ObservatoryNANO

Nanotechnology and electric vehicle batteries

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Executive Summary

Electric vehicles are a great opportunity to increase Europe's transport energy efficiency. They can be up to three times more efficient compared to their internal-combustion-engine counterparts. They are also able to significantly reduce the environmental impact of the transport and even reduce the oil dependency of Europe.

The xEV battery market is currently virtually all Nickel Metal Hydride technology. However, the development tends to push to a shift in technology towards Lithium-Ion, which offers numerous advantages over NiMH. The term "Li-Ion" does not refer to a single technology but to family of chemistries, each of which has its own characteristics in terms of energy, power, cost, lifetime and safety.

For now, no battery chemistry meets all of the needed criteria for xEVs. There are still many technological barriers to overcome in order to produce vehicles that can work with the same performance of today's cars and a price that can be accepted by the customers. However Li-Ion chemistries have the potential to meet the needed requirements in the near future.

Nanotechnology can have a role in this development. Enhanced electrolytes, cathode nano-coatings or nano-size particle containing anode composite materials are just few examples of how nanotech research can improve specific attributes of future lithium batteries.

Introduction

1.1 General overview

Electric vehicles (EVs) are those that use for their propulsion one or more motors powered by electric energy. By definition, electric vehicles include e-bikes and scooters, electric cars, buses or even trucks.

Electric mobility is increasingly important because of its potential to reduce Europe's transport-related CO_2 emissions and the oil dependency from third countries. Transport is responsible for 23-26% of all greenhouse gas emissions and also requires around 70-75% of all the oil consumed in Europe. Reducing this figure would reduce the effect on the environment and on citizens' health, increase the energy control of the countries and enforce the national economy (for USA it is estimated that a 10% reduction of oil imports and a consequent increase in domestic energy production (coal, nuclear or renewable) would add at least $60 billion to the economy[1]). It is worth mentioning that in 2008 EU-27 countries had to buy 53,8% of the total energy they consumed[2].

Basic principles for vehicle batteries

As the battery is the critical component in the electric vehicles powertrain and the main topic discussed all along this report, it is therefore important to include some reminders about battery working principles.

A battery is a device that stores electrical energy in chemical form. It generally consists of a negative electrode (the cathode) and a positive electrode (the anode). The electrodes, necessarily made from different materials, do not touch each other but are electrically connected by the electrolyte, which can be either solid or liquid. In many cells, the materials are enclosed in a container, and a separator, which is porous to the electrolyte, prevents the electrodes from coming into contact. Two states occur in rechargeable batteries: charging and discharging as shown in the following figure.

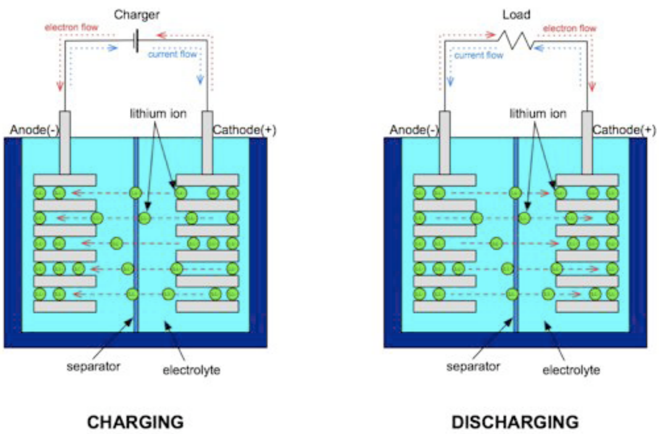


Figure 1: Working principle of a Li-ion battery[3]

As shown in the above graph, charging corresponds to the state where electrons are pumped from the cathode to the anode. Positively charged lithium ions move from the cathode through the separator via the electrolyte to the anode. During discharging, positively charged lithium ions move from the anode through the separator via the electrolyte to the cathode. Electrons move through the external load from the anode to the cathode, resulting in a current that provides power to the load.

There has been constant progress in materials from compact rechargeable NiCd (Nickel-Cadmium) batteries to NiMH (Nickel-Metal-Hydride), Li-ion (Lithium-Ion) and Lithium-polymer. This evolution corresponds to an improvement in the power output and in the speed of the discharge/recharge cycles.

Current battery technologies allow combining them into modules, which including with power electronics and control systems constitutes the battery-pack of electric vehicles. The battery module consists of several batteries in series-parallel, parallel-series or matrix arrangements, as shown in following figure. Series connections between cells provide voltage capacity whereas parallel connections provide current capacity. The battery pack's voltage specification is dictated by the system design. The battery pack's power and energy specifications are dictated by the vehicle's acceleration and range requirements.

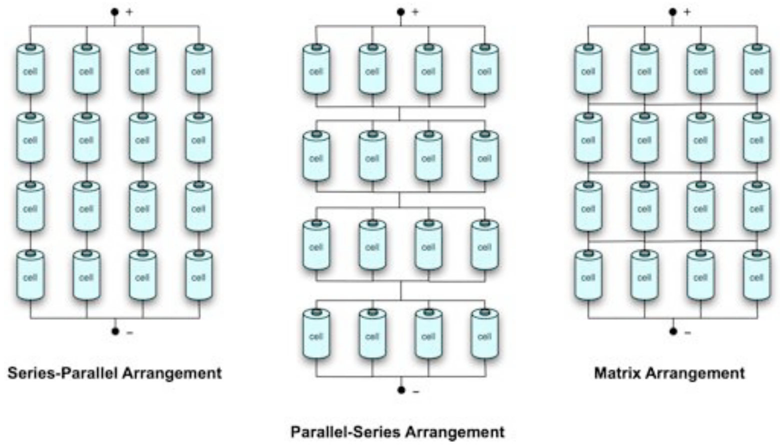


Figure 2: Different arrangements of batteries to form a module

Types of electric vehicles

According to the extent to which they use electrical energy (always compared to the use of the internal combustion engine - ICE), electric vehicles are classified in three major categories. The general term we will use to refer to all three types is 'xEV'. The battery to be selected for the vehicle could be slightly different from one type to another.

1. The first type of electric vehicles is HEVs (Hybrid Electric Vehicles) that uses batteries to boost the fuel efficiency and that still possess a sizeable ICE (Internal Combustion Engine). This is the type of electric vehicle that is currently the most developed. The recharging of the batteries is possible only by driving the vehicle. Three subtypes of HEVs can be distinguished:

    - Micro HEVs where the battery pack does not provide any additional torque to the engine; but instead is used to provide auxiliary power, manage engine start/stop (stop of the engine during idle, and instantly start when the vehicle is required to move), and (in some vehicles) absorb energy from regenerative braking. They allow saving from 5 to 15% of the fuel. They mainly operate on lead-acid, advanced lead-acid and NiMH batteries.
    - Mild HEVs where the Batteries perform the same tasks as in a micro-hybrid, but also provide some additional torque to the engine, which is never the sole source of propulsion. They allow saving from 15 to 30% of fuel. They mainly operate on NiMH batteries.

- Full HEVs where Batteries perform the same tasks as in a mild hybrid, but where the electric motor is sometimes the sole source of propulsion. They allow saving 40 to 50% of fuel or even 100% when driving only on battery power. They mainly operate on NiMH and Li-ion batteries.

2. The second type of vehicles is all-EVs or PEVs (Plug-in Electric Vehicles). They are powered solely by electric drivetrains. The batteries can be charged via an external cable plugged into the power grid and via regenerative braking. They have no ICE at all so the fuel saving is of 100%. The mainly operate on Li-ion batteries.

3. The third type of vehicles is PHEVs (Plug-In Hybrid Electric Vehicles). They lay in-between HEVs and EVs: they possess ICE but more powerful battery packs than HEVs. The batteries of those vehicles can be charged either via an external cable plugged into the power grid, via the ICE and a generator or via regenerative braking. They allow saving from 55 to 85% of fuel. They mainly operate on Li-ion batteries. Two subtypes of PHEVs can be distinguished:

   - Series PHEVs where the electric drivetrain is in a series configuration with the ICE drivetrain. The electric motor spins the wheels, while the ICE only charges the batteries when depleted. They are also known as an extended-range electric vehicle, or EREV.

   - Series-Parallel PHEVs where electric drivetrain is in a series/parallel configuration with the ICE drivetrain. They can operate in all-electric mode, gasoline mode while recharging the batteries or any combination. The power is split between the ICE and the electric motor to optimize efficiency and minimize overall consumption.

Main differences between Internal Combustion Vehicles and Electric Vehicles

The change to an electric powertrain affects an important part of the complete vehicle. The engine and the drivetrain will have to change (or even disappear), while auxiliary systems, such as the HVAC (heating, ventilation and air-conditioning) will have to be redesigned for electric cars.

Comparing with ICE vehicles, the three main systems that change in the electric vehicles are:

- **Battery pack and energy management system:** Replacing the oil tank by the battery implies a whole new systems including the battery and also the related systems to control the temperature, manage the recharges, control the energy content, etc. Most of these electronic systems will be integrated in the battery-pack, which will be customized for each vehicle depending on the OEM preferences and the vehicle's expected use.
- New architectures: The differences in size and requirements between batteries and oil tanks and between internal combustion engines and electric motors bring new possibilities to vehicle designers. From essential changes in the appearance, for example a shorter front module, to complete futuristic designs, such as foldable cars (Hiriko), many different architectures are presented in the EV prototypes.
- Electric traction system: The new powertrain system implies the introduction of many new electric components like motors, inverters, etc. Several layouts are being developed, characterized by the number and final position of the motors: (a) 1 central electric motor, (b) 2 smaller near-wheel motors (c) 2 in-wheel motors (d) 4 in-wheel motors. The electric traction system has many

advantages compared to ICE, such as high efficiency and reduced or smaller parts, for example using a single-ratio gearbox. New systems to avoid electromagnetic incompatibilities and hazards from the powerful electric components will have to be specifically designed and included.

There are also some emphasised trends for the electric vehicles, of which the most important ones are lightweight design and electric efficiency. Automotive experts argue that the weight has a direct effect in the range of the electric vehicles, suggesting that the vehicle's mass has to be reduced as much as possible (e.g. redesigning the parts, using light metals or composites). Furthermore, all electric devices competing with the motors for the battery energy (e.g. A/C, navigation, entertainment, lights, etc.) will have to be extremely efficient in order not to decrease the driving range significantly.

1.2 Keywords

Electric vehicles, nanotechnology, hybrids, lithium-ion batteries, electric powertrain, power, energy, cost, lifetime, safety, anode, cathode, electrolyte, electrode

1.3 Methodology

The content of this report is the result of a desk analysis of information from publicly available documents. For an analysis of the present status, future visions and economic perspectives of nanotechnology, expert interviews either personally or via on-line questionnaires were also carried out (These answers to the future predictions and future products are at least regarded as a good indicator of future developments from the present point of view). The final conclusions were also crosschecked with well renowned experts.

The final version of the report was reviewed by a pool of experts selected based on their background and experience.

Chapter 2 S&T Aspects

The main S&T limitations for EVs are the batteries. The developments to reduce the cost while improving the energy content and power of the current batteries will very much affect the performance of the vehicles and therefore their market acceptance.

In the field of electric vehicles, the battery performance requirement differs very much from portable devices: energy and power are much higher, lifetime is longer and cost has to be very controlled. New developments need then to be implemented. Nanotechnologies have the potential to bring some improvements.

2.1 Requirements

Several parameters should be taken into account to validate the use of battery in automotive.

1) ENERGY
The specific energy is the energy capacity per unit of mass (Wh/kg) whereas the energy density is the energy capacity per unit of volume (Wh/l). The battery energy translates into vehicle range, considering the vehicle's consumption. High energy is needed to provide adequate range within weight and space constraints.

2) POWER
The specific power is power capacity per mass (W/kg) whereas the power density is the power capacity per unit of volume (W/l). The power translates into torque and acceleration. The energy and power required will depend on the type of electric vehicle considered. HEV mostly require high-power battery, PHEV mostly require power battery and EV mostly require high-energy battery.

3) COST
Cost is most often discussed in per-energy (€/kWh) and per-power (€/kW) terms, with significant differences comparing cell-level vs. pack-level data. Battery packs represent 50% to 80% of the drivetrain costs depending on the kind of electric vehicles considered. These drivetrain costs themselves represent from 65% to 75% of the total cost of the vehicle. Reduction of the battery cost is fundamental to provide consumers with a cost-efficient car. For now, the cost of the battery is around 600 to 800 €/kWh and should be reduced to at most 250 €/kWh by 2020.

4) LIFETIME
It is considered in terms of calendar-life and cycle-life. Cycle-life can be defined as micro-cycles (small changes in state of charge) and/or full-cycles (full discharge/charge). The state of charge (SOC) is correlated to the depth of discharge (DoD) – deep discharges tend to reduce the capacity of the battery faster than shallow ones. HEVs operate in charge-sustaining mode and require sufficient micro-cycle lifetime. EVs operate in charge-depleting mode and require sufficient full-cycle lifetime. PHEVs have perhaps the most difficult requirements, requiring both micro- and full-cycle lifetimes. All vehicles require a calendar life of 10-15 years.

5) SAFETY
Safety relates to: operating temperature range, heat generation, response to overcharging, short circuit, mechanical damage, etc. Safety is a very important parameter as battery failure in automotive applications may result in serious vehicle damage or human injury.

The following table summarises the performance requirements for batteries for the three electric vehicle types.

	Power - P	Energy - E	P/E ratio	Behaviour at Low T	Cycle life	Calendar life	Cost	Safety
HEV	1-2 kW/kg	<100 Wh/kg	>20	-30°C cold cranking	500.000 cycles shallow cycling	15 years operating life	low	high
EV	-	>120 Wh/kg	2 - 3	-	3.000 cycles to 80-90% DOD	>10 years	< 300 $/kWh (2020)	high
PHEV	-	100-150 Wh/kg	5-15	5C charge at -30°C	5.000 deep cycles + 500.000 cycles shallow cycling	>10 years	low	high

Methods for improving EV batteries are:

To increase energy density, it is possible to increase the cell voltage but it will compromise lifetime & safety. It is also possible to thicken electrode materials but then the power capacity is reduced. New electrode nano-chemistries could be developed, while keeping the cost at an acceptable level.

To increase power density, it is possible to slim down electrode materials but it reduces energy density. Another solution requires the use of nanomaterials to increase surface area of electrodes, although it impacts cost. Alternatively it could be possible to operate at high rates of discharge, which has the limitation of decreasing that lifetime and safety.

To reduce cost, the most obvious solution is the use of inexpensive electrode materials but then it leads to the reduction of energy, power, lifetime or safety. The cost reduction could also be obtained thanks to inexpensive packaging and safety mechanisms but this can pose a safety risk. The development of new manufacturing processes is also possible but it is a single-impact solution, not improving the other goals. Scaling up production should allow manufacturing economies without adverse impact on the other goals. For this, nanotechnologies applied to batteries have to be ready-to-scale when the market matures.

To increase the lifetime, advanced anodes based on nanomaterials are developed; they tend to be safe but their current cost is high. Limiting energy and power density is also a solution. On one hand, operating the battery within a small state-of-charge window effectively limits energy density but also increases the total cost. On the other hand, operating the battery at reduced rates of discharge effectively limits power density.

To increase safety, new electrode materials specifically to replace the graphite anode are under development. They can also improve lifetime, but the cost remains high. As previously mentioned, limiting energy and power density is also a solution but it brings the same pros and cons. An obvious solution is then to add internal safety devices and external control systems, even if it can significantly impact cost. Alternative or semi-solid compositions (using nanotechnology) are also being investigated as solutions for increased safety.

As described above, nanotechnology can have a big impact in the batteries of the electric vehicles. However, nano-enabled parts and systems can also improve the performance in the rest of the vehicle: nanostructured metals, polymer nanocomposites and nano-enhanced power electronics and sensors can contribute to many vital aspects in the vehicles such as energy efficiency, weight reduction, improved communications and control.

2.2 State of R&D and nanotechnology impact

2.2.1 Batteries

As explained in the previous section, energy, power, cost, lifetime and safety criteria should be considered in order to evaluate the performance of a battery regarding its use in electric vehicle. Unfortunately, no current technology meets all the goals. In summer 2008, Rocky Mountain Institute proposed a summary of the most common battery technologies and their performance regarding the previous criteria. It also indicated at which level of development those technologies were.

			Energy	Power	Cost	Lifetime	Safety	State of development	Notes
Chemistry		Pb-Acid	Extremely limited energy density	Very limited power density	Very low cost.	Proven cycle and calendar life for conventional vehicles, but not adequate for xEV applications	Proven record of safety. Environmental impact mitigated by extensive lead recycling infrastructure	Mass Commerci-alization	Very well understood technology with proven reliability, safety, & cost for ICE vehicles, but little chance of usefulness for xEV applications
		Ni-Cd	Very limited energy density	Limited power density	Relatively high cost with little room for reduction	Good cycle and calendar life	Proven safety record in consumer electronics. Cadmium is toxic	Mass Commerci-alization	"Memory effect" if not fully discharged. All but abandoned due to short comings compared to NiMH and Li-Ion
		NiMH	Limited energy density	Limited power density	Limited prospects for cost reductions	Proven longevity for calendar and cycle life	Proven history of safety	Mass Commerci-alization	Mature technology with little room for further improvements in energy, power, and cost
	Li-ion	$LiCoO_2$ / Graphite (LCO)	Good energy density	Good power density	High: cost of cobalt is a limiting factor for cost reduction possibilities	Cycle life is suitable for consumer electronics, but poor for automotive applications	Low to moderate: thermal runaway problems would be disastrous in automotive applications	Commerci-alization	Most common chemistry for consumer electronics, though may not be suitable for automotive applications
		$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$ / Graphite (NCA)	Good energy density	Good power density	Moderate: limited cost reductions due to use of cobalt and nickel	Good cycle life and calendar life	Moderate: nickel-based electrodes are thermally unstable and degrade at high states of charge	Pilot	Other similar chemistries are being developed to mitigate safety and cost concerns
		$LiFePO_4$ / Graphite (LFP)	Moderate energy density	Good power density	Low: one of the least expensive Li-Ion chemistries due to iron based cathode	Good: can be operated at wide SoC window and still achieve good cycle life	Moderate to good: stable cathode material does not release oxygen, but graphite anode still reactive with electrolyte	Pilot	May be one of the most promising chemistries, due to advantages in cost, safety, & cycle life
		$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ / Graphite (NCM)	Moderate to good energy density	Moderate power density	Moderate: limited cost reductions due to use of cobalt and nickel	Poor cycle life	Moderate: nickel-based electrodes are thermally unstable and degrade at high states of charge	Pilot	Similar to NCA, intended to be cheaper than NCA. Capable of high cell voltage
		$LiMn_2O_4$ / Graphite (LMS)	Moderate energy density	Moderate power density	Moderate: low cost per kg, but cost per kWh limited due to limited energy density	Moderate to excellent: potential for above-average cycle life, calendar life may have issues	Good: manganese-based electrode material is potentially safe	Developmental	Manganese dissolves in electrolyte, reduces at anode, reducing cell performance

		$LiMn_{1.5}Ni_{0.5}O_4$ / $Li_4Ti_5O_{12}$ (MNS)	Moderate energy density	Good power density	Moderate	Unknown	Excellent	Research	Promising technology which solves many of the problems associated with LMO batteries
		$Li_{1.2}Mn_{0.6}Ni_{0.2}O_2$ / Graphite (MN)	Excellent energy density	Excellent power density	Moderate	Unknown	Excellent	Research	Highest capacity chemistry developed at Argonne
	Zn-Air		High energy density	Limited power density	Low cost (driven by cost of zinc)	Long life for mechanically rechargeable type. Life unknown for electrically rechargeable type.	Very safe in storage, use and disposal	Commerci-alization	Typically not rechargeable except mechanically by replacing zinc in anode. Electrically-rechargeable zinc-air batteries are in research phase.
	NaNiCl (ZEBRA)		High energy density	Limited power density	Moderate cost, though potentially high cost due to use of nickel.	Low cycle life	Very safe components, safe in operation and disposal	Pilot	Requires high temperature (270°C) to operate correctly.

Nanotechnology could play an important role in achieving certain performance goals.

Graphite powder is traditionally used on the negative electrode as intercalation material for lithium ions. Replacing the micrometer-sized particles by nanometer sized carbon materials would increase the rate of lithium insertion/removal and thus the rate (power) of the battery. Graphite nanoparticles such as carbon nanotubes could bring this positive effect. Nevertheless these materials display high surface areas that seem to led to a decrease of the cell efficiency and to high safety concerns due to surface phenomena, such as excessive lithium deposition at the surface of the nanoparticles.

On the contrary, nanowires made of TiO_2 or even tin or vanadium oxides, seem to be as promising as negative electrode materials.

Most current materials and battery technologies used in various applications, even if they respond to a part of electric vehicle battery requirements, are unlikely to fulfil them all. Rechargeable lithium batteries seem to be the best solution for electric vehicle applications until now.

Nanotechnology, among other technological improvements, can create valuable properties to complete the performance of specific materials or systems. Nevertheless, nanotechnologies are not de facto the best compromise. Structuring a material at nanoscale decreases its volumic weight, which is a drawback for automotive application. Increasing the specific surface of a compound makes it unstable, especially at electrode of batteries. This degrades its safety characteristics, which is a dominating criterion in this sector.

Nanotechnologies are often considered as a means to improve existing compounds already displaying interesting properties. In this frame, their positive contribution has to be precisely measured.

An important compromise under research is between capacity improvement and safety, which are two main parameters for automotive applications. Energy of the battery can be increased by increasing the voltage of the positive active material, resulting in reduced system stability. Current commercial oxide materials are promising, but most of them involve high costs or safety limitations. $Li(NiCoAl)O_2$, $Li(NiMnCo)O_2$, $LiMn_2O_4$, $Li(AlMn)_2O_4$ or $LiCo_2O_4$ are good examples of such compounds. Nanostructuration of these materials would improve their intercalation capacity (and therefore their lifetime[4,5]). For example, lamellar $Li(Ni,Mn,Co)O_2$ type is extensively studied to better define the structural and transport properties and the improvement of performance of the electrode compared to the un-layered system[6,7,8]. It also increases the reactivity of the electrodes surface with the electrolyte, leading to safety concerns and poor calendar life. This is why coating the active electrode material with a layer that limits interactions with electrolyte and oxygen depletion seems to be a useful method[9]. Tin layer coating has been proposed to protect electrode materials made of nanoparticle or nanotube[10,11].

Electrode nanostructuration improves the electrode current density, due to the reduction of lithium diffusion path, in addition to the increase of the electronic conduction. New materials allow much higher charge transport speed than classical bulk materials, almost without degrading storage capacity. Different forms of materials at nanometre scale for positive or negative electrodes are under study: nanowires, nanotubes, nanopillars, mesoporous, core-shell nanoparticles. This induces drastic modification of surface, morphology, and size of particles, thus improving material performance[12].

$LiFePO_4$ and other related materials are synthesised as nanoparticles. This allows associating the remarkable stability properties of this class of compounds with a higher insertion capacity. Electrochemical behaviour of the cathode material (e.g. reaction of lithium-ion insertion) is extensively studied, expecting charge/discharge capacity improvements[13]. The main drawback of $LiFePO_4$ is its low electronic conductivity, which tends to limit the capacity of the system. Many recent works try to improve this parameter by adding conductive material such as carbon nanotubes, to obtain a nanocomposite structure or a coating of the nanosized $LiFePO_4$ particles[14,15,16,17]. These mixtures and coatings can be produced by various processes[18,19]. This can result in higher Li^+ intercalation capacity systems for high-energy applications, such as full-EVs[20]. Different structures have been devised to increase the electrode/electrolyte surface, such as porous carbon based materials infiltrated with $LiFePO_4$ precursor[21] or three-dimensional structure electrodes[22].

Li_2S offers theoretical energy density several times higher than $LiCoO_2$ electrodes, making it interesting for automotive application. A recent work[23] showed that when structuring this material together with an ordered carbon structure, the carbon framework not only acts as an electronic conduit to the active mass encapsulated within, but also serves as a mini-electrochemical reaction chamber. This allows a dramatic increase in its electronic conductivity, and a good reversibility of the electrochemical reaction.

2.2.2 Other areas where nanotechnology can have an impact

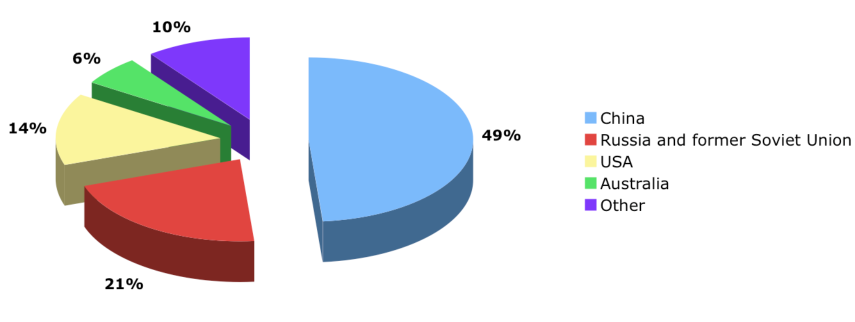
Apart from the batteries, nanotechnology can also contribute to the development of other parts of the electric vehicles, such as motor magnets, tyre rolling resistance, weight reduction, efficient electrical/electronic systems, etc.

Electric vehicles can use **motors with permanent magnets**. Full hybrids require 2-3 kg of magnet mass, while mid-sized PEVs with in-wheel motors would require 5-6 kg of magnets. Until now, the most advanced magnet types are NdFeB, but still new solutions are necessary.

Scarcity of materials for EV motors?

Rare-earth metals necessary for magnets, like neodymium (Nd), dysprosium (Dy) and Terbium (Tb) are finite natural resources, concentrated in few countries.

The graphic below shows the distribution of the known resources:



This distribution could reduce the price control, or even generate in the long-term new politic conflicts related to natural resources.

The demand in rare-earth metals for electric motor magnets is expected to increase drastically with the mass introduction of electric vehicles. Improving magnet properties can reduce the motor cost using less rare-earth metals. **Nanocomposite magnets** could be the next-generation of magnets.

Reducing the rolling resistance results in lower energy consumption and increases the driving range. Several types of nanofillers can be added to the tyres to reduce this coefficient, the most important being nano oxides, carbon nano fibers, carbon nanotubes and lamellar nanomaterials (developed by Pirelli[24]). Rolling resistance is especially relevant for urban cars, which will be most probably the first type of mass produced electric cars.

To reduce the overall weight of the vehicle, nanotechnology can provide advanced technologies, like stronger **nanostructured light metals** (aluminium or magnesium) **or polymer nanocomposites** that could replace heavier parts currently produced in steel.

Electric cars will have a considerable amount of electric and electronic systems, sensors, lighting systems, power electronics or even solar panels. **Nano-enabled electric and electronic elements, as well as new production techniques for them**, can achieve downsized and more efficient systems and therefore vehicles.

Lastly, electric vehicles will share nanotechnology applications with current vehicles. As an example, nanopaints and nanocoatings can achieve surfaces with special properties such as hydrophobia or wear resistance.

2.3 Additional demand for research

2.3.1 Batteries

The main barrier to the commercialization rollout of electric vehicles is the battery. Aspects of cost, safety, technology, production and raw materials make them difficult to develop.

The high cost of raw materials is the biggest obstacle to large-scale commercialization of lithium batteries for electric vehicles, while lithium production capacity can be a potential bottleneck. At the same time, performance and safety targets dictated by regulations and the market are particularly high for electric vehicle batteries.

These demanding requirements, combined with a €250 per kWh cost target by 2020, mean that the race for electromobility will be won or lost on the successful applications of innovations leveraging nanotechnology.

2.3.2 Other products: technological barriers to overcome

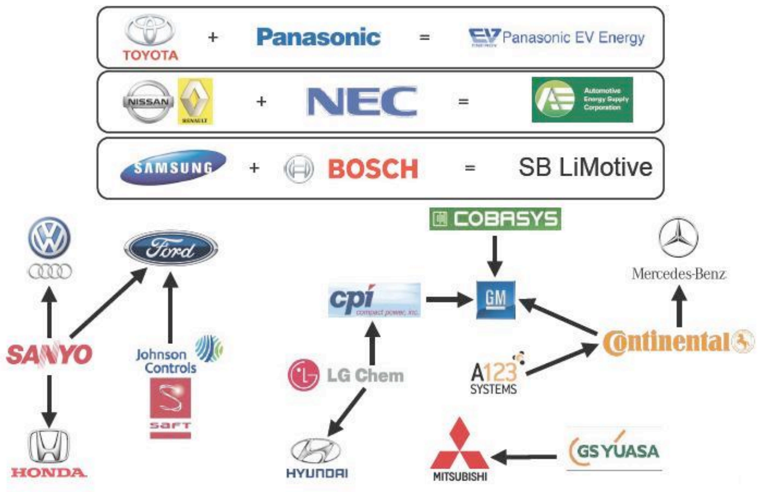
Primary demand for EVs is expected to be low, in comparison to ICE cars (2008 some 16 million cars produced in the EU). This makes economies of scale difficult to achieve, but on the other hand it opens up new opportunities for the introduction of new materials and technologies. However, it is estimated that from 2020 onwards the production will be higher. To be ready for that stage, **successful nanotechnology-enabled developments have to be able to scale-up production within the next 10 years.**

Technologies (based in nanotechnology or not) that can achieve controlled and robust results at an economic price and sufficient volume have to get priority in development.

2.4 Current situation within the EU

Asia seems to lead the EV race with Toyota, Sanyo, Panasonic, NEC and BYD, most of them being battery manufacturers for mobiles and laptops.

Foreseeing the trend between environmental concerns, rising oil prices and electric vehicles, several OEMs and Li-ion battery manufacturers have already established joint ventures, such as GM - LG Chem/Compact Power and Toyota - Panasonic. This schematic shows some of the most important worldwide partnership between OEM and batteries manufacturers.



2.4.1 EV situation

European OEMs, universities and research centres are gaining knowledge on electrical drive systems, to be able to comply with the forthcoming EU CO_2 regulations and compete with the Asian competition when the market for EVs grows, probably after 2020.

<u>EU CO_2 regulation</u>

The approved EU regulation about CO_2 is putting pressure on OEMs policies to have EVs in their product offering, to balance the CO_2 emissions of the rest of their vehicle range.

→ The European regulation mandates a reduction in CO_2 exhaust emissions to an average of 130 g/km (by 2012 for 65% of newly registered cars, increasing to 100% by 2015).

→ By 2020, the Commission plans to reduce it down to 95 g/km

The fines for the CO_2 excesses can be significant for all the OEMs, but especially for those specialised in high-class vehicles. Daimler, for example, could face fines about €3 billion if Mercedes fails to reduce the average emissions from 160 g/km down to 130 g/km by 2015[1].

2.4.2 Batteries EU policy options

The necessary investment for mass-producing Li-ion batteries and electric cars is very high and will require significant government support. The USA has already issued around $8 billion in battery and electric vehicle loans from a $25 billion programme. Loan receivers include Ford, Nissan, Tesla and Fisker.

The electric car is an opportunity for European industry economic growth and the environment. It seems appropriate for the EU to provide equilibrium to this heavy government support in other parts of the world, for example by drafting and budgeting a substantial European strategy to address the obstacles which implementation of this technology may come up against.

Besides financing and risk reduction, EU policies could promote standardisation of battery specifications among car manufacturers, which could allow increasing the production volumes per battery types. The present fragmentation is an important barrier to overcome reducing the vast number of charging terminals models now being developed and installed across Europe. A first move has been made by France and Germany, which have agreed to harmonise their plugs and create a uniform billing system.

Chapter 3 Economic aspects

3.1 General market description

For decades, individual companies have been developing and have tried to market electric drive vehicles. Ford in the 80's produced an electric sedan, which never made it past the test stage. GM introduced a full-EV in 1996, called EV1, but decided to withdraw it from the market in 1999.

In recent years electric vehicles are starting to be seen as a viable option to substitute traditional ICE vehicles by more than just a few pioneers. Experts and scientists point out that the recent changes in electricity production & transport efficiency together with the growing availability of renewable sources of electricity have changed the business case for electric automobility, making electric cars economically viable and attractive for investments.

The hype around electric vehicles makes it difficult to predict the real potential market. Optimistic forecasts suggest that hybrid and full-electric vehicles will have a market share of about 20% by 2020[32,], while more conservative visions estimate between 3% - 7,8% of total annual sales at the end of the decade[25] (the range in the estimation depends on the oil price). All experts seem to agree that there will be a big growth in the market from 2020.

First EV models (2010-2012) will probably be produced in volumes of tens of thousands of units per year, reaching by the year 2015 a production availability of only 28,000 cars or 0.2% of the 14 million vehicles manufactured annually in Europe.

Bicycles and mopeds are already being produced and successfully competing with their traditional counterparts. Hybrid and electric motorcycles and small cars will be launched in the market in this decade. However, full-electric cars of larger class are not expected to hit the market before 2020, as they still need technical developments before they can offer the customer a range-price comparable to thermal-engine vehicles.

The key component of all electric vehicles is the battery, which is where the competitive advantages from the different manufacturers are expected to be. Lithium-ion batteries are especially seen as the future batteries, although nickel metal hydride batteries still power many of the hybrid vehicles.

Until recently NiMH batteries represented almost 100% of the HEV North American market share. This ratio is likely shrink to 70% within the next 5 years and to 30% within the next 10 years. But as the global U.S. battery market size will continuously grow within the next 10 years, the market size of NiMH battery will remain almost stable. In addition, the market size of Li-ion batteries will drastically increase.

Most of today's lithium-ion batteries are used in computers, cell phones and portable tools. In the previous decades these markets have been the key-drivers to achieve high-density (low weight, high capacity) batteries to store electric energy.

3.2 Drivers and barriers

3.2.1 Drivers

Lightweight

The automotive industry is constantly working to reduce the vehicles' mass. Heavier vehicles need more energy for their traction, which in electric vehicles translates to bigger and costlier batteries for the same range of usage.

Some experts argue that this trend will not be as important in the electric vehicle because of its potential to recover up to 90% of the car's kinetic energy during braking or descents. Real regenerative braking energy recovery of a vehicle is limited by the requirement to keep the driving experience smooth and to avoid abrupt high g-force braking; most carmakers estimate in practice not to reach beyond 50% re-gen braking energy recovery. Other experts stress that the weight of vehicles has a major influence on the rolling resistance, which is one of the two most important causes of energy loss in urban driving (along with the resistance to acceleration). Therefore, decreasing the EV's weight can lead to a substantial increase in the percentage of the driving range, given a limited battery energy capacity (or overall cost reduction given a minimum required range).

Preliminary studies show that for every kilogram saved from the total car weight, there is a large reduction of the car's overall cost – larger in electric vehicles than in traditional ones. This encourages OEMs to invest more money (€/kg saved) into new light-weighting solutions for EVs than they did with ICE vehicles.

As a consequence, up to now considered too expensive technologies become affordable for E-automotive applications: lightweight materials such as advanced composites, high-performance steel and aluminium, advanced combinations of metal parts with carbon fibre reinforcements, etc. Nanotechnology can have an important impact in these lightweight materials too, for example upgrading polymer nanocomposites with strength and impact resistance properties.

Efficiency

In EVs, the electric systems (radio and entertainment, navigator, heating and A/C, lighting, electronic controls, etc.) will be competing for energy with the powertrain. As the battery energy will be very valuable (as it determines the driving range) the auxiliary systems must be highly efficient.

3.2.2 Barriers

Safety, performance, durability

There are some requirements that can become a barrier for nanotechnology to be used in the electric vehicles. Especially for the batteries, the new technologies have to ensure performance, durability and safety.

The batteries contain combustible materials such as lithium or electrolyte solvents. In case of overheating, accident or in extreme conditions, there is the risk for the battery to generate fire or explosion. Additionally, many lithium-ion cells have lower performance at very low and very high temperatures. Regarding durability, as lithium-ion batteries are costly, they will be required to work for at least 15 years during thousands of cycles (300.000 for hybrid and 7.000 for pure electric vehicles[1]) keeping at least 80% of their initial capacity.

Overcapacity

Another barrier is that automotive production plants are normally designed to cover the maximum demand, which leads to an almost-constant situation of overcapacity. As the overcapacity implies an important resistance to investments and product modifications, it affects the uptake of new technologies in the automotive industry and might even affect the transition towards newly designed electric vehicles.

Overcapacity is also an issue for battery manufacturers. According to Roland Berger[26], the planned investment will result in significant overcapacity between 2014 and 2017, reaching 200% of the demand projected for 2016. This point is likely to make the survival of battery manufacturers very challenging. According to the same analysis by Roland Berger, the critical size for 2015 will be approximately €600 million in revenues, and only 6 to 8 global battery manufacturers will survive.

3.3 Boundary conditions

Two of the most important boundary conditions for nano-enhanced products to be competitive in the electric vehicles' race are **production volumes** and **cost**.

Even though in the first years the electric vehicles will be a niche market, it is foreseen than from 2020 onwards the market will grow rapidly. To satisfy demand, the products using nanotechnology will have to be able to scale up production until the usual volumes in the automotive industry (up to 500-1000 units a day).

The automotive industry and supply chain is known for working with tight profit margins. To enter the market, suppliers of parts and systems will have to develop the necessary technologies and production techniques at low-cost and competitive prices.

> Electric vehicle battery costs
>
> Important costs reductions are expected in the batteries. Continental presented in 2009 some price reduction estimations adding up to 65% in the period 2010-2020. This 65% was split according to the reasons:
>
> ✓ 35% due to production optimisation
>
> ✓ 15% due to new materials
>
> ✓ 10% due to cell standardisation
>
> ✓ 5% due to material price reduction

These two boundary conditions, volume and cost, are important for nano-enabled products not only in the automotive industry but also in other sectors, such as textiles, packaging industry, energy.

3.4 Economic information and analysis

The market for electric vehicles and their components is likely to develop during the next years. There are a number of variables and uncertainties that will influence the market: customers uptake, lithium production scale-up, development of improved technologies, cost reduction, etc.. Experts estimate that 2012 will be the "make-or-break" year, when the market will or will not increase sufficiently to catch up the new products and expectations.

Public authorities have a very important role in the market penetration and the market acceptance of these new products. They can stimulate the EV market setting strict environmental regulations or incentives for the EV sales or the electricity for their use. They can also stimulate the technological uptake with special programmes for industrial eco-conversion. For example, as part of the 2009 Economic Stimulus Package, the US Government has allocated $2 billion in grants for the development of advanced automotive battery technologies in order to benefit HEVs, PHEVs and PEVs, as well as $400 million for "transportation electrification demonstration and deployment projects"[27].

Many countries, regions and continents have started to stimulate the development, production and deployment of EVs. Some have started early, such as China in which even today hundreds of thousands of hybrid vehicles are produced. An inspiring example can be the company BYD founded in 1995 with a staff of 20 to develop battery technology for portable ICT equipment and that now employs 120 000 people, 6.000 of which are involved in R&D. BYD focused originally on rechargeable batteries and only in 2003 did it acquire an automotive company in order to transform into an EV OEM. This subsidiary, BYD Auto, has in 2010 a capacity to produce 300.000 vehicles per year, all of which can be PHEV if the market demands that. A company like BYD (listed on the Hong Kong stock exchange) belies the often held myth that the Chinese may have low cost labour, but that their science or innovation capabilities would be less than those of US or EU based companies.

As explained in previous chapters, the most important opportunity for nanotechnology to contribute in the electric vehicles is in the battery. The table below summarises the main market estimations for batteries for electric vehicles:

Source	Market Estimate	Scope
Deutsche Bank[1]	$10-15 billion by 2015 $30-$40 billion by 2020	World
Pike Research[28].	$8 billion by 2015	World
Rocky Mountain Institute[3]	$18 billion/year by 2020, of which more than 85% market share, i.e. over $15 billion/year is for lithium ion-batteries	USA
Lux Research	$16.9 billion in 2012, for lithium-ion batteries [29] $44,4 billion in 2015, market for batteries, supercapacitators and fuel cells targeting smart grid and transportation applications[30]	World
Boston Consulting Group[31]	$60 billion by 2020 in accelerated scenario $5 billion by 2020 in steady-pace scenario, with low governmental support	World

As for electric motors and e-machines for vehicles, another vital part of EVs, the market has been estimated in €4 billion to €9 billion market by 2020[32].

3.5 Selected company profiles

3.5.1 A123 systems

The technology used by the company is Lithium Iron Phosphate ($LiFePO_4$ / Graphite) which addresses cost problems.

It developed “Nanophosphate” electrode technology with MIT, based on doped nanoscale iron phosphate particles, which is inherently stable and allows for high charge and discharge rates with minimal loss of capacity, and low impedance growth resulting in less heat and longer life. Long cycle lifetime and wide state-of-charge window results in batteries that do not require oversizing, thus reducing overall cost.

It has development contracts with GM for the Saturn Vue Plug-In Hybrid via a partnership with Cobasys, and for the Chevy Volt Plug-In Hybrid. It has production contracts with BAE Systems for a Hybrid Bus Propulsion System, and with Think Electric Vehicles. It has a plug-in hybrid electric battery technology development contract with the USABC. It produces millions of cells annually for power tools (DeWalt / Black & Decker), demonstrating the capability for commercial-scale manufacturing.

www.a123systems.com

3.5.2 Compact Power

It is now a subsidiary of LG Chemical.

It developed Manganese Spinel ($LiMn_2O_4$ / Graphite) as a cathode material addressing cost issues, while adding proprietary cathode and electrolyte additives to increase energy density, lifetime and safety. It also developed “Safety-Reinforced Separator” (SRS) to prevent internal short-circuits and the resulting thermal runaway.

It utilizes LG Chem’s immense manufacturing capability and low-cost process for laminated package and plans to establish manufacturing and assembly operations in North America.

It has development contracts with the USABC, and with GM for the Chevy Volt and a production contract with Hyundai Motor Company.

http://www.compactpower.com/

3.5.3 Evonik / Li-Tec

Evonik Industries is an industrial corporation in Germany owned by RAG Foundation. It mainly specialised in Mining/Chemicals, Energy and Real Estate.

Li-Tec Battery GmbH is a joint venture of Evonik Industries AG and Daimler AG which develops, produces and markets large-scale lithium ion battery cells for automotive and other applications. The company mass-produces the ceramic CERIO® battery cells equipped with ceramic SEPARION® high performance separator and LITARION® electrodes.

Current Evonik/Li-Tec high -energy cells (for full EVs), have an energy density of 0.2 kWh/kg, and a power density of 1.3 kW/kg. The high power cells (for hybrids) offer an energy density of 0.08 kWh/kg, and peak power density of 3 kW/kg.

In 2008 Daimler and Evonik announced their plans for a new joint venture to produce lithium ion batteries for the automaker's upcoming hybrid and electric vehicles. The two companies will invest an extra €200 million to expand cell production from the originally-announced 300,000 units in 2011 to 2.9 million by 2013. As part of the agreement, Mercedes will use Li-Tec lithium-ion cells in upcoming series-production electric vehicles.[33]

http://www.li-tec.de

3.5.4 Altair Nano

Headquartered in Nevada, Altairnano is a leading provider of energy storage systems for clean, efficient power and energy management.

Altairnano is the first company to develop nano-structured lithium titanate ($Li_7Ti_5O_{12}$). Altairnano's research into the electro-chemistry of battery materials discovered nano-structured lithium titanate, when used to replace graphite in conventional lithium-ion batteries, results in distinctive performance attributes required by power-dependent energy storage applications, including extremely fast charge and discharge rates, high round-trip efficiencies, long cycle life, significantly greater thermal stability and ability to operate under diverse environmental and extreme temperature conditions.

Lithium titanate batteries provide a very high specific power (4000 W/kg) and over 25,000 charge and discharge cycles, which makes them attractive for use in HEV and PHEV applications.

http://www.altairnano.com/

3.5.5 SK Energy

SK Energy is South Korea's leading energy provider, involved in many sectors, including oil, gasoline, coal, lubricants, petrochemicals and batteries.

SK Energy was the first Korean company, and the third in the world, to independently develop a lithium-ion battery separator, which features proprietary technology for low shrinkage and heat resistance. The company began commercial Li-ion battery production in 2005, targeting mobile devices, and is developing high energy density power batteries for hybrid electric (HEV), plug-in hybrid electric (PHEV) and electric (EV) vehicles.

SK Energy's advanced lithium-ion batteries utilize a unique lithium manganese oxide cathode material; a surface-modified graphite on the anode; a gel polymer electrolyte; and a ceramic-coated separator. Its mix of technologies achieves a higher voltage cell with excellent safety characteristics and higher energy density, while avoiding lifecycle decay at high temperature. As a result more than 90% of the power remains even after 200 days storage at 45°C. More than 70% of the capacity and power is maintained after 5000 full cycles at 5C.

The company invested US$127 million to expand its lithium-ion battery production. In 2009 it announced that it has developed 2 lithium-ion cells for HEV applications and 4 targeted at PHEV applications.

In 2009 it was selected by Daimler to supply Li-ion batteries for Mitsubishi Fuso's hybrid electric vehicles, while in 2010 it announced that it would provide lithium-ion batteries for Hyundai's i10 EV and upcoming electric vehicles from both Hyundai Motors and Kia Motors.

http://eng.skenergy.com/

3.5.6 Magna

Magna is Canada's largest auto-parts maker. Magna E-car Systems, the new division for new generation green vehicles that includes a deal with South Korean battery maker Kokam Co., is working on key EV components as battery packs, the computers that control electric vehicles, and the gears that drive electric motors.

Magna developed the fully electric Ford Focus E in 2008, while it has also won contracts with Daimler AG and Volvo Powertrain, the division of AB Volvo that develops engines and transmissions for the company's heavy truck and bus businesses. Production of these battery systems, which incorporate A123Systems' 32113 Li-ion cells, will begin in August 2009 at Magna Steyr's facility in Graz, Austria. From 2010 Magna is planning to high-energy develop battery solutions for more commercial vehicles.

The auto parts giant is searching for sites in North America and Europe to build two plants to manufacture the batteries. The potential investment is between $400-600 million and production of batteries could begin in 2013.

The auto parts maker has purchased a 13-per-cent stake in Lithium Americas Corp., a deal that gives Magna the right to acquire 25 per cent of the lithium produced by the Toronto-based mining company at a 5-per-cent discount from the market price. Lithium Americas expects to be producing lithium by 2014.

http://www.magnasteyr.com/xchg/ecar_systems/

3.5.7 Shenzhen O'Cell

Founded in 2008, O'CELL is one of the new growing manufacturers in lithium iron phosphate ($LiFePO_4$) power solutions. The company offers an array of products from cathode materials to cells to packs and modules

The main products of O'CELL include: Lithium Ion & Lithium Polymer batteries, Lithium Thionyl Chloride Batteries ($Li-SOCl_2$), Lithium Manganese Dioxide batteries ($Li-MnO_2$), Lithium Iron Phosphate ($LiFePO_4$) Batteries, and $LiFePO_4$ Battery packs for various applications.

http://www.ocelltech.hk/

3.5.8 Celgard

Celgard, a subsidiary of Polypore International, is a global leader in the development and production of specialty microporous membranes and has the broadest portfolio of products available in the lithium battery separator industry.

Battery separators play a critical role in the performance and life of lithium-ion battery cells by providing a barrier between the positive and negative electrodes –

preventing short circuits while controlling the exchange of lithium ions from one side of the battery to the other. With features including oxidation resistance and zero TD shrinkage, Celgard® Monolayer PP and Trilayer PP/PE/PP separators provide excellent chemical stability, high temperature integrity, and extended cycling performance in EDV lithium-ion battery applications.

Celgard is constructing a new 150,000 square-foot lithium battery separator manufacturing plant in the International Business Park in Concord, N.C, USA. of a total investment of around $100 million, expected to come online by 2012.

http://www.celgard.com/

3.5.9 Renault-Nissan

The French car-maker, founded in 1898, is since 2009 the European (traditional) OEM with a stronger and clearer position regarding electric vehicles.

Renault is planning to release a full range of EV models from 2011: Twizy Z.E. Concept, Zoé Z.E. Concept, Fluence Z.E. Concept and Kangoo Z.E. Concept. All these models include lithium-ion batteries.[34]

In 2008 Nissan formed a joint venture with NEC, called Automotive Energy Supply, aiming to annually produce up to 200.000 lithium batteries for electric vehicles by 2011. It is also reported that they plan to open a new factory in Portugal for assembling japanese-made NEC batteries in 2012.

Renault-Nissan has been the first strategic partner of the mobility management company Better Place. In September 2009, Better Place an

d Renault committed to a volume of at least 100,000 units of the Renault Fluence ZE in Israel and Denmark by 2016.

http://www.renault.com/

3.5.10 Think

Think is a Norwegian OEM that produces electric cars since the early 1990s.

The THINK City is produced at Valmet Automotive’s high-technology manufacturing base in Uusikaupunki, Finland. The car can be bought with a sodium battery, or lithium-based battery. For the latter, Think is collaborating with Enerdel which is also an investor and shareholder in the company.[35]

http://www.thinkev.com/

3.5.11 Pirelli

Pirelli is the world’s fifth largest manufacturer in terms of turnover on the tyre market[36]. The company develops new products using nanomaterials[24].

In 2010, Pirelli presented the Scorpion Verde, the first high-performance eco-friendly tire for SUVs and Crossovers at the Idiada International Testing Circuit in Barcelona (Catalonia). Scorpion Verde consists of nano-filler particles within the compounds and a polymer structure that helps the tire adapt to various road conditions. It claims to have 20% lower rolling resistance and to reduce fuel consumption up to 3.9% for city driving and of 3.4% for mixed routes, while also being quieter by 1 db (around 30%).

www.pirelli.com

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