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TECHNOLOGY ROADMAP ENERGY STORAGE FOR ELECTRIC MOBILITY 2030

PREFACE

ENERGY STORAGE TECHNOLOGIES FOR ELECTRIC MOBILITY

Electric mobility symbolises a promising trend for the future of mobility and has become an inherent part of the public discussion in Germany. Its realisation is mainly determined by which energy storage technologies are in the research and development state and when these will be available for the industry.

The government's "National Platform for Electric Mobility" (NPE), which was initiated in Mai 2010, identified battery technology as a "lighthouse" in research and development in its second interim report of Mai 2011 and NPE strongly recommended its support.[1] In the third update report of June 2012 The NPE describes on which topic clusters and projects the estimated project budget of 601 million euro will be distributed over three years. The funding emphasis now lies on research topics which are crucial for the market preparation and especially for setting up pilot facilities for the cell and battery production. The technological development appears to be open at this point in time. For this reason, NPE is pursuing a dual strategy. It covers both lithium-ion and post-lithium-ion technologies.

From NPE's point of view, the relevant markets for the electric mobility of the future are:

- Battery electric vehicles (BEV)
- Plug-in hybrid electric vehicles (PHEV)
- Range-extended electric vehicles (REEV)
- PHEV-utility vehicles

The battery technology based on lithium is considered to be the door opener. It offers the best battery option currently available to realise an acceptable range for the applications mentioned above. However, the fuel cell technology could reach market maturity in years to come, too. Therefore, this technology with its specific challenges and potentials should also be watched closely.

TECHNOLOGY ROADMAP ENERGY STORAGE FOR ELECTRIC MOBILITY 2030

The technology roadmap lithium-ion batteries 2030 published in 2010 focussed on the development of cell components, cell types and cell properties of lithium-ion batteries and its correlation, including the surrounding technology environment from 2010 to 2030.[2] In terms of content, the current technology roadmap energy storage for electric mobility 2030 goes beyond the lithium-based technology. It shows the development trends of electrochemical high energy storages which have been identified on the cellular level and continued on the system level. It also includes the fuel cell technology as a serious alternative. Compared to the market maturity of battery systems located in the roadmap, the industry talks of another time leap of five to ten years for the introduction to electric vehicles depending on the application. Therefore, current battery developments are to be expected in commercially available electric vehicles in only a few years' time.

The current roadmap concentrates on technology development for electric mobile applications. The emphasis is on mobile concepts for BEV and PHEV since they have special requirements for batteries with high energy density and count as key concepts for market introduction and diffusion in electric mobility both in the short to medium term (PHEV) and medium to long term (BEV).

The specific requirements for energy storage for electric vehicles are in part significantly different than the requirements for storage for stationary applications, consumption electronics and other niche applications which were already discussed in the product roadmap lithium-ion batteries 2030, which was published at the beginning of 2012.[3] Therefore, a specific technology roadmap for stationary energy storage 2030 will be compiled and published by the end of 2012.

METHODOLOGY AND PROCESS MODEL

The compilation of the technology roadmap energy storage for electric mobility 2030 is based on a methodological process model. Therefore, qualitative and quantitative research methods were combined. The process model is structured in four steps:

- Technology and market analyses including the latest publications, market studies, strategy documents by different governments etc.
- Expert and company interviews to test quantitative hypotheses and to obtain feedback to validate the results of the workshop described below
- Holding an expert workshop to compile the roadmap
- Methodically differentiated elaboration of the roadmap

The aforementioned technology and market analyses served as a basis for the compilation of the roadmap. Furthermore, relevant energy storage concepts were identified beforehand and processed for discussion in the central expert workshop.

The expert and company interviews were used as input for the construction of the roadmap. Selected expert statements serve to additionally validate and confirm the results. The technology roadmap itself was created during an expert workshop organised by Fraunhofer ISI in Frankfurt am Main in 2011. Seventeen renowned experts from applied research and industry took part in this event. Following a review of the workshop results by the participants and after including their feedback, the estimations and target values in the roadmap were put in the context of strategic target values of worldwide leading nations in battery research and development for a further independent validation and an international comparison.

The current technology roadmap locates, rates comparatively and presents the key energy storage technologies for electric mobility for the planning period from 2011/2012 to 2030 for the first time with their quantitative performance parameters and regarding technological challenges for the future.

Step 1
ANALYSES

Aim
Starting point for constructing the technology roadmap: Identification of potential contacts and framework conditions etc.

Approach
Technology and market analyses

Result
Quantitative assessments of the properties of different energy storage concepts as well as a comprehensive coverage of the technologies in question

Step 2
EXPERT SURVEY

Aim
Inventory of the expertise regarding energy storage concepts and questions e.g. concerning factors such as energy density and costs

Approach
Interviews with experts from research and development of energy storage concepts

Result
Confirmation of the quantitative assessments and preparation of the workshop

Step 3
WORKSHOP

Aim
Construction of the roadmap through interactive discussion and mapping the content and timing of all the objects of consideration in a planning perspective

Approach
Central workshop with researchers and developers from industry and science

Result
First version of the roadmap including all the relevant content

Step 4a
TECHNOLOGY ROADMAP

Aim
Documenting scientific and technical developments and evaluating the properties

Approach
Cooperation with battery developers

Result
Technology roadmap

Step 4b
PRODUCT ROADMAP

Aim
Documenting battery technology applications and evaluating their requirements

Approach
Cooperation with battery users

Result
Product roadmap

Step 4c
COMPREHENSIVE ROADMAP

Aim
Combining the technology roadmap and the product roadmap and detecting any gaps

Approach
Cooperation with battery developers and users

Result
Comprehensive roadmap

WORLDWIDE ENERGY STORAGE MONITORING AND BENCHMARKING

INTERNATIONAL TARGET VALUES FOR R&D OF LITHIUM-ION BATTERIES

When looking at the status quo of battery research, development and production for the use in applications of electric mobility, it becomes apparent that only a few countries worldwide possess the starting basis and the potential to establish a leading market for electric mobility with regard to battery production. These include – in terms of publication, patent and market share of the cellular production of lithium-ion batteries in general and large-scale lithium-ion batteries for electric vehicles in particular – Japan, South Korea, China as well as the United States and in Europe primarily Germany and France.

In recent years, a number of governments around the world have announced their national targets for the market introduction and diffusion of electric vehicles. If these goals are achieved, about 1.5 million new electric vehicles in 2015 and about 7 million in 2020 would be registered worldwide, based on plug-in hybrids (PHEVs) and all-electric vehicles (BEV). These objectives correspond well with the calculated predictions for the coming years.[4,5] To achieve these goals, governments have begun in recent years to initiate government R&D funding, measures of industrial promotion and development of infrastructure and prepare conditions for the spread of electric mobility. The funding or investment amounts for electric mobility seem to be similar in size for the world's leading countries and regions. There are differences in setting priorities and in the ways these objectives will be achieved. Especially for the two criteria of energy density and costs*, roadmaps and strategy documents of these countries show specific objectives, which allow a first comparison of essential strategies and priorities.

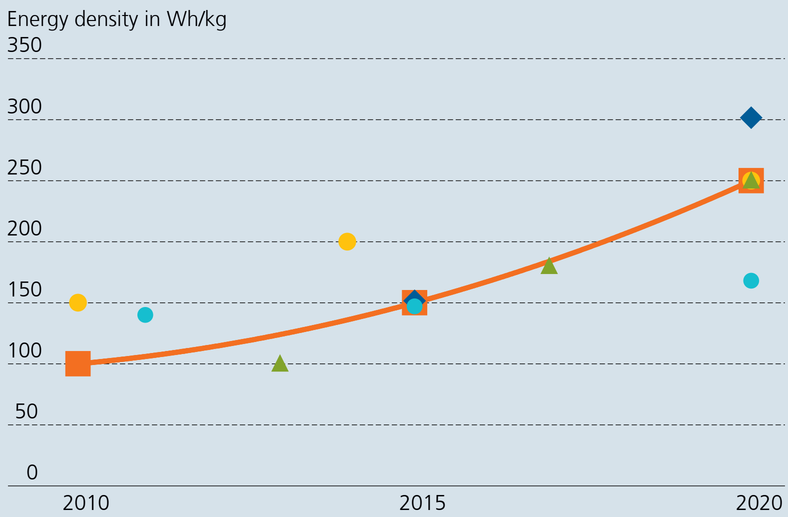
Japan's traditionally grown importance in the battery industry also results in the fact that the target values of the NEDO regarding the development of energy density and costs receive the most attention worldwide. For 2015, the NEDO submitted the figures 150 Wh/kg and 300 €/kWh and for 2020 250 Wh/kg and 200 €/kWh as an ambitious target for large-scale lithium-ion battery cells (for PHEV and BEV).[6] South Korea as a rapidly innovating and rising competitor also communicated targets for the development of battery cells through the MKE. Energy density and costs are to be thus 100 Wh/kg and 350 €/kWh in 2013 and should improve to 180 Wh/kg and 210 €/kWh by 2017 and to 250 Wh/kg and 150 €/kWh by 2020.[7] Regarding China, the relevant ministries MIIT and MOST have not yet reached a consensus. While the MIIT envisages 150 Wh/kg and 250 €/kWh on the battery module level for 2015, the MOST expects only 120 Wh/kg, but ambitious 180 €/kWh. These costs are not expected by the MIIT for battery cells until the year 2020, but with an energy density of 300 Wh/kg.[8,9] So far, the U.S. has played a minor role in battery production, but the country has set particularly ambitious goals for the coming years. The DOE sees 200 Wh/kg and 230 €/kWh for the year 2014 and 250 Wh/kg and 100 €/kWh for 2020 as target values for battery cells.[10]

The National Platform for Electric Mobility (NPE) has defined goals for Germany at system level. For the year 2014, 105 Wh/kg and 400 €/kWh are expected, for 2017 110 Wh/kg and 300 €/kWh and for the year 2020 130 Wh/kg and 280 €/kWh.[11] These target values correlate very well with the values for the development of lithium-ion batteries of the third generation of batteries, which renowned experts worked out for the present technology roadmap commissioned by the BMBF. For the year 2015, 110 Wh/kg and 475 €/kWh were documented. In terms of the high-voltage (5V) lithium-ion batteries, 126 Wh/kg and 400 €/kWh are expected for the year 2020. For lithium-sulfur batteries (Li-S) as part of the fourth generation of batteries and post-lithium-ion batteries (Post-LIB), 315 Wh/kg and 250 €/kWh are expected. In order to achieve market maturity however, other parameters have to be considered and optimized, for example durability and safety.

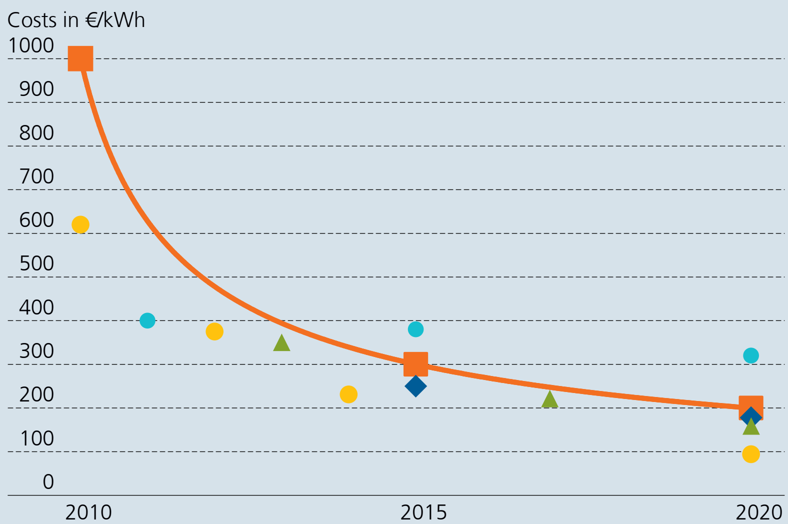
* All foreign currencies have been converted into Euro and rounded to smooth figures for better legibility. Reference date: 11. October 2012

The cellular level however, and thus in direct comparison to the aforementioned government objectives, shows that the German target values are well below those of the world's leading countries. This technology roadmap documents, based on third generation battery cells, for the year 2015 147 Wh/kg and 380 €/kWh and for the year 2020 168Wh/kg and 320 €/kWh. However, fourth generation battery cells could achieve 420 Wh/kg and less than 200 €/kWh until 2020 by using new lithium-sulfur technology (similar targets for this technology are also known from other countries, e.g. China). Thus, in the opinion of the experts, real technological advances in energy density cannot be achieved before 2020 using Post-LIB. A significant cost reduction is tied to the achievement of larger production volumes and thus to the market acceleration of lithium-ion batteries in electric vehicles. Particularly interesting is the fact that many nations around the world seem to orient themselves on the Japanese target values. While China and South Korea are trying to follow or even outperform the development goals of Japan in the medium term, the U.S. is aiming high in the short term. In an international comparison, Germany errs on the side of conservatism in terms of energy density and costs. The focus in this country tends to be on batteries with high quality, reliability and security in order to develop sustainably assertive battery technologies.

Targets of leading countries worldwide to reach energy densities (Wh/kg) of large-scale LIB cells of the third battery generation (application in BEV/PHEV)



Targets of leading countries worldwide to reach costs (€/kWh) of large-scale LIB cells of the third battery generation (application in BEV/PHEV)



- Japan (NEDO)
- South Korea (MKE)
- China (MOST/MIIT)
- USA (DOE)
- Germany (BMBF/ISI)

Can be based partly on different definitions of market maturity and number of units (e.g. between prototypes with low numbers of units and market entry/small-scale series with larger numbers of units).

BATTERY-POWERED ELECTRIC MOBILITY VS. FUEL CELL TECHNOLOGY

THE FUEL CELL IN THE CONTEXT OF THIS ROADMAP

The fuel cell represents an energy converter and therefore cannot stand for itself. Therefore, the following working definition is taken as a basis in the technology roadmap energy storage for electric mobility in 2030. The system in question is a so-called proton exchange membrane fuel cell (PEM-FC), a system comprising a low-temperature fuel cell stack with a hydrogen tank favored in vehicles.[12] This description of the system together with its properties (see box on page 7) is comparable with other energy storage technologies in the technology roadmap and their evaluation.

Really viable alternative fuel cell technologies are not available for electric mobility. Alkaline fuel cells work at low operating temperatures, but do not reach the necessary operating times due to limited material stability and are therefore only suitable for use in niche areas. The phosphoric acid fuel cell, the molten carbonate fuel cells and solid oxide fuel cells are not seen as relevant technologies for the use in mobile electronic systems due to their high operating temperatures of up to 750°C.

A technological alternative to the PEM-FC is the direct methanol fuel cell, in which hydrogen is used as fuel instead of methanol. The direct use of liquid methanol facilitates the storage of the fuel, so that the entire system of fuel cells and storage has an energy density which is five times higher than that of lithium-ion batteries.

Major difficulties are due to the costly use of catalysts and the losses caused by the direct diffusion of methanol through the membrane.[13,14] The storage of gaseous hydrogen on the other hand is a technical challenge which needs to be improved – the mass of the tanks in question is relatively large compared to the amount of energy transported, which also limits the range of vehicles.[15] The resource examination also results in a cost issue (keyword: Hydrogen production): The efficiency of the fuel cell system is about 60 per cent, which can almost be achieved by fuel cell vehicles. This case does not show the cycle efficiency for hydrogen, it only considers the discharge case. The efficiency decreases in due consideration of the hydrogen production. Even under the assumption that the electricity used is produced from 100 per cent renewable energy sources, losses due to the electrolysis efficiency and the conditioning and transportation of hydrogen should be included. Overall, an efficiency of about 35 per cent in the well-to-wheel analysis[16] can be achieved and therefore, the energy balance of fuel cell vehicles is not as good as the energy balance for battery vehicles (see page 11).

Another major challenge for the implementation of this system on the market is providing a comprehensive hydrogen infrastructure, comparable to today's refueling infrastructure. Establishing this is, particularly in the early stages, a challenge because it is capital-intensive and under-utilized in the first years. For full coverage, the initial investment could amount to three billion euros, and therewith includes the hydrogen production, distribution and retail.[17] The battery however, will mostly be charged at home or at work, and can still fall back on the existing infrastructure, especially at the beginning. In comparison to the structure of the charging infrastructure for lithium-ion batteries, the necessary investments for hydrogen infrastructure are much higher.

Among the experts, there is a consensus that sufficient progress in battery technology is unlikely to achieve a breakthrough in electric mobility with respect to all types of vehicles and user profiles. With currently available batteries, the coverage of BEV could at best double by 2020. Therefore, they are in favor of seeing batteries and fuel cells not only as competitors, but also as possibly complementary technologies.

While lithium technologies are more suitable for shorter ranges and smaller vehicles, fuel cells will probably offer the best long-term technological properties for larger vehicles and long ranges. Both approaches appear virtually unrivalled for their specific applications or just in competition with the internal combustion engine. They are considered as key technologies for electric vehicles today. As hybrid technologies, they offer a chance to discover both operational areas. A compromise solution would be the PHEV vehicle concept or the use of range extenders.

First customers seem to accept the fuel cell vehicles. In BEV, the limited range plays an important role for customer acceptance, although the range meanwhile may add up to more than 100 kilometers. Small vehicles are difficult to equip with fuel cell systems due to their compact design however, which is why lithium batteries have advantages here.

The relationships described above as well as the comparison of properties of different drive concepts (see table) show that vehicles with fuel cells already have some advantages over PHEV and BEV. These include the higher energy content in the tank (or the higher energy density respectively), the significantly greater range and much lower refuelling duration. Advantages of battery-electric powered vehicles are a much higher efficiency and a higher power density. In terms of energy density, it is thus already clear that vehicle concepts based on lithium batteries will not be competitive until the fourth generation of batteries (and a significantly higher energy density) with respect to high ranges. Most experts however, do not expect this in market maturity before 2025 or 2030.

Reference system: The proton exchange membrane fuel cell (PEM-FC)

(see roadmap double page 8 and 9)

The energy density of the PEM-FC is located at 450–500 Wh/l and 1100 Wh/kg respectively, and therewith well above the energy densities achievable with lithium systems today but also in the foreseeable future. With the defined reference vehicle (in the car: 400–500 km range, middle class, small series of more than 5000 vehicles/year), a mileage of 250,000 km is possible, the calendar life is designed for ten years. Vehicle manufacturers today guarantee calendar lives of 2000 hours[18], equivalent to a mileage of about 100,000 km. Calendar life of 5000-6000 operation hours are expected in the coming years. The tolerable environmental conditions lie between -25°C (low T) and +90°C (high T). Security data refer to the hydrogen in the high-pressure tank.

The fuel cell is expected in an automobile in combination with high-pressure storage of hydrogen in series production from 2014 on. Larger numbers of units with the fuel cell in automotive engineering are expected from 2020 onwards. Platinum-free fuel cells will probably never exist according to expert estimates. Nevertheless, the trend of platinum reduction in fuels as part of the ongoing development will continue until about 2017 and beyond. The system costs are now at 150 €/kWh (for the comparison between the reference systems, the cost of the fuel cell based on the above-defined reference vehicle were converted to euro per kWh. At 100,000 units/year, the costs will drop to 100 €/kWh (these costs could be reached by 2020).

Selected properties of different drive technologies[19]

Property	Gasoline vehicle	Plug-in hybrid	Lithium-ion battery vehicle	Fuel cell vehicle
Abbreviation	ICE	PHEV	BEV	FCEV
Energy content (tank)	445 kWh	200 + 10 kWh	24 kWh	140 kWh
Volume (tank)	50 liters	25 + 50 liters	90 to 170 liters	120 to 180 liters
Weight (tank)	37 kg	20 + 100 kg	150 to 250 kg (cell + system)	4 + 80 kg (fuel + system)
Range	> 700 km	50 + 600 km	< 150 km	~ 400 km
Refuelling frequency	Every 2 weeks	Every day + every 2 weeks	Every 3 days full, 30% every day	Every 1 to 2 weeks
Refuelling duration	3 minutes	3 minutes + 2 hours	0.5 to 8 hours	3 minutes

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LIB 2015 BMBF INNOVATIONSALLIANZ

TIME →		2011		SHORT-TERM		2015	
PROPERTIES							
		Gravimetric (Wh/kg)	Volumetric (Wh/l)	Gravimetric (Wh/kg)	Volumetric (Wh/l)	Gravimetric (Wh/kg)	Volumetric (Wh/l)
Energy density	Cell	140	230	n/a	n/a	147	242
	System	105	170	1100	450–500	110	179
		Gravimetric (W/kg)	Volumetric (W/l)	Gravimetric (W/kg)	Volumetric (W/l)	Gravimetric (W/kg)	Volumetric (W/l)
Power density	Cell	600	900	n/a	n/a	630	945
	System	400	650	n/a	n/a	420	683
Life-time	Cycle life	2500–3500 cycles		250,000 kilometres		2500 cycles	
	Calendar life	10 years		10 years		<10 years	
Ambient conditions (temperature)		High temp.: +50 °C Low temp.: -25 °C		High temp.: +90 °C Low temp.: -25 °C		High temp.: +50 °C Low temp.: -25 °C	
Safety (EUCAR level)		≤4		H_2 safety		≤4	
Costs	Cell	400 €/kWh		n/a		380 €/kWh	
	System	500 €/kWh		150 €/kWh		475 €/kWh	
Efficiency		>90 %		60 %		>90 %	
Challenges						Lifetime/safety possibly reached >2015	
ENERGY STORAGE							
Li-based		Reference system: Li-ion battery (4 V)		4,3 V Li-ion		4,4 V Li-ion	
Fuell cell				PEM-FC Nafion/Pt	PEM-H_2 (pressure) 400-500 km Range small series >5000 units/year	Stack + system + H_2-tank (pressure) 140 kWh	
Not Li-based		Ni / MH	Pb			Zn-air (mechanically rechargeable)	

TECHNOLOGY ROADMAP ENERGY STORAGE FOR ELECTRIC MOBILITY 2030

MID-TERM		2020				LONG-TERM	2030/>2030
Gravimetric (Wh/kg)	Volumetric (Wh/l)	Gravimetric (Wh/kg)	Volumetric (Wh/l)	Gravimetric (Wh/kg)	Volumetric (Wh/l)	Gravimetric (Wh/kg)	Volumetric (Wh/l)
161	265	420	345	161	265	168	276
≤121	≤196	315	255	116	187	126	204
Gravimetric (W/kg)	Volumetric (W/l)	Gravimetric (W/kg)	Volumetric (W/l)	Gravimetric (W/kg)	Volumetric (W/l)	Gravimetric (W/kg)	Volumetric (W/l)
690	1.035	400	300	<600	<900	720	1080
≤460	≤748	250	200	<400	<650	480	780
~500 cycles		≤1000 cycles		<1000 cycles		1500 cycles	
<10 years		n/a		n/a		<10 years	
High temp.: +50 °C Low temp.: -25 °C		High temp.: +65 °C Low temp.: -50 °C		High temp.: +80 °C Low temp.: +50 °C		High temp.: +50 °C Low temp.: -25 °C	
≤4		≤4		≤2		≤4	
≥400 €/kWh		<200 €/kWh		n/a		320 €/kWh	
≥500 €/kWh		250 €/kWh		n/a		400 €/kWh	
>90 %		ca. 75 %		ca. 90 %		>92 %	
Cycle life/lifetime possibly reached >2015		Power density/ cycle life/safety possibly reached >2020		Thermal management needs to be observed. Safety of ≤2 is required for a useful concept.		Lifetime/safety possibly reached >2020	

Li-alloy/ C-composite >800 mAh/g	Li-S	Li-polymer	Li-solid (non-polymer)	5 V Li-ion	Li-air
PEM-FC H_2 Pt-reduced		PEM-H_2 (pressure) 400-500 km range small series >20,000 units/year			
		Zn-air (rechargeable)		Mg-air/Mg	Al-air/Al

Timeframe
Question of market maturity of the technologies at system level (not in the vehicle), evaluation of the properties in comparison with the reference system

Reference system
LIB in electric vehicle; 4 volt as well as NMC or LFP cathode und graphite anode, PHEV: 5 kWh; range extender: ~10 kWh; BEV: >15 kWh

- ● (red) Selection of specific promising cell types by participants
- ● (black) Evaluated in the workshop
- ● (grey) Key parameters

ENERGY STORAGE FOR ELECTRIC MOBILITY

GENERAL INTRODUCTION

In the technology roadmap, technological developments of lithium-based systems are estimated in the timeframe from 2011/2012 to 2030 and beyond. In order to be able to classify the technologies in the current roadmap chronologically, the market entry was taken as a basis on the level of electrochemical systems, meaning after cell development, but before the application in electric vehicles. For some technologies, it was distinguished among technical upscaling or by numbers of units e.g. for fuel cells and therefore to differentiate between low and high volume production.

As an additional technological option besides lithium-based systems, the fuel cell technology was included in the roadmap (see discussion on page 6 and 7). As an electrochemical reference technology, lithium-ion batteries were used with a cathode made of nickel manganese cobalt (NMC) or lithium iron phosphate (LFP), an anode made of graphite (for the application with 4 V) for the application in PHEV (with ~5 kWh capacity), with range extender (with ~10 kWh capacity) and pure BEV (with ~15kWh capacity) respectively. For the assessment, the vehicle concepts of PHEV and BEV were used with corresponding capacities in the range of 5 to 15 kWh, and thereby small (e.g. micro, mild and pure hybrids) as well as larger applications (e.g. hybrid buses) were left out, as for these applications partly different performance parameters are a priority and need to be optimised.

The experts rated the following systems as especially promising for the application areas mentioned above under consideration of their achievable properties:

- Lithium-ion batteries (with NMC or LFP as well as graphite/ 4 V) as electrochemical reference technology
- Fuel cell PEM-FC with stack and hydrogen high-pressure storage as an alternative reference technology from 2014
- 4.4 V lithium-ion systems around 2015
- Lithium-based systems with lithium-alloys/carbon composites after 2015
- Lithium-sulphur systems around 2020
- Lithium-polymer systems around 2020
- 5 V lithium-ion systems after 2020

The following property parameters were documented:

- Energy density (on cell and system level as well as gravimetric in Wh/kg and volumetric in Wh/l)
- Power density (on cell and system level as well as gravimetric in W/kg and volumetric in W/l)
- Lifetime (cycle life in cycles and calendar life in years)
- Ambient conditions (tolerated high and low temperatures in °C)
- Safety (with regards to the EUCAR-level)
- Costs (of cell and system, in €/kWh)
- Efficiency in per cent

A comparison of performance data is helpful for an estimation of technological developments. Hereafter, the figures achievable from today´s point of view are stated for the properties used. The distinction between technical parameters and properties on cell and system level considered here provide starting points regarding possible losses on the system level such as losses in energy and power density.

Reference system: The 4 V lithium-ion battery

(see roadmap double page 8 and 9)

The values for energy and performance densities achieved by the reference system are located in the roadmap. Additionally improved systems have to achieve higher energy densities in particular. According to the experts, 40–50 ampere hours at a peak duration of 10 seconds are required for the reference system. Therefore, the data generally refer to the peak performance.

The cycles of the reference system amount to between 2500 and 3500 cycles. The calendar life is ten years. The tolerable ambient conditions for high temperatures are +50 °C and -25 °C for cold temperatures. Concerning safety, the EUCAR-level is 4. The flammable electrolyte is crucial for the safety properties. The condition for improved systems is therefore at least the same safety level – or better.

According to the experts, the costs are approximately 400 €/kWh when producing one to two million cells annually. Costs can only be reduced when a voltage over 5 Volt is reached and the energy storage density is increased respectively, which is the same as a reduction in the number of cells in the system. The cells cause 70 to 80 percent of the costs; the rest can be traced back to the system. Production and quantity effects can reduce the cell costs only to 60 or 70 per cent. A noticeable reduction on the cell level is therefore only achieved by an increase of energy storage density. Experts estimate the costs for the reference system on the system level at 500 €/kWh for a production of 20,000 units annually.

The efficiency of the reference system is more than 90 per cent. Current well-to-wheel-analyses for BEV result in a total efficiency of between 70 and approx. 80 per cent[20,21] even when considering all losses incurred for example when conducting and charging electricity. These efficiencies can be achieved by the use of 100 per cent renewable energies and are reduced more significantly the more conventional energy sources are used. This even exceeds vehicle concepts with the best combustion engines significantly and also fuel cell vehicles. It has to be noted that all data are only applicable to BEV. For hybrid electric vehicles (HEV) and PHEV, the costs are up to a factor of 2 higher, as fewer cells are used in the battery system and therefore the system share is higher, amongst others.

LITHIUM-BASED ENERGY STORAGE

INTRODUCTION TO THE R&D OF LITHIUM-ION HIGH-VOLTAGE BATTERY SYSTEMS

The technology roadmap lithium-ion batteries 2030 which has been already published distributes the technology development of high-voltage cells starting from the already defined reference system of lithium-ion batteries with 4 volt up to 5 V-cells before 2020.

The development of cells based on LTO anode material and a 5 V-cathode material (hereafter referred to as LTO/5 V-cells) will not be completed before 2013 to 2014. The commercial availability of the electrolyte may even lie further into the future. The experts expect it to be available after 2015 (also see 5 V-electrolytes in the technology roadmap lithium-ion batteries 2030). The development of LTO/5 V-cells refers to the development of 5 V-cathode materials with a compatible electrolyte. However, on system level and without a specification of the cell chemistry, a steady improvement and scaling is to be expected respectively. Therefore, the development of 4.3 V-systems is estimated to begin in 2012, 4.4 V-systems in 2015 and 5 V-systems in 2020. The question regarding with which cell chemistry these developments will be achieved is still open. Indications can be found in the technology roadmap lithium-ion batteries 2030.

4.4 V-SYSTEM AROUND 2015

The 4.4 V-system provides about 5 per cent more specific energy compared to the lithium-ion battery reference system. The same applies to power density. Using the 4.4 V-system, 2500 cycles should be achievable. The calendar life depends on the electrolyte quality. Calendar life is a key parameter for 4.4 V-systems which has to be achieved by further R&D. If the lifetime of the 4.3 V-system cannot reach the mark of ten years applied in BEV by 2015, further development time would be necessary and the market entry will be delayed accordingly. The tolerated ambient conditions are -25 °C (low T) and +50 °C (high T). Safety is a second critical parameter which has to be at least as high as the safety of the reference system. Car manufacturers would not install other systems only due to their cost, if these reduce lifetime and safety. Therefore, the cost reduction (cell and system) is probably less than 5 per cent compared to the reference system since at the same time, more expensive materials have to be used. The efficiency of the 4.4 V-system should be above 90 per cent, but complete well-to-wheel-analyses for BEV exist only for the reference systems and are covered in the first part of this brochure. The 4.4 V-system represents an alternative only if comparable lifetime (ten years) and safety (EUCAR-level 4) with the reference system can be achieved.

LITHIUM-ALLOY/CARBON-COMPOSITE-SYSTEM AFTER 2015

The improvements focusing on gravimetric and volumetric energy density should be plus 15 per cent on the cell level and plus 15 per cent on the system level for each case. The cathode material stays unchanged; merely an improved anode with 30 to 50 per cent higher specific energy is used. By 2015, around 500 cycles could be achievable, today around 200 relatively stable cycles are possible. Therefore, the cycle number is obviously lower than in the 4.3 V-system (considerably lower than 2500 cycles). The cycle number is a potential key parameter for lithium-alloy/carbon-composite-systems. Perhaps a longer development time is needed beyond 2015 in order to reach the mark of about 2500 cycles and a lifetime of 10 years. The tolerated ambient conditions are -25 °C (low T) and +50 °C (high T). The safety (EUCAR-level 4) should be achievable with this system. It is not a critical parameter. The composite production is very cost-intensive. However, effects in cost reduction appear on the system level, since fewer cells have to be installed in the battery system due to the increasingly high energy density of battery cells. Both cell as well as system costs will probably be slightly higher than those of the reference system. The efficiency should be above 90 per cent. Therefore, the lithium-alloy/carbon-composite-system is an alternative only and as recently as respectively, if a lifetime can be achieved comparable to the reference system (around 2500 cycles and ten years calendar life). Similar to the scaling of electrolytes due to their potential among high-voltage systems, anode materials could be scaled due to e.g. their specific capacity among lithium-alloy/carbon-composite-systems. From 2017 for instance, specific capacities lower than 800 mAh/g are to be expected. This system can be found in the roadmap.

LITHIUM-SULPHUR SYSTEM BEFORE 2020

The lithium-sulphur battery (Li-S) already exists today. However, from the experts' point of view, it will not be able to maintain 100 cycles before 2017. A milestone in 2017 should be the availability of Li-S cells with 10 ampere hours. Experts expect this type of system to be available by 2020, but the application in electric vehicles not until 2030. The chronological location of the technologies is uncertain. If the market maturity of a technology was known, its development could be calculated down to individual cells. The lack of knowledge creates time leaps which possibly have to be accepted. That is why there is great uncertainty when looking at the actual chronological development of the technologies regarding Li-S batteries (as well as with Li-air batteries).

The energy density of Li-S systems can be four times as high as the energy density of the reference system. However, the fourfold energy density is only achievable with the best cells existing. These are not automatically suitable for application in electric vehicles. An improvement factor of 1.5 (volumetric) up to 3 (gravimetric) for cell and system for the application of the Li-S system in vehicles is reasonable. The power density is notably worse than that of the reference system and is therefore a key parameter for the realisation of this technology. The achievable cycle number is around 1000 and poses another key parameter. At this point, the calendar life of the Li-S system is not really predictable. The tolerated ambient conditions are -50 °C (low T) and +65 °C (high T) Safety is a huge issue and therefore very difficult to predict as a key parameter. A different anode material could be necessary. The cost estimate is to be considered with caution, as the system achieved in 2020 may contain a material whose availability is not yet assured today. The rest of the system contains cheap components and would not create a cost increase. From the experts' point of view, there might be a high cost potential. Nevertheless, there is a great uncertainty about what is achievable with the Li-S systems. The experts estimate the costs at less than 200 €/kWh on the cell level and 250 €/kWh on the system level. They expect the costs to be cut in half compared to the reference system. Regarding sulphur, there is low cell potential. The efficiency is 75 per cent. The Li-S system represents an alternative only if a lifetime (particularly with regard to the cycle number), power density and primarily safety can be achieved which is comparable to the reference system.

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

Fraunhofer ISI

LIB 2015 BMBF INNOVATIONSALLIANZ

TIME →		2011		SHORT-TERM		2015	
PROPERTIES		Gravimetric (Wh/kg)	Volumetric (Wh/l)	Gravimetric (Wh/kg)	Volumetric (Wh/l)	Gravimetric (Wh/kg)	Volumetric (Wh/l)
Energy density	Cell	140	230	n/a	n/a	147	242
	System	105	170	1100	450–500	110	179
		Gravimetric (W/kg)	Volumetric (W/l)	Gravimetric (W/kg)	Volumetric (W/l)	Gravimetric (W/kg)	Volumetric (W/l)
Power density	Cell	600	900	n/a	n/a	630	945
	System	400	650	n/a	n/a	420	683
Life-time	Cycle life	2500–3500 cycles		250,000 kilometres		2500 cycles	
	Calendar life	10 years		10 years		<10 years	
Ambient conditions (temperature)		High temp.: +50 °C Low temp.: -25 °C		High temp.: +90 °C Low temp.: -25 °C		High temp.: +50 °C Low temp.: -25 °C	
Safety (EUCAR level)		≤4		H_2 safety		≤4	
Costs	Cell	400 €/kWh		n/a		380 €/kWh	
	System	500 €/kWh		150 €/kWh		475 €/kWh	
Efficiency		>90 %		60 %		>90 %	
Li-based + fuel cell		Reference system: Li-ion battery (4 V)		PEM-H_2 (pressure) 400-500 km Range small series >5000 units/year		4,4 V Li-ion	

LITHIUM-POLYMER/LITHIUM-SOLID/ LITHIUM-METAL SYSTEMS AROUND 2020

Regarding Li-solid and Li-metal systems, the question occurs if and how Li-metal and lithium-conducting solids like polymers or glass and ceramics respectively can be used in the future. It is uncertain whether the conductivity at room temperature will be high enough in the future. From a safety point of view, it has furthermore to be discussed whether a Li-metal system can be deployed in a vehicle. In addition to Li-polymer and Li-solid systems (not polymer-based; e.g. with ceramics separator), Li-metal systems around 2020 were compared. Li-polymer and Li-solid systems are expected from 2020.

If by 2018 a cycle-stable material is available, from the experts' point of view the cells should preferably not contain metallic lithium. As of 2020, the term "lithium" could stand for lithium itself or another high-capacity lithium-based material. The first steps in that direction could be taken with composites by 2020, and after that, lithium-alloys could be deployed. Looking at the Li-polymer systems, improvements of 15 to 20 per cent compared to the reference system are achievable regarding energy density, on the system level around 10 per cent. The power density will probably just achieve the power density of the reference system. The cycle number may be less than 1000 cycles by 2020. The lifetime, as for Li-S systems as well, is very hard to estimate at the moment. The reason is above all that the temperature range at application has not been described sufficiently.

MID-TERM		2020				LONG-TERM	2030/>2030
Gravimetric (Wh/kg)	Volumetric (Wh/l)	Gravimetric (Wh/kg)	Volumetric (Wh/l)	Gravimetric (Wh/kg)	Volumetric (Wh/l)	Gravimetric (Wh/kg)	Volumetric (Wh/l)
161	265	420	345	161	265	168	276
≤121	≤196	315	255	116	187	126	204
Gravimetric (W/kg)	Volumetric (W/l)	Gravimetric (W/kg)	Volumetric (W/l)	Gravimetric (W/kg)	Volumetric (W/l)	Gravimetric (W/kg)	Volumetric (W/l)
690	1.035	400 ●	300 ●	<600	<900	720	1080
≤460	≤748	250 ●	200 ●	<400	<650	480	780
~500 cycles ●		≤1000 cycles ●		<1000 cycles		1500 cycles	
<10 years ●		n/a		n/a		<10 years ●	
High temp.: +50 °C Low temp.: -25 °C		High temp.: +65 °C Low temp.: -50 °C		High temp.: +80 °C Low temp.: +50 °C ●		High temp.: +50 °C Low temp.: -25 °C	
≤4		≤4 ●		≤2 ●		≤4 ●	
≥400 €/kWh		<200 €/kWh		n/a		320 €/kWh	
≥500 €/kWh		250 €/kWh		n/a		400 €/kWh	
>90 %		ca. 75 %		ca. 90 %		>92 %	
Li-alloy/ C-composite >800 mAh/g		Li-S		Li-polymer		5 V Li-ion	

Timeframe
Question of market maturity of the technologies at system level (not in the vehicle), evaluation of the properties in comparison with the reference system

Reference system
LIB in electric vehicle; 4 volt as well as NMC or LFP cathode und graphite anode, PHEV: 5 kWh; range extender: ~10 kWh; BEV: >15 kWh

● Selection of specific promising cell types by participants
● Evaluated in the workshop
● Key parameters

The tolerated ambient conditions are +50 °C (low T) and +80 °C (high T). A thermal management has to be developed in order to be able to operate the system. This is one of the key parameters. Safety improves due to the application of polymers. Li-metal or an alloy is used as anode. However, the experts are sceptical whether it is possible to develop the membrane in such a way that it matches the safety requirements and still is functional at lower temperatures as well. From the experts' point of view, the system is only viable if a EUCAR level of two or lower can be reached, meaning that the safety has to be increased considerably. For this reason, safety is the central key parameter. Currently, it is not possible to estimate the costs reliably. The efficiency may be around 90 per cent. A possibly required increased operation temperature is always connected with thermal losses and a lower efficiency. According to experts, the advantages concerning energy density in compound systems/alloys are easy to exploit. The essential thermal management represents a disadvantage in Li-polymer systems. Around 2020, a technology advance e.g. by maximising the cell potential should exist which will make this system attractive. The Li-polymer system can overall only be an alternative to the reference system, if it ensures the required safety. For deepening analyses and due to the broad category "Li-polymer", reference chemistries should be defined at first.

5 V-LITHIUM-ION SYSTEM AFTER 2020

The energy density can be improved by about 20 per cent compared to the reference system (cell and system). Power density improvements of about 10 per cent compared to the reference system are achievable (cell and system). The cycle life may be in a range of 1500 cycles. The calendar life poses a critical parameter, since it is still not known how good the electrolytes will be in 2020. In this case, the challenge is to find suitable electrolytes.

The tolerated ambient conditions are -25 °C (low T) and +50 °C (high T). Another key parameter is the safety which has to be ensured (EUCAR-level 4). It should be achievable to reduce the costs to 320 €/kWh (cell) and 400 €/kWh (system) respectively, and reach an efficiency of more than 92 per cent.

The 5 V-system can become an alternative only if it can reach a lifetime (ten years) and safety (EUCAR-level 4) comparable to the reference system. In comparison to the 4.4 V-system, the energy and power density can be improved and the costs can be reduced.

POTENTIAL SYSTEMS FOR THE TIME AFTER 2030

The Li-air technology can be found on the cell level in the technology roadmap lithium-ion batteries 2030 for the timeframe after 2030. Due to long development periods for the realisation of the system and implementation in the application, these technologies still won't matter in traction applications within the foreseeable future. Therefore, the Li-air battery is to be expected to be applicable for electric mobile applications clearly in a timeframe past 2030. From today's point of view, it seems unlikely that the realisation of this technology as a rechargeable system can be achieved until 2030, even on the cell level. Despite the intense discussions about the Li-air battery as energy storage, there is still no coherent concept available and the technological challenges are still great. The state of the art hasn't left basic research yet. The technological development is hard to judge. There will be no usable concepts on a small scale for another ten years. After another ten years, an application in vehicles may be possible. The development paths documented in the technology roadmap only refer to the component level, not the product level. For systems such as e.g. Li-air, which are expected beyond 2030, there are no reliable predictions for performance data as of today. Therefore, they have not been rated within this technology roadmap.

ALTERNATIVE ENERGY STORAGE CONCEPTS

DEVELOPMENTS IN THE TECHNOLOGY FIELD AND THEIR RELEVANCE

In the technology roadmap, other energy storage technologies were implemented as well, since these could be relevant for electric mobility. However, they have not been discussed in detail due to the reasons listed below and they were ruled out from later application in the vehicle concepts PHEV and BEV. An exception is the fuel-cell technology, which is listed in this technology roadmap and will be considered for an application in electric mobility, especially when hydrogen is used as an energy source.

Partly relevant – however above all on foreign markets

Lead batteries are very important for emerging countries such as e.g. India in order to produce affordable vehicles and to offer a wide, affordable mobility for society. For the German and European market respectively, they are not considered as promising for traction purposes, and are rather seen as state of the art in the field of starter batteries. This is, among others, due to the fact that they have reached the end of their development potential and lie clearly behind e.g. lithium-ion batteries regarding their performance.

Relevant in the short-term – however just for a transition period

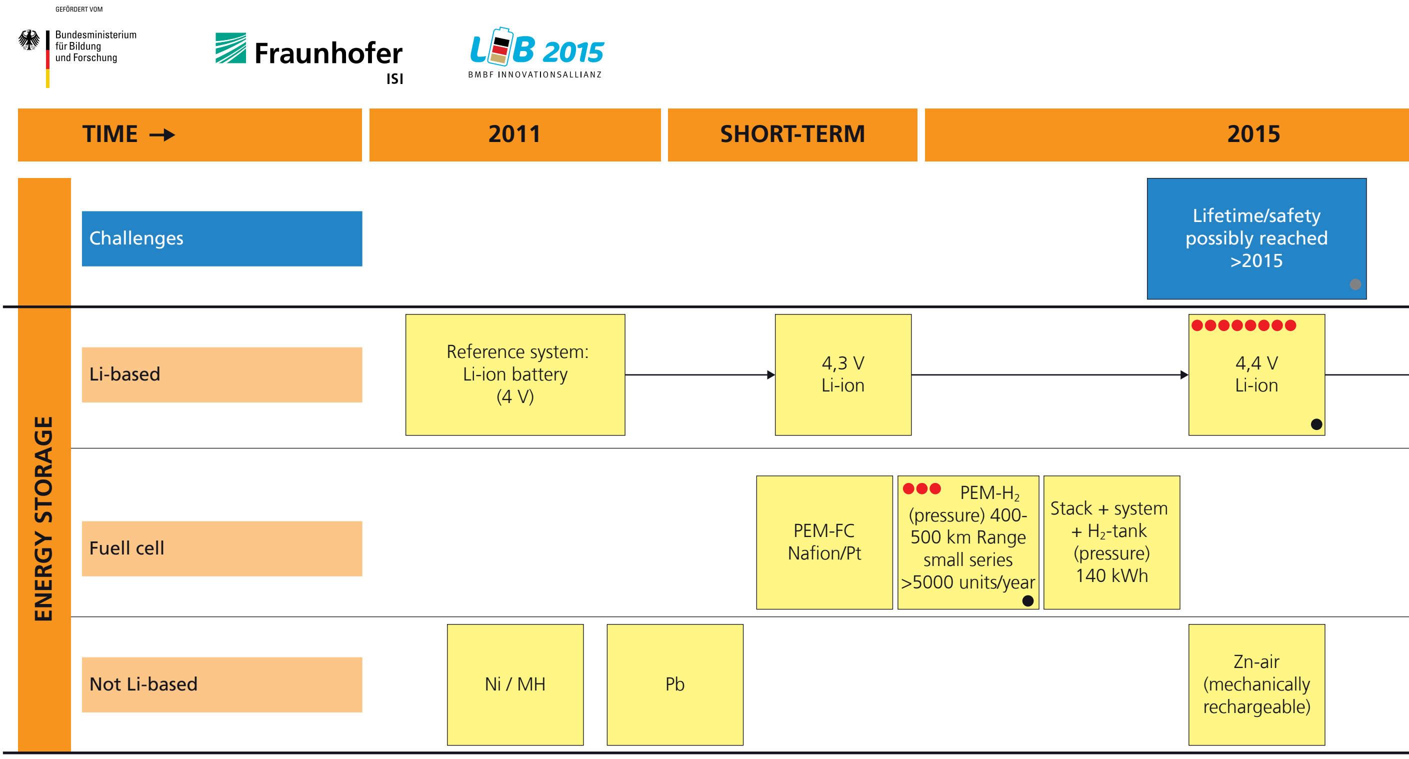
Nickel-metal hydride batteries (Ni/MH) are specially constructed for HEV. They are not described in detail in the current technology roadmap, since HEV are excluded. Ni/MH-batteries offer only a low potential for the automotive industry. Nickel and its supply situation pose an issue. Regarding the cost comparison, Ni/MH-batteries cannot keep up with lithium-ion batteries, because the nickel used is too expensive. The material costs for lithium-ion batteries are already lower than those of Ni/MH-batteries today. Furthermore, the environmental record is far worse.

Relevant in the long-term – however technology is not mature yet

From the experts' point of view, the **nickel-zinc cell (Ni/Zn)** will not be available before 2020, as documented on the cell level in the technology roadmap lithium-ion batteries 2030. By now, there are more and more doubts whether it will have a significant relevance, which is the reason why it has not been recorded in the roadmap yet. Since the Ni/Zn-cells are considered to be only a marginal niche product, there should not be an intensive program for their development. After long periods of research and development there is not a single Ni/Zn-cell which can exceed a lifetime of 100 cycles. Therefore, it seems that it cannot be used as a rechargeable battery. Nevertheless, the battery is already available as a stationary storage in the range of MWh (effective in 2012).

Flow-energy storage such as the **vanadium redox flow batteries (VRFB)** are already available in a lower performance classes, but not for electric mobility. Such battery technologies seem to be rather relevant for stationary storage applications due to their low energy density. The **redox flow battery (RFB)** with improved energy density and calendar life in comparison to today´s commercially available systems was located in the technology roadmap lithium-ion batteries 2030 around 2020. In the long-term, one has to differentiate between aqueous and non-aqueous storage. Non-aqueous batteries are to be expected from 2030 forward, especially for mobile applications. Until 2030, aqueous RFB are primarily discussed. For electric mobile applications, RFB would offer the advantage of simple refuelling by refilling the electrolyte and therefore advantages regarding the installation of infrastructure. However, the energy density is much worse than that of lithium-ion batteries.

In case of metal-air batteries, the competitive, mechanically rechargeable **zinc-air battery (Zn-air)** is not to be expected before 2015. Disadvantages are the lack of infrastructure as



well as the high transportation costs for recycling associated. The electrically rechargeable Zn-air battery is expected at the beginning of 2020.

The technical requirements for the **magnesium-air battery (Mg-air)** should be fulfilled around 2030 and magnesium may sufficiently be obtained. However, the mechanically rechargeable Mg-air battery is factored out when considering electromobile applications. It is still doubtful whether the Mg-air as well as the **aluminium-air battery (Al-air)** can function without a solid electrolyte. Due to physical reasons known already today it is unlikely. Therefore, high operation temperatures are necessary and e.g. in case of the aluminium-based batteries, there is no working concept that can maintain these high temperatures.

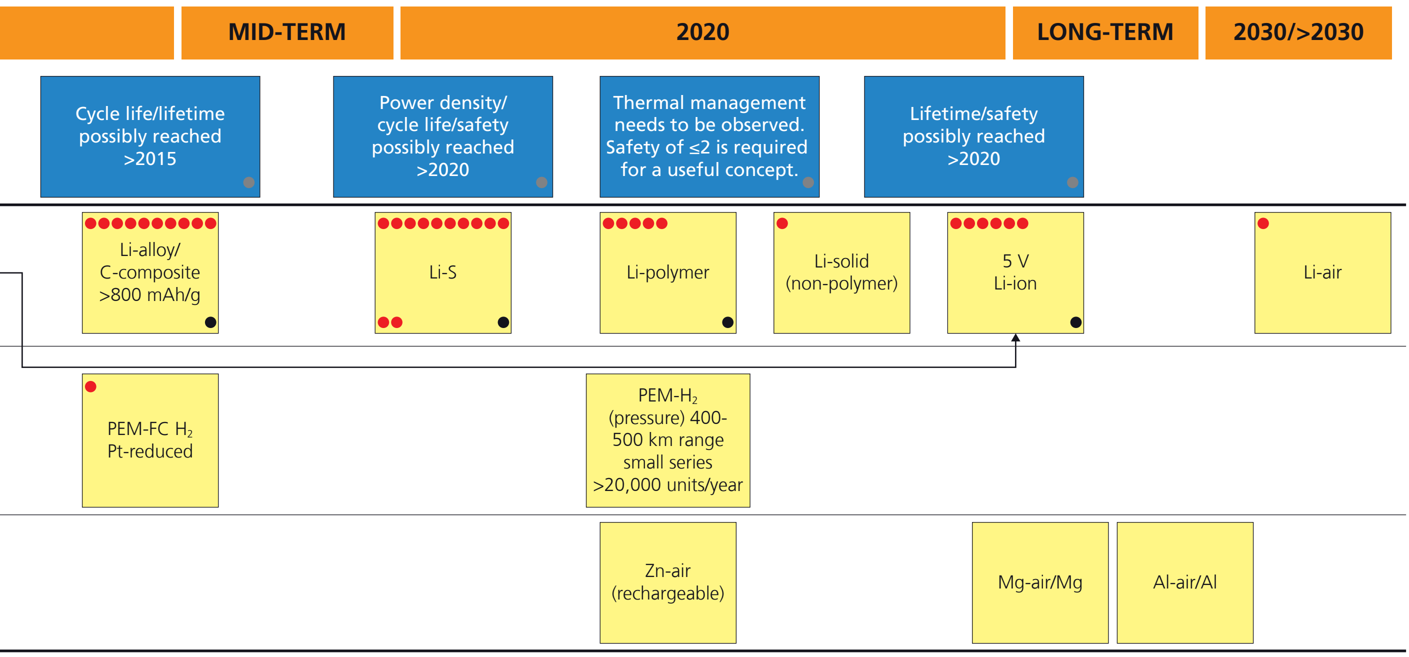
Non-relevant energy storage technologies

High-temperature storage such as e.g. **sodium-nickel-chloride batteries** or **sodium-sulphur batteries (NaS)** are of no relevance for applications in electric mobility. That is why they have not been discussed further and were factored out in the technology roadmap.

Supercaps as well as lithium-based hybrid capacitors have been discussed by the experts as energy storage with high power. However, the current technology roadmap focusses on high achievable energies. That is the reason why these systems have not been observed further. The experts have made clear that a comparison of lithium-ion batteries (high-energy systems) and super caps (high-power systems) is not very helpful. From today's point of view, supercaps can only be used in the automotive industry for on-board power supply and micro-systems (less than 60 V) respectively.

Energy storage technologies for stationary vs. electric mobile applications

Stationary storage – particularly decentralised stationary energy storage with a strong linkage to e.g. photovoltaic or wind power plants – have been factored out from this technology roadmap. To these stationary storage belong, besides lithium-based batteries for small- to medium-size storage and cyclisation, e.g. high-temperature storage like sodium-nickel chloride, sodium-sulphur batteries and redox flow storage. Furthermore, compressed air storage and hydro energy storage have to be considered regarding larger storage and cyclisations. Details of these storage technologies have been specifically documented in the already mentioned technology roadmap stationary energy storage 2030 and should be released by the end of 2012. Mechanical storage concepts have not been considered in the current technology roadmap either.



Timeframe
Question of market maturity of the technologies at system level (not in the vehicle), evaluation of the properties in comparison with the reference system

Reference system
LIB in electric vehicle; 4 volt as well as NMC or LFP cathode und graphite anode, PHEV: 5 kWh; range extender: ~10 kWh; BEV: >15 kWh

- ● Selection of specific promising cell types by participants
- ● Evaluated in the workshop
- ● Key parameters

CONCLUSION AND OUTLOOK

CONCLUSION

This technology roadmap identifies central energy storage technologies for electric mobility with a focus on the most promising vehicle concepts in terms of market potential, PHEV and BEV. Starting with a definition of the fuel cell and lithium-ion battery, the quantification of the major performance parameters of future energy storage technologies is the base for the identification of decisive key parameters. A high level of security plays an important role in this context, followed by the longest possible lifetime and high power density.

Developments of the third generation of batteries with a high-voltage path of development (from 4 V to 5 V systems) can be clearly distinguished from the fourth generation of batteries (particularly lithium-sulfur technology around 2020). The lithium-ion batteries of the third generation of batteries will be available in the next decade in addition to already existing battery systems (second battery generation), and will be relevant for the implementation and market acceleration of electric vehicles. Post-lithium-ion batteries of the fourth generation of batteries will be available for application beyond 2020. In addition to lithium-ion batteries for electric vehicles, the fuel cell should be considered a complementary technology already in the medium-term. Particularly the proton exchange membrane fuel cell is already operating at energy densities which lithium-based batteries will not reach before the distant future.

In the international context, the objectives in terms of energy density and costs at national level can be sorted well up to 2020. However, the strategies to achieve these goals differ among the most important actors Japan, South Korea, China and the United States compared with Germany.

UPDATING THE ROADMAP ...

The technology roadmap energy storage for electric mobility 2030 is a work in progress in terms of it being continuously refined and updated. The Fraunhofer ISI has set up a project website which can be used to comment on the roadmap and make suggestions for its further development. The roadmap can be downloaded at: www.isi.fraunhofer.de/trm-esemroad.php. For 2013, it is planned to complement the present technology roadmap with a product roadmap energy storage for electric mobility 2030.

... AND THE NEXT STEPS

The envisaged product roadmap will focus on aspects of market development: What are the demands on energy storage from the perspective of promising applications such as the PHEV or BEV vehicle concepts? Apart from evaluating the demands for the various properties, the market development regarding these applications will be quantified and located until the year 2030, as long as sound data exists. Besides, also policy- and market-related development trends regarding regulation/legislation, norms/standards, infrastructure and customer acceptance, should be examined and processed among others.

RELATED PROJECTS ON ELECTRIC MOBILITY

The Fraunhofer ISI is involved in a number of research projects concerning electric mobility, each with a specific area of focus. The spectrum ranges from a systemic approach examining the socio-economic aspects of electric mobility through issues of energy supply, the organisation of charging infrastructures and the development of battery and vehicle concepts right up to new mobility concepts and user acceptance.

PROJECTS

PROJECT	MAIN FOCUS OF FRAUNHOFER ISI	FUNDING
Roadmapping project accompanying the innovation alliance "Lithium ion batteries 2015" (LIB 2015)	Roadmapping regarding the technology- and market-related development possibilities for lithium-ion batteries (LIB)	BMBF
Energy storage monitoring for electric mobility (EMOTOR)	Project with focus on technology monitoring within the priority programme "Key technologies for electric mobility" (STROM)	BMBF
Fraunhofer System Research on Electric Mobility (FSEM)	Socio-economic study accompanying the Forum Electric Mobility	BMBF
Topic area user acceptance	Social science-oriented networking of projects for customer acceptance research, both regarding private and commercial use, as well as integrated mobility services from both the users' and the operators' perspective	BMVBS
intelligent Zero Emission Urban System (iZEUS)	Subproject "grid integration of renewable energies and acceptance studies" regarding electric mobility with questions concerning the right level of network control, automation and user acceptance	BMWi
Fleet trial electric mobility	System integration of renewable energies by electric mobility	BMU
Innovation report "System perspective of electric mobility"	Concepts of electric mobility and their importance for the economy, society and the environment	TAB
Integration forecast for fuels & modeling of private household demand for the integration of electric mobility in Germany	Forecast of the demand of final energy for three sectors in Germany until 2035 and determination of the total electricity load curve as well as analysis of the development of energy demand on the level of households in Germany until 2035 in due consideration of electric mobility particularly	E.ON AG
Regional Eco Mobility (REM) 2030	Development of a concept for and implementation of an efficient regional individual mobility for 2030	FhG, federal state of Baden-Wuerttemberg

GLOSSARY

Ah

The ampere-hour is a physical unit for measuring electric charge and indicates the charge (often called "capacity" in conversational language) of a battery. One ampere hour is the charge quantity which passes a conductor within one hour (h) at a constant current of one ampere (A).

Al-air

Aluminium-air batteries generate electricity through the reaction of oxygen in the ambient air with aluminium and the reduction of oxygen at the cathode and the oxidation of aluminium at the anode respectively. The battery technology has a significantly higher energy density than lithium-ion batteries theoretically, but there are still problems with the realisation. Aluminium-air batteries can be mechanically recharged.

Battery generation

The term can be traced back to the proposal of the German company BASF SE that is widely used by battery experts already, dividing the ongoing battery development into well-defined periods such as:

First battery generation

The first battery generation corresponds to the state of the art: Lithium cobalt oxide (LCO) as cathode material completed with graphite as anode material and organic carbonates with lithium hexafluorophosphate (molecular formula LiPF6) as electrolyte. Batteries of the first generation are nowadays established for the application in consumer electronics, but due to safety reasons the application in electric vehicles is limited to an extent.

Second battery generation

Concerning the cathode material, the second battery generation implicates the introduction of new layered structures and layered oxides (such as e.g. NMC or NCA) respectively or olivine structures (such as e.g. LFP), spinel structures (such as e.g. LMO). Improved carbon-based anode materials will keep finding their way into battery development, just the same as titanate-anode materials and lithium-alloys (see Li-alloys/C-composite; e.g. with aluminium, silicon and tin) as well as carbon-composites (with silicon). The electrolytes will continue to be optimised with additives, and the amount of hexafluorophosphate at first reduced and even replaced completely in the future. In addition to that, (gel-)polymer-electrolytes etc. will be developed. Compared with the first battery generation, the second battery generation defines itself by eliminating LCO-cathode material as well as the development of safer batteries. Technologies of the second battery generation are already used in commercially available electric vehicles today.

Third battery generation

The third battery generation is related to the improvement of the cell voltage of lithium-ion batteries (see high-energy development). This goes hand in hand with the need for high-voltage electrodes as well as electrolyte materials for the 5 V-lithium-ion battery. Concerning the differentiation in comparison with the second battery generation, the focus lies on the development of high-energy batteries (5 V-batteries). Technologies of the third battery generation are still in the research and development stage today and are estimated to be market-ready for the application in electric vehicles in the following years.

Fourth battery generation

In the fourth battery generation, post-lithium-ion batteries will be developed. These include Li-based systems such as Li-S or Li-air batteries as well as further metal-air systems or prospective new battery concepts with significantly increased energy density. Compared with the third battery generation, the fourth battery generation thus shows a technology leap regarding the energy density and therefore also the range of electric vehicles.

BEV

Abbreviation for "battery electric vehicle": A vehicle which is powered electrically by a rechargeable battery.

BMBF

Abbreviation for "Bundesministerium für Bildung und Forschung", the German Federal Ministry of Education and Research. In October 2012, headed by Professor Dr. Annette Schavan (CDU).

BMVBS

Abbreviation for "Bundesministerium für Verkehr, Bau und Stadtentwicklung", the German Federal Ministry of Transport, Building and Urban Development. In October 2012, headed by Dr. Peter Ramsauer (CSU).

BMU

Abbreviation for "Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit", the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. In October 2012, headed by Peter Altmaier (CDU).

BMWi

Abbreviation for "Bundesministerium für Wirtschaft und Technologie", the German Federal Ministry of Economics and Technology. In October 2012, headed by Dr. Philipp Rösler (FDP).

Capacitor

A capacitor is a storage media which stores electric charges on the surface of its two electrodes. The capacitor is charging when power is applied, by switching the direction it is discharging. Since the energy density is very low, capacitors aren't seen as exclusive energy storage in the area of electric mobility.

Comprehensive roadmap

A variation of the general term "roadmap" which aims to integrate a technology roadmap and a product roadmap in such a way that the gap between what a technology accomplishes (technology push) and what a market demands (market pull) can be determined and the resulting challenges can be identified.

CO_2

The molecular formula for carbon dioxide, a chemical combination of carbon and oxygen. Carbon dioxide is considered to be the most important greenhouse gas as it is held responsible for climate change caused by mankind, and its emissions are therefore increasingly restricted.

DOE

Abbreviation for the "Department of Energy" in the United States of America. In October 2012, headed by Minister Steven Chu.

E.ON

E.ON AG is one of the largest energy providers in Germany. The company's head office is in Düsseldorf. E.ON has about 79,000 employees and a turnover of 113 billion euro.

EUCAR-Level

Abbreviation for "European Council for Automotive R&D" (EUCAR), a large association of the most important automotive and utility vehicle manufacturers in Europe. Pre-competitive research and development projects are supported and coordinated with the aim to accomplish the highest efficiency, effectiveness and profitability in research and development. This in turn should help the automobile technology to keep achieving a high level of lifetime, quality, safety and reliability combined with a decreasing environmental impact at acceptable costs.
EUCAR sets hazard grades for electric energy storage technologies which are based on the resilience of a technology in view of misuse terms. The full scale, description as well as classification criteria and effects can be found in a chart on page 27. Manufacturers and suppliers have to develop and test their batteries accordingly in order to ensure that they reach the necessary EUCAR-levels.

FCEV

Abbreviation for "fuel cell electric vehicle": A vehicle whose engine is based on a fuel cell which supplies the electric motor with energy.

FhG

The Fraunhofer Society for the Advancement of Applied Research e.V. (a registered association) is with more than 20,000 staff (status: October 2012) the largest organization for applied research and development services in Europe and runs more than 80 research facilities within Germany, 60 of which are Fraunhofer Institutes.

Full hybrid

This variation of hybrid vehicles (see HEV) can start, drive and accelerate only by using its powerful electric motor. It represents the basis for serial hybrids.

Gravimetric energy/power density

With the physical unit of gravimetric energy/power density, the distribution of energy/power (in Wh and W respectively) per mass of a substance (in kg) is named. In this case, it is important for applications that the main focus is on the weight of potential energy storage technologies.

H_2

Hydrogen is a chemical element with the chemical symbol H. Hydrogen is the most common element in the universe. On earth, it is a component of water and part of almost every organic compound.

HEV

Abbreviation for "hybrid electric vehicle": A vehicle driven by at least one electric motor and one additional energy converter (e.g. a conventional internal combustion engine with petrol or diesel).

High-energy development

This term points concretely to those battery technologies that are prospective within the third battery generation. Starting with the reference system of the 4 V-lithium-ion battery, these are the developments up to 5 V-systems.

ICE

Abbreviation for "internal combustion engine": A vehicle whose engine is driven by a conventional combustion engine for petrol or diesel.

kg

Abbreviation for kilogram.

km

Abbreviation for kilometre.

kWh

Abbreviation for kilowatt hour (equals one thousand watt hours, see Wh).

l

Abbreviation for litre.

LCO

Abbreviation for "lithium cobalt oxide" (molecular formula $LiCoO_2$), an established cathode material for lithium-ion batteries of the first battery generation. It shows a high stability, a relatively high power density and therefore can be charged and discharged quickly. Batteries with this cathode material show low self-discharge as well as high cycle stability. Particularly the low energy density is to be mentioned as a disadvantage.

LFP

Abbreviation for "lithium iron phosphate" (molecular formula $LiFePO_4$), a cathode material for lithium-ion batteries. Battery cells with this cathode material as well as an anode consisting of graphite offer admittedly a lower energy density than batteries based on the conventional cathode material lithium cobalt oxide (see LCO). Since they have a longer lifetime and higher power density as well as an improved safety, they offer benefits for the application in electric vehicles.

LIB

Abbreviation for "lithium-ion battery": An electrochemical energy storage technology. It is used for the plural term as well.

LIB 2015

The innovation alliance "Lithium Ionen Batterie LIB 2015" was founded in 2007. It consists of about 60 project partners from politics, industry and science. Their common goal is to ensure progress in research and development of efficient lithium-ion batteries. In this context, an industry consortium committed to invest 360 million euro in research and development in the next few years. This was supplemented by subsidies of 60 million euro provided by the BMBF.

Li-air

In the lithium-air accumulator, the cathode is replaced by air, the anode consists of lithium. Since it can be fully transformed and the oxygen needed for the reaction can be taken from the ambient air, only the size of the anode determines the capacity of the battery cell. For that reason, at least the theoretically achievable energy density is higher than that of all other battery technologies. However, it is still not certain whether lithium-air batteries can be realized as rechargeable systems for electric vehicles.

Li-alloys/C-composite

Lithium can be alloyed with other materials whereby electrode properties regarding capacity are considerably improved in comparison with graphite-based electrodes. The volume changes occurring in the process are difficult to control, but the middle course of carbon-alloy-composites as new anode materials allows considerable improvements of the battery electrodes, since even small nano-structured amounts of the alloy have a positive effect.

Li-polymer

Stands for lithium-polymer accumulators and thus an advancement of lithium-ion batteries, in which the electrodes consist of graphite and lithium metal oxide. The distinctive feature is the non-liquid electrolyte based on polymers which is installed as a solid or jelly-like foil.

Li-S

Lithium-sulphur accumulators work similar to sodium-sulphur accumulators (see NaS), whereby sodium is substituted by lithium. However, they are not high-temperature batteries. Lithium-sulphur accumulators have an anode consisting of lithium and a cathode consisting of sulphur, which results in a very high energy density. During discharging, the lithium from the anode reacts with sulphur, during charging the compound formed is solubilised again.

Li-solid

Lithium-solid batteries have solid electrolyte materials which ensure fast energy absorption at high heat stability amongst other things. Therefore, complex cooling mechanisms are not needed in a lithium-solid battery and this reduces the required space at an equal or higher performance compared to other battery technologies. Besides, it is much safer than today´s lithium-ion batteries (e.g. of the first battery generation).

LMO

Abbreviation for "lithium manganese oxide" (molecular formula $LiMn_2O_4$) is a cathode material for lithium-ion batteries. Its advantages lie in low costs as well as higher safety. Disadvantages exist regarding the lifetime.

LTO

Abbreviation for "lithium titanium oxide" (molecular formula $Li_4Ti_5O_{12}$), a promising anode material for certain niche applications which require a high cycle stability and a long calendar life. LTO-based battery cells have a lower cell voltage which improves their safety. The batteries can be charged quickly and due to their chemical stability, they can operate within a larger temperature range. They have a lower energy density compared with other lithium-ion batteries; their power density can be higher depending on the cathode material. High costs due to expensive materials are a further disadvantage.

METI

Abbreviation for the "Ministry of Economy, Trade and Industry" in Japan. In October 2012, headed by Minister Yukio Edano.

Mg-air

Magnesium-air batteries generate electricity due to the reaction of oxygen coming from ambient air with magnesium and the reduction of oxygen at the cathode and the oxidation of magnesium at the anode respectively. This battery technology theoretically has a much higher energy density than lithium-ion batteries. However, it still remains to be seen whether magnesium-air cells can be realized as electrically rechargeable batteries.

Micro hybrid

Micro hybrid vehicles (see HEV) use a break force recovery and a start-stop-automatic in order to charge a small starter-accumulator, which results in fuel savings. The energy is not used for the drive.

MIIT

Abbreviation for the "Ministry of Industry and Information Technology" in the People's Republic of China. In October 2012, headed by Minister Miao Wei.

Mild hybrid

In this hybrid vehicle concept (see HEV), the electric drive assists the combustion engine, which results in an increased performance whereby the break force can be recovered partly. Mild hybrids often are parallel hybrid drives.

MKE

Abbreviation for the "Ministry of Knowledge Economy" in the Republic of Korea. In October 2012, headed by Minister Choi Kyung Hwan.

MOST

Abbreviation for the "Ministry of Science and Technology" in the People's Republic of China. In October 2012, headed by Minister Wan Gang.

MWh

Abbreviation for megawatt hour (equals one million kilowatt hours, see Wh).

Nafion®

Nafion is a tetrafluoroethylene-polymer with proton-conducting sulfonate groups. This Teflon-modification established a whole new group of ionomeres and is a registered trademark of the company DuPont (one of the world's largest chemical corporations from the United States of America). Nafion finds a technical application possibility as membrane in proton exchange membrane fuel cell (see PEM-FC).

NaS

Sodium-sulphur accumulators which deploy electrodes consisting of the aforementioned elements. A sodium ion conducting ceramic is used as a solid electrolyte.

NCA

Abbreviation for "nickel cobalt aluminium (oxide)" (molecular formula $Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$), a cathode material for lithium-ion batteries. The advantages of this material are the relatively high lifetime, the specific energy and the specific capacity. Disadvantages are relatively high costs and an increased safety risk.

NEDO

Abbreviation for the "New Energy and Industrial Technology Development Organisation", Japan's largest public organization for funding research and development and supplying new industrial, energy and environment-based technologies. The largest part of its budget is provided by METI.

Ni/MH

Nickel-metal hydride accumulators have electrodes made of nickel-oxide hydroxide and a hydrogen storage alloy made of nickel and so-called mischmetal ("mixed metal") with rare earth elements. The electrolyte is a solution of potassium hydroxide. These batteries are mainly used in hybrid vehicles.

Ni/Zn

Nickel-zinc batteries are rechargeable. A cathode made of nickel and an anode made of zinc give the technology a relatively high energy density.

NMC

Abbreviation for "lithium nickel manganese cobalt oxide" (molecular formula $Li(Ni_xCo_yMn_z)O_2$), an entire substance system. Batteries based on this cathode material combine several advantages of other battery technologies: The high capacity of lithium cobalt oxide, the good high-current properties of lithium nickel oxide and the overcharge stability as well as the low price of lithium manganese oxide. Furthermore, they have a high mean discharge voltage and can be charged relatively quickly.

NPE

Abbreviation for "Nationale Plattform Elektromobilität", the German National Platform for Electric Mobility. The panel of experts has advised the German government since May 2010 and gives recommendations on how to implement electric mobility in Germany. It is composed of representatives from unions, industry, politics, associations and science.

Pb

Lead-acid accumulators electrodes made of lead and lead oxide as well as an electrolyte consisting of diluted sulphuric acid.

Peak duration

This technical term describes how long a battery system can potentially deliver its highest performance.

PEM-FC

Abbreviation for "proton exchange membrane fuel cell".

PHEV

Abbreviation for "plug-in hybrid electric vehicle": A vehicle with a hybrid drive whose battery can be additionally charged externally through the grid. Compared with hybrid electric vehicles, it often has a larger battery and is therefore a cross between the latter and an entirely electric vehicle.

Post-LIB

Abbreviation for "post-lithium-ion batteries", often used by German battery experts synonymous for technologies of the fourth battery generation.

Product roadmap

A variation of the general term "roadmap" which aims to document the development of market requirements, e.g. on a certain technology.

Pt

Platinum is a chemical element with the chemical symbol Pt.

Range extender

These are devices for extending the range of electric vehicles. Combustion engines which drive a generator are used most often. The generator then powers the batteries and electric motor with electricity (see REEV).

REEV

Abbreviation for "range-extended electric vehicles": These vehicles are built in a way that they can be operated mainly based on the battery performance. However, they are also equipped with a gas or diesel generator in order to charge the battery when its charge draws to a close.

RFB

Stands for redox flow battery, an accumulator concept which is based on the reduction and oxidation of pumped electrolyte solutions from storage tanks on a stack which resembles that of a fuel cell.

Roadmap

The term roadmap is generally used for a preparatory project plan in which the steps to be carried out are mapped far into the future. There are 27 different types of roadmaps, e.g. product roadmap or technology roadmap. Their common feature is that creating them reveals dependencies between the individual steps and therefore risks and uncertainties.

Sodium-nickel chloride

A sodium-nickel chloride cell (also termed ZEBRA battery) is a rechargeable accumulator. The solid electrolyte is supplemented by a combination of liquid and solid electrodes. The anode located on the outside of the battery which is isolated by a separator, is made of liquid sodium. The cathode is made of sintered nickel with nickel chloride saturated with a liquid brine solution made of sodium-aluminium chloride. In order to maintain the high operating temperature, a heater needs to be used in addition to thermal insulation.

Supercaps

Short for "supercapacitors", electrochemical double layer capacitors use battery-like electrodes made of activated carbon with a large surface which are submerged in an electrolyte (see capacitor). Characteristics are the very high power density, low energy densities are considered a disadvantage.

T

Abbreviation for temperature.

TAB

The Office of Technology Assessment at the German *Bundestag* (German "Büro für Technikfolgen-Abschätzung beim deutschen Bundestag" TAB) is an independent scientific institution which advises the German parliament and its committees on questions regarding scientific-technical change.

Technology roadmap

A variation of the general term "roadmap" which aims to document technological progress.

V

Abbreviation for volt.

Vanadium redox flow battery

This battery technology is a variation of the redox flow battery (see RFB). However, the process of the vanadium redox flow battery uses vanadium ions in their various oxidation states in order to store chemical energy in different tanks in form of dissolved redox pairs. The current conversion happens in a separated power module. During the discharge process, the electrodes continuously get material from the storage tanks and react with it and the emerging product is returned into the same tanks respectively. The storage capacity is mostly determined by the size of the storage tanks, and the efficiency is at over 75 per cent. Redox flow batteries have a similar energy density as lead accumulators.

Volumetric energy/power density

With the physical unit of volumetric energy/power density, the distribution of energy/power (in Wh and W respectively) per volume of a substance (in l) is named. In this case, it is important for applications that the main focus is on the size of potential energy storage technologies.

Well-to-wheel-analysis

This term describes the life-cycle analysis of vehicle drives. In the process, a holistic examination approach is taken as a basis, for which energy consumption and greenhouse gas emissions are rated based on an integrated approach which contains both the upstream chain of fuel provision (well-to-tank) and the usage in the vehicle (tank-to-wheel). In addition, the overall costs are considered. This method enables the calculation of comparable overall efficiencies.

W

Abbreviation for watt, the physical unit which states the energy per time and therefore can be used to describe energy consumption (see Wh).

Wh

Abbreviation for watt hour, the physical unit which functions as a measurement of work performed or power. One watt hour represents the energy which one energy converter with a power of one watt absorbs or delivers within one hour.

Zn-air

Currently, the zinc-air battery only exists as primary cell, i.e. it can only be discharged. With an anode made of zinc and the ambient air converted at the cathode, a high energy density can be realised, however, at quite low open-circuit voltage only. This is the reason why zinc-air batteries have only been relevant in the consumer sector and for hearing aids respectively up to now.

EUCAR Hazard Levels and Descriptions[26]

Hazard Level	Description	Classification Criteria & Effect
0	No effect	No effect. No loss of functionality.
1	Passive protection activated	No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	Defect/Damage	No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	Leakage Δmass < 50%	No venting, fire, or flame*; no rupture; no explosion. Weight loss <50% of electrolyte weight (electrolyte = solvent + salt).
4	Venting Δmass ≥ 50%	No fire or flame*; no rupture; no explosion. Weight loss ≥50% of electrolyte weight (electrolyte = solvent + salt).
5	Fire or Flame	No rupture; no explosion (*i.e.*, no flying parts).
6	Rupture	No explosion, but flying parts of the active mass.
7	Explosion	Explosion (*i.e.*, disintegration of the cell).

* The presence of flame requires the presence of an ignition source in combination with fuel and oxidizer in concentrations that will support combustion. A fire or flame will not be observed if any of these elements are absent. For this reason, we recommend that a spark source be use during tests that are likely to result in venting of cell(s). We believe that "credible abuse environments" would likely include a spark source. Thus, if a spark source were added to the test configuration and the gas or liquid expelled from the cell was flammable, the test article would quickly progress from level 3 or level 4 to level 5.

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Innovation Research ISI
Breslauer Strasse 48
76139 Karlsruhe, Germany
info@isi.fraunhofer.de
www.isi.fraunhofer.de
Project head: Dr. Axel Thielmann

German Federal Ministry of Education and Research (BMBF)
Division 511, New Materials, Nanotechnology
53170 Bonn, Germany
www.bmbf.de
Project management: Dr. Herbert Zeisel

Project management
Project Management Jülich
Division: New Materials and Chemical Technologies, NMT
52425 Jülich
www.fz-juelich.de
Project manager: Dr. Peter Weirich

Authors
(All the following persons were employed at Fraunhofer ISI
when the German brochure was compiled and published.)

Dr. Axel Thielmann
Telephone +49 721 6809-299, Fax +49 721 6809-315
axel.thielmann@isi.fraunhofer.de

Andreas Sauer
Telephone +49 721 6809-458, Fax +49 721 6809-315
andreas.sauer@isi.fraunhofer.de

Prof. Dr. Ralf Isenmann
Telephone +49 721 6809-393, Fax +49 721 6809-330
ralf.isenmann@isi.fraunhofer.de

Prof. Dr. Martin Wietschel
Telephone +49 721 6809-254, Fax +49 721 6809-272
martin.wietschel@isi.fraunhofer.de

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Orders
Fraunhofer Institute for Systems and
Innovation Research ISI
Competence Center Emerging Technologies
Dr. Axel Thielmann
Breslauer Strasse 48
76139 Karlsruhe, Germany
Telephone +49 721 6809-299
Fax +49 721 6809-315
axel.thielmann@isi.fraunhofer.de
www.isi.fraunhofer.de

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