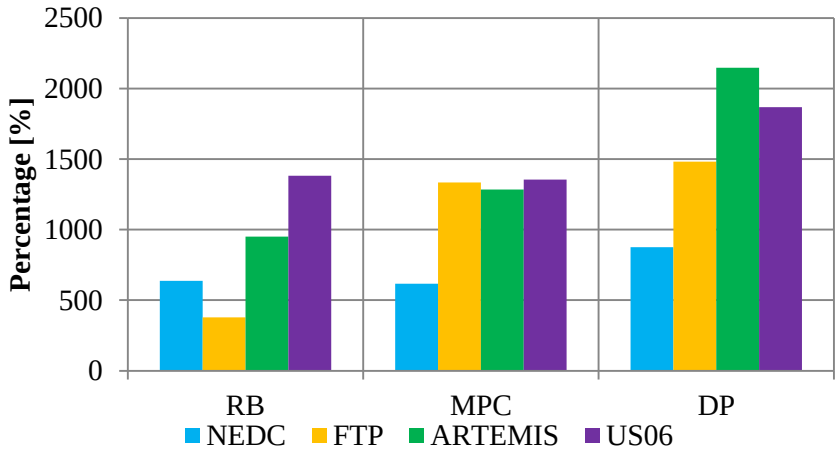


Fig.10. Percentage of battery life increase in the presence of supercapacitor for the different algorithms and driving cycles.

KIT conducted detailed cost analyses for the AUTOSUPERCAP supercapacitor cells at the different stages of their development. Fig.11 presents the evaluated cost structure for the cost of a pilot-scale AUTOSUPERCAP cell: it can be seen that the fraction of materials cost is 6% and energy cost is only 2%, with the biggest component being labour cost at 35%, and other items such as overheads, sales and administration, depreciation, profits after taxes, guarantee, etc. accounting for a significant share of the total cost. Given the variation of the labour rates in Europe (Fig.12), the estimated cost of the pilot-scale produced large AUTOSUPERCAP cell was in the range of 9.7-43 €/kW where the lower limit is within the project target of 10 €/kW. Furthermore, the estimated material cost for the

AC powder produced by MAST Carbon, using a batch process, is expected to be further reduced when the AC powder production process becomes continuous at large-scale production.

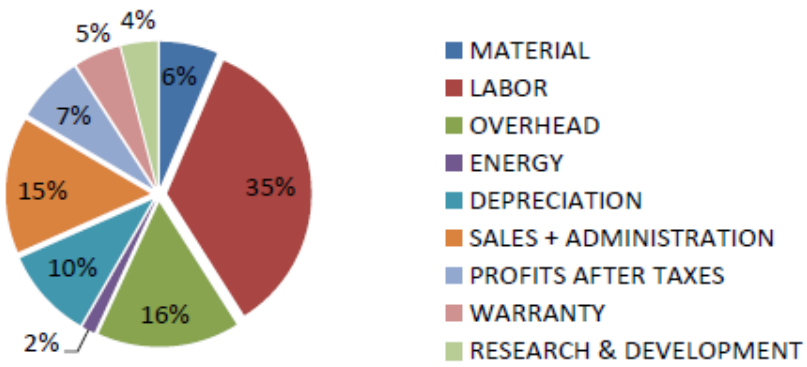


Fig.11. Overview of the structure of total average costs for the production of one AUTOSUPERCAP supercapacitor pilot-scale cell [cost analysis carried out by KIT].

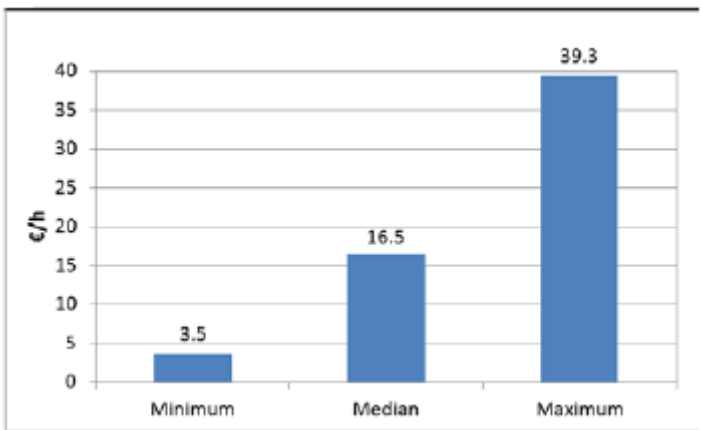


Fig.12. Price rates of labour used for cost calculations [from eurostat, "labour cost levels," Aug-2014. [Online]. Available: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=lc_lci_lev&lang=en.]

A life cycle analysis of supercapacitors and power systems in automotive applications was also carried out. Fig.13 presents the estimated energy consumption for the AUTOSUPERCAP cell and a comparison with estimates from the literature for a Li-ion cell.

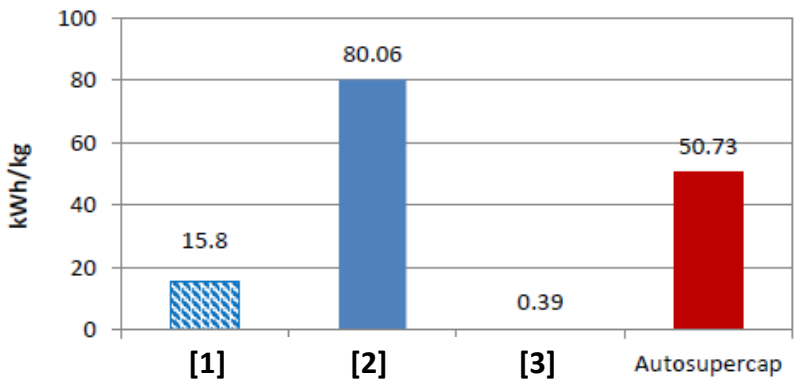


Fig.13. Comparison of energy consumption per kg for the production of a Li-ion cell reported in literature and the energy consumption estimated for the AUTOSUPERCAP cell. Dashed blue bars indicate electricity consumption only, whereas solid coloured bars indicate electricity and heat consumption [1]–[3].

Recycling protocols for the supercapacitor parts and materials were assembled in a process flow diagram and were tested. Conducting the recycling process at laboratory-scale, the carbonaceous material recovery of the recycled 'simulated' supercapacitor before the regeneration step was estimated to be 68%, by taking into consideration that a PVDF-originated compound and $TEABF_4$ recovery was approximately 31.2% (PVDF had suffered changes and in fact it is inappropriate to use the word recovery) and 67.7%, respectively. Finally the carbonaceous material was used to make new supercapacitor cells which were tested in cyclic voltammetry: it was found that the so recycled carbonaceous material does not suffer any additional degradation during recycling which means that it can be possibly used in the fabrication of supercapacitors for automotive applications. Furthermore, separation of high value nanomaterials, such as carbon nanotubes, from the rest of carbonaceous materials (AC carbon) on the basis of differences in their zeta potential has been proposed as an additional recycling step by the University of Surrey.

The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

First of all, the contributions of the project towards **each expected impact in the work programme** are described, followed by additional impacts.

Expected impact 1: Performance and cost targets for batteries and supercapacitor:

Cells were fabricated in which our novel electrodes well reached and exceeded the workprogramme goals, where depending on material and electrolyte, they reached maximum energy density of 25-70 Wh/kg and maximum power density of 60-10 kW/kg, respectively. Indeed, we manufactured supercapacitors with 50% multiwall carbon nanotubes (MWCNTs) in the electrode coating which reached power performance above 100 kW/kg, but lower energy density than our targets. The proposed various carbon type electrodes were of much lower cost than nickel and cobalt oxides, making our supercapacitors of much lower cost than other energy storage devices. The estimated cost of the pilot-scale produced large AUTOSUPERCAP cell was in the range of 9.7-43 €/kW where the lower limit is within the work programme target of 10 €/kW. Furthermore, the estimated material cost for the AC powder produced by MAST Carbon, using a batch process, is expected to be further reduced when the AC powder production process becomes continuous at large-scale production.

Offer of novel supercapacitors in wide range of power and energy densities: As a result of the novel developments in AUTOSUPERCAP, we have developed a number of novel supercapacitors covering a wide range of power and energy densities to satisfy different applications. For example, our novel AUTOSUPERCAP bank for the 12 V TSS application of Table 1 offers more than double the energy available by an equivalent bank assembled using the best commercial supercapacitor cells of similar weight and operating in the required discharge voltage range of 17 to 9 V (without the use of a DC/DC converter). Our proposed pouch cells are designed for both mass and space savings and can be used for automotive but also other applications ranging from electronics to the grid. This means that AUTOSUPERCAP technologies and materials have the potential to make substantial future contributions to the development of EVs, environmentally friendly HEVs (with highly efficient energy recovery), fuel cell-EVs, grid, power-efficient electronics.

Scientific impact to science and R&D European industrial communities: The participation of key European industries in AUTOSUPERCAP with researchers working in the area of energy materials and devices (even when changing companies) and our on-going dissemination of key scientific findings contributed to accelerating the R&D of not only supercapacitors but also batteries and other devices, and related materials, and improvement of the performance of these devices ad materials or viability of some new devices and materials. For example, the inclusion of carbon nanotubes in active battery electrode material by 3M/Germany in paper below:

Vincent L. Chevrier, Li Liu et al "Evaluating Si-Based Materials for Li-Ion Batteries in Commercially Relevant Negative Electrodes", J. of Electrochemical Society, 161(5), 2014, A783-A791. Abstract: **"….**The materials are then evaluated in graphite-containing composite electrodes having high areal capacities (> 2 mAh/cm^2). In a well designed composite electrode including carbon nanotubes, 3M V6 material was found to cycle with little fade and high coulombic efficiency (~99.8%) while maintaining a stable dQ/dV. A composite electrode of equivalent volumetric

capacity with nano Si powder shows similar capacity retention over 50 cycles but an unacceptably low coulombic efficiency (~99.2%)…..”

Expected Impact 2: The expected impact has to be credibly motivated in terms of performance, cost, recyclability and life-cycle sustainability.

Clearly the development of the novel supercapacitor materials and technologies were motivated in terms of performance as extensive laboratory scale and test rig large scale testing took place in this project, coupled with computer simulations of the power system. Cost was also a very important factor and a cost analysis was included in WP10 to give a final cost estimate for each type of fabricated supercapacitor. Selection of supercapacitors to be scaled up to fabricate banks of supercapacitors were carried out primarily on performance and cost criteria. In the meanwhile WP10 included several aspects of life-cycle-analysis (LCA) including environmental (e.g. LCA, fate of nano particles) and economic sustainability (including energy consumption for the production of supercapacitors in an LCA), where the issue of recycling was an integral part of them. KIT-G was the expert partner who led the cost and LCA Workpackage. WP9 focussed on recycling issues and delivered recycling protocols and recycling technologies meeting all objectives of WP9.

Furthermore, the approach to rely exclusively on carbon materials as electrodes in the supercapacitor technologies addressed the issue of noble metals and other rare materials. In particular, Li-Ion batteries require a large projected amount of Li (for the $LiCoO_2$ based cathode electrode) and when compared to the AUTOSUPERCAP approach to use elements like porous and/or large surface area carbon for energy storage, our proposed carbon-based technologies are most attractive and underline the sustainability of our approach. An important advancement of AUTOSUPERCAP is the use of SBR binder in the electrode coatings for the large supercapacitor bank, which means that NMP is not used as a solvent for coating manufacturing anymore but has been replaced by water which leads to a more sustainable process (lower evaporation point of solvent) and reduces health risks for workers.

Expected impact 3: Fostering the constitution of interdisciplinary consortia.

The AUTOSUPERCAP consortium is truly interdisciplinary, because it has partners from the chemical, materials, automotive as well as battery and power fields. This in combination with the academic partners, which bring in competences in materials chemistry as well as system analysis in power systems, makes a consortium which was able to deal with the complex task of turning basic materials into a working automotive power system. Furthermore such competencies have been drawn across 4 European countries with several connections between the various partners already from industrial collaborations and past research collaborations. Furthermore, CRF, BTS and Oerlikon-Graziano are international organisations with wide commercial, industrial and research collaborations.

Expected Impact 4: Establishing the basis for a world level European automotive battery and electrochemical capacitors industry

The AUTOSUPERCAP Consortium includes industrial partners across the full value chain, including materials (MAST Carbon, BTS), battery manufacturing (AGM), automotive systems

manufacturer (Oerlikon Graziano), automotive user (CRF). Two large automotive organisations CRF and Oerlikon-Graziano participate in the AUTOSUPERCAP consortium as well as two SMEs: MAST Carbon International Ltd, a key player in the development of activated carbon electrode materials who intends to exploit further MAST's development of these high performance supercapacitor electrode materials with more alliances and promotion of the technology to higher TRL; AGM Batteries Ltd, an SME with increasing activities in the R&D and scaling up area who intends to exploit the supercapacitor manufacturing technologies for automotive applications. Furthermore, the R&D in AUTOSUPERCAP has made significant advancements for the establishment of industry of supercapacitors for automotive applications in Europe.

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