Battery requirements for future automotive applications

EUCAR Overview

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Expert Group BEV & FCEV

EUCAR is committed to supporting the targets of the 2015 Paris climate change conference, COP 21. Its highest priority is to mitigate the impacts of climate change by reducing greenhouse gas emissions. To achieve these goals EUCAR is committed to developing and providing sustainable powertrain technologies that contribute to an enhanced quality of life of the EU citizens.

The practical work on R&D issues is performed by the EUCAR Expert Groups (EG) which consist of experts from the members companies. It is in the EGs where the research needs are identified and formulated. The Expert Group Battery Electric Vehicles and Fuel Cell Electric Vehicles (EG BEV&FCEV) focus its work in improving the performance and efficiency of xEVs while ensuring the industrial and economic feasibility.

Battery Requirements 2030 (Version 2019)

The purpose of this document is to provide an automotive perspective on the requirement targets for the main traction battery in BEVs and (Plug in Hybrid Electric Vehicle) PHEVs by the year 2030. Based on today's understanding of the state of art of battery technologies and their applications and forecasting their development into the next decade, the expert group has set challenging targets for battery requirements. These targets are meant to be used as values that can guide researchers, policy makers and other interested parties towards setting goals that can be realistically achieved in the mentioned timeframe. In order to track the fast paced battery and EV development, the expert group recommends to check, expand and update this document version on an annual basis. In this version, the targets will be presented in a table each for BEV and PHEV with the focus on average mass market vehicles and does not consider specific requirements of high performance or speciality vehicles.

Automotive requirements widely differ due to a large variety of vehicle sizes and applications within the transportation sector. Vehicle segments such as passenger cars have small size two seaters to premium large SUVs, light commercial vehicles have different space and business needs, whereas medium and heavy-duty trucks and buses have different use cases. This version of the battery requirements will start with overall driving range, power and lifetime expectations from the industry and evolve into regular updated versions in the following years to include other important factors such as performance, sustainability, recycling, second life, etc. Battery technology is evolving at a rapid speed, with chemistries and cell designs optimised to improve certain key features. Comparison for automotive applications have therefore to be made on a system level rather than cell level especially when improvements in only one area may need additional system components to ensure overall suitability. Therefore, the battery requirement targets presented in this document are not exclusive in nature but have to be considered in context of specific transportation applications.

Scope

The Battery Targets 2030 proposes values for relevant characteristics of battery cells and battery pack. These values may differ depending on the applications, vehicle segment and driving range. This version will cover for BEVs 3 cases; passenger cars with low range (~400 km) and high range (>600 km), and commercial heavy-duty vehicles (CV HDV). For PHEV type, there are 3 cases; passenger car (e-range ~100 km), distribution truck (e-range ~70 km) and long-haul commercial vehicle (e-range ~150 km).

General battery description:

A battery is an energy storage system used in automotive application to supply power (watts) to electronic equipment. Battery system is made up of number of cells connected in series or parallel to provide the needed power and energy for the targeted application. Each cell consists of two electrodes which can store the electric charge carriers. In charging mode, the charge carriers are brought to one electrode via external charging source under application of high voltage on the cell. When a charged cell is connected to an electrical device, electrons can flow through this external circuit to run an electric device, e.g. an electric machine. This process depletes the charge carrier from the anode, which can be observed by the drop-in voltage. The cell is completely discharged when its permissible lower voltage is reached, after which it needs to be charged again before reuse. The operational voltage window of a cell is determined by the types of materials within the electrodes used and this allows the cell to charge and discharge within this voltage range in repetition.

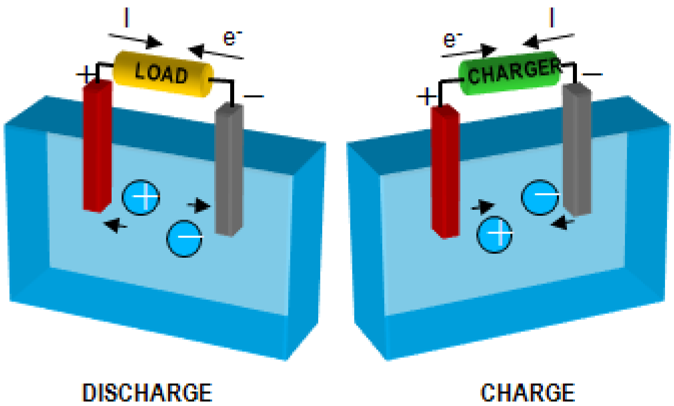

Fig. 1: Cell operations (Source: https://ti.arc.nasa.gov/tech/dash/groups/pcoe/battery-prognostics/battery-basics/)

Power capability of a cell is the ability of the cell to provide high amount of current flow over a certain time duration, whereas the energy capability of the cell is the ability to provide the current flow over a longer duration until the cell is considered empty, which means that the lower discharge voltage is reached. The total amount of charged carriers stored in a single cell and the potential difference between anode and cathode determine the energy content of the cell, whereas the speed at which the carriers can sustainably deliver the charge at the electrodes determines the power capability. Different cell chemistries are available and have their own advantages and disadvantages (see figure 2).

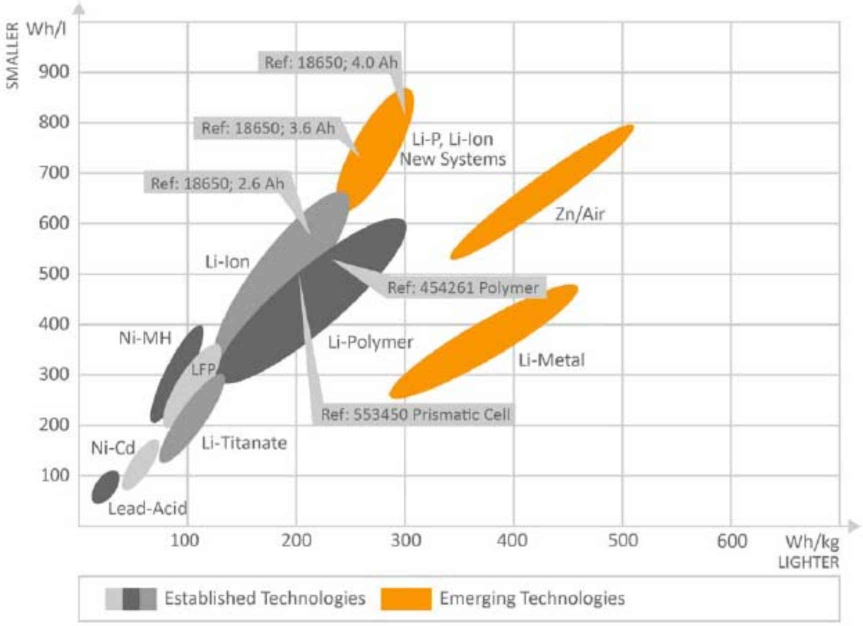

Fig. 2: Comparison of specific energy and energy density of established (grey) and emerging (orange) material systems in reference cells with various dimensions (18650 = cylindrical cell with 18mm diameter and 65mm height) DESCRIPTION (Source: E. Rahimzei, K. Sann, M. Vogel, Kompendium: Li-Ionen-Batterien im BMWi Förderprogramm IKT für Elektromobilität II: Smart Car – Smart Grid – Smart Traffic. Grundlagen, Bewertungskriterien, Gesetze und Normen. Juli 2015:

https://www.dke.de/resource/blob/933404/fa7a24099c84ef613d8e7afd2c860a39/kompendium-li-ionen-batterien-data.pdf)

Commonly known batteries used in automotive applications are lead acid batteries. Individual cells with just over 2 volts nominal voltage are connected 6 cells in series to reach over 12 volts to supply power for the vehicle board net. In an electrified car with a traction motor, higher power and energy are required beyond the capability of the lead acid chemistry. Cells with lithium ion-based chemistries have proven to be most suitable for this application until now. They have a range of nominal voltage from 2 V to 3.75 V and have a much higher specific energy (Wh/kg) and energy density (Wh/l) compared to Lead-Acid cells. High energy cells allow the electric car to drive longer distances.

Table 1. - Battery requirements for future Battery Electric Vehicle (BEV) applications

BEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Specific energy	Wh/kg	@ 1/3C charge and discharge at 25°C (charging with CC and CV step)	~250	450	450	450
Energy density	Wh/l	@ 1/3C charge and discharge at 25°C (charging with CC and CV step)	~500	1000	1000	1000
Continuous specific power - discharge	W/kg	180s, SOC100%-10%, 25°C	750	1000	1000	1000
Continuous power density - discharge	W/l	180s, SOC100%-10%, 25°C	1500	2200	2200	2200
Peak specific power PC - discharge Peak specific power CV - discharge	W/kg	10s, SOC50%, 25°C / -25°C (PC) 60s, SOC50%, 25°C / -25°C (HDV)	1500/500	1800 / 600	1800 / 600	1350 / - due to performance
Peak power density PC - discharge Peak power density CV - dischqrge	W/l	10s, SOC50%, 25°C / -25°C 60s, SOC50%, 25°C / -25°C	3000/1000	4000 / 1300	4000 / 1300	3000 / -
Charging rate	C (1/h)	SOC 0%-80%	3	3.5	3.5	3
Self discharge	%	SOC100%, 25°C, 30 days	1	1	1	1
Cycle lifetime WLTP for cars Cycle lifetime for truck / bus	Energy throughput MWh	25°C, DOD90% until SOH80%	~20	22 to 24	22 to 24	N/A
Hazard level	EUCAR safety levels		<=4	<=4	<=4	<=4
Cost	€ / kWh		220	70	70	70
BEV - Parameter at PACK level	**Unit**	**Condition**	**State of the art 2019 (approximated average**	**Target 2030 Mass market PC low range ~400km**	**Target 2030 Mass Market PC high range >600km**	**Target 2030 Mass market Commercial HDV**
Cell volume per battery pack	%		60	75	75	75
Cell weight per battery pack	%		70	80	80	80
Lifetime expectation	Years & km	DOD90%	lifetime of a car 150.000km	lifetime of a car 150.000km	lifetime of a car 150.000km	N/A
Cost	€ / kWh		*+30% of cell cost	*+20% of cell cost	*+15% of cell cost	N/A

Table 2.- Battery requirements for future Plug-in Hybrid Electric Vehicle (PHEV) applications

PHEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Specific energy	Wh/kg	@ 1/3C charge and discharge at 25°C (charging with CC and CV step)	~200	350	350	350
Energy density	Wh/l	@ 1/3C charge and discharge at 25°C (charging with CC and CV step)	~500	800	800	800
Continuous specific power - discharge	W/kg	180s, SOC100%-10%, 25°C	750	1750	1750	1750
Continuous power density - discharge	W/l	180s, SOC100%-10%, 25°C	1500	3850	3850	3850
Peak specific power PC - discharge Peak specific power CV - discharge	W/kg	10s, SOC50%, 25°C / -25°C (PC) 60s, SOC50%, 25°C / -25°C (HDV)	1500/500	3500 / -	3500 / -	3500 / -
Peak power density PC - discharge Peak power density CV - dischqrge	W/l	10s, SOC50%, 25°C / -25°C 60s, SOC50%, 25°C / -25°C	3000/1000	7700 / -	7700 / -	7700 / -
Charging rate	C (1/h)	SOC 0%-80%	4	5	10	10
Self discharge	%	SOC100%, 25°C, 30 days	1	1	1	1
Cycle lifetime WLTP for cars Cycle lifetime for truck / bus	Energy throughput MWh	25°C, DOD90% until SOH80%	~20	15 to 24	N/A	N/A
Hazard level	EUCAR safety levels		<=4	<=4	<=4	<=4
Cost	€ / kWh		220	100	120	120
PHEV - Parameter at PACK level	**Unit**	**Condition**	**State of the art 2019 (approximated average values)**	**Target 2030 Mass Market PC PHEV e-mode ~100km**	**Target 2030 Typical distribution truck e-mode ~70km**	**Target 2030 Typical long-haul truck e-mode ~150km**
Cell volume per battery pack	%		60	70	70	70
Cell weight per battery pack	%		70	75	75	75
Lifetime expectation	Years & km	DOD90%	lifetime of a car 150.000km	lifetime of a car 150.000km	lifetime of a car 150.000km	N/A
Cost	€ / kWh		*+30% of cell cost	*+20% of cell cost	*+15% of cell cost	N/A

Parameters and Conditions

The list of parameters presented in the tables cover typical characteristics on cell and pack level that are considered in the automotive industry for evaluation of the technologies. Each parameter is accompanied with the condition under which the values should be achieved. It should be clear that all parameters need to be achieved at the same time. These conditions are carried over from the existing battery datasheet created by cell manufacturers and commonly accepted by OEMs. Any deviation from standard conditions for future cell chemistries and technology can be accepted, if the improvements are substantial and automotive application is possible. However, overall efficiency of the system should be considered while evaluating such technologies.

On a cell level basis many material combinations appear promising when calculating and measuring first cell characteristics. But nevertheless, on a detailed consideration, many additional components are needed in order to keep the system running that are not mentioned in detail but are necessary.

As an example, Solid State batteries that need extra system level support components such as heating, or pressure pads compared to high energy Li-ion batteries still need to be better on a system level compared to today's lithium ion batteries. A comparison only on cell level is not beneficial for improved battery pack performance.

Also for the so called "lithium-air" batteries, it is often not mentioned that pure oxygen is mandatory instead of a typical air mixture, and that in some cases a special oxygen tank needs to be carried along in order to reversibly store the oxygen in the system. These additional "features" reduce the potential of some technologies, but clearly need to be stated by the researchers if those are needed.

Similar deviation from targets and conditions can also be acceptable if overall improvement can be proven for specific applications. For example, certain cell technologies may not be suitable for passenger cars but can be proven beneficial when total cost of ownership for commercial vehicles is considered. In such cases certain parameters may not reach the challenging target but improvements in other parameters provide a definite benefit for a specific application. In case of the LTO cell chemistry, it has lower energy density compared to Li-ion NMC but offers very high cycle life and power capability. These characteristic makes it a viable candidate for certain commercial vehicle applications today.

Detailed Description of Parameters

Specific energy and energy density

Definition: The energy storage capacity of a cell or a complete battery pack system is characterized by the parameters specific energy (Wh/kg) and energy density (Wh/l) and is therefore1 directly influencing the achievable driving range. Former is calculated by the product of specific charge density (Ah/kg) and cell voltage (V) and defines the stored energy content per mass of the cell. The energy density defines the stored energy content per volume of the cell and is calculated by the product of charge density (Ah/l) and cell voltage.

[1] *Kompendium: Li-Ionen-Batterien im BMWi Förderprogramm IKT für Elektromobilität II: Smart Car – Smart Grid – Smart Traffic Grundlagen, Bewertungskriterien, Gesetze und Normen.*

BEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Specific energy	Wh/kg	@ 1/3C charge and discharge at 25°C (charging with CC and CV step)	~250	450	450	450
Energy density	Wh/l	@ 1/3C charge and discharge at 25°C (charging with CC and CV step)	~500	1000	1000	1000

PHEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Specific energy	Wh/kg	@ 1/3C charge and discharge at 25°C (charging with CC and CV step)	~200	350	350	350
Energy density	Wh/l	@ 1/3C charge and discharge at 25°C (charging with CC and CV step)	~500	800	800	800

Unit: The unit of this parameter is Wh/kg and Wh/l, respectively.

Condition: In order to measure the capacity as representative as possible, but at a maintainable condition, a typical C-rate of 1/3C has been established. CCCV is standard charging protocol for lithium-ion batteries[2]. This means that the cell is being charged with a constant current step with a corresponding C-rate of 1/3 until the upper charging voltage is reached, followed by a constant voltage phase at the upper charging voltage until the current drops below a certain threshold value. Cell is charged and discharged between lower and upper cell voltage. Typical measurement temperature is room temperature, defined as 25°C.

Relevance: The higher the cell specific energy the lower is the total weight of the complete battery pack and thereby lower the electric consumption upon driving. Installation volume in electric cars is typically much more limited, so more attention is spent to the energy density. As a rule of thumb, the higher the cell energy density the more compact a battery pack can be designed. The total energy density at pack level of course is dependent on many more factors like thermal management, pressure units etc. An energy density benefit on cell level can quickly be neutralized by special requirements on system level that may take a lot of weight and space.

The defined target values are based on one of the most promising and potential cell technologies that may emerge in future lithium battery systems. This estimation comes from the so called all-solid-state technology where the liquid electrolytes are replaced by solid ion conductors and opens potential to apply a metallic lithium anode with significantly increased energy compared to today's graphite-based anodes. New developments in different cell chemistries can offer improved performances and show potential even beyond solid state cells. This would be considered in the subsequent version updates of this document as an when such a situation arises.

Lithium-Ion batteries [3] can be divided into energy-optimized batteries with high capacities, lower power densities, moderate discharge currents and power-optimized batteries with lower energy densities, high power densities and temporary very high discharge currents. Former are especially important for BEVs, because the driving range is dependent on the installed energy. In contrast for PHEVs requirements for power density and therefore for high currents are much higher. This is especially valid during electric take-off and acceleration where peak power is demanded from the electric drive train and vice versa during breaking and recuperation of energy.

[2] Moderne Akkumulatoren richtig einsetzen, A. Jossen or Lithium-Ion Batteries: State of the Art and Application Potential in Hybrid-, Plug-In Hybrid- and Electric Vehicles B. Ketterer, U. Karl, D. Möst, S. Ulrich.

[3] *Kompendium: Li-Ionen-Batterien im BMWi Förderprogramm IKT für Elektromobilität II: Smart Car – Smart Grid – Smart Traffic Grundlagen, Bewertungskriterien, Gesetze und Normen (if source is necessary)*

For further clarification, please see ANNEX 2 at the end of this document.

Specific power and power density

Definition: Two important parameters that cover most situations during e-driving have been established as continuous and peak power density. Continuous power density is a measure that should represent a continuous driving situation of an electric vehicle, whereas peak power density should be representative for acceleration or breaking procedures. Both values are related to either weight or volume (like for the energy density). The main difference between continuous and peak power can be found in the duration of the power requirement and the required power output.

BEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Continuous specific power - discharge	W/kg	180s, SOC100%-10%, 25°C	750	1000	1000	1000
Continuous power density - discharge	W/l	180s, SOC100%-10%, 25°C	1500	2200	2200	2200
Peak specific power PC - discharge Peak specific power CV - discharge	W/kg	10s, SOC50%, 25°C / -25°C (PC) 60s, SOC50%, 25°C / -25°C (HDV)	1500/500	1800 / 600	1800 / 600	1350 / - due to performance
Peak power density PC - discharge Peak power density CV - dischqrge	W/l	10s, SOC50%, 25°C / -25°C 60s, SOC50%, 25°C / -25°C	3000/1000	4000 / 1300	4000 / 1300	3000 / -

PHEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Continuous specific power - discharge	W/kg	180s, SOC100%-10%, 25°C	750	1750	1750	1750
Continuous power density - discharge	W/l	180s, SOC100%-10%, 25°C	1500	3850	3850	3850
Peak specific power PC - discharge Peak specific power CV - discharge	W/kg	10s, SOC50%, 25°C / -25°C (PC) 60s, SOC50%, 25°C / -25°C (HDV)	1500/500	3500 / -	3500 / -	3500 / -
Peak power density PC - discharge Peak power density CV - dischqrge	W/l	10s, SOC50%, 25°C / -25°C 60s, SOC50%, 25°C / -25°C	3000/1000	7700 / -	7700 / -	7700 / -

Unit: The unit of this parameter is W/kg and W/L, respectively.

Condition: As a representative value for continuous driving the power capability for 180s at +25°C has been established. The value should be valid for SOC=100% to SOC=10% to ensure mobility over the entire state of charge range of a battery. For fast acceleration or recuperation peak power values with shorter duration are more relevant. Typically, peak power is defined to 10s at an average SOC e.g. SOC=50%. As for the energy density, continuous and peak power values are related to the cells weight and volume respectively. Therefore, the relevant unit for power values are W/kg or W/l.

Since electrified passenger cars have to operate as well at low temperatures, the value at -25°C is as interesting as for room temperature. Overall vehicle performance at required operating temperature range and SOC range are specific to the application and individual parameters are set accordingly by OEMs.

Heavy-duty vehicles (HDV) such as buses and trucks typically have lower acceleration and retardation rates compared to passenger car. Hence, the condition for peak discharge power, corresponding to typical vehicle acceleration to normal traffic velocity (50-80 km/h), is 60s. However, the operating conditions with respect to ambient temperature and cold-start requirements are too diverse to form a strict condition for low-temperature performance.

Relevance: The values in the table for passenger cars are divided in values for mid-range cars (~400km driving range) and high-range cars (~600km driving range). Assuming an electric consumption of 15kWh/100 km the battery packs of mid-range cars will have ~60kWh and for long-range cars ~100kWh. Corresponding to the installed energy electric machines for these cars will deliver power between 125kW and 300kW. Therefore, the highest average C-rate of ~2,2 can be derived for continuous driving and thus the continuous power output of the cell should be around 1000 W/kg (450 * 2,2). For peak power requirements, which would represent a very fast acceleration or breaking, a maximum C-rate of 4C is defined to cover most automotive use cases. As mentioned before, a BEV has to work at low temperatures, which means that a certain basic mobility needs to be ensured. This basic mobility would cover the ability of starting the car and driving at average speed, as long as the cell have been heated to more preferred working conditions. For these low temperature requirements, the value was set to 1/3 of the value at 25°C. It is assumed that the low temperature condition is only on an interim basis, since batteries heat up very quickly due to large inner resistances.

Similarly, a BEV HDV typically require peak discharge rates of 150-300kW depending on type and total weight. With battery sizes ranging from less than 100 kWh (opportunity charged) to more than 300 kWh (depot-charged), the peak discharge power may range from ca 1C-rate to 3C-rate.

Charging Rate

Definition: Charging rate is the continuous C-rate capability permissible in charging mode. Charging rate of a cell = Max. Charging continuous Current (A) / Nominal Cell Capacity (Ah)

BEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Charging rate	C (1/h)	SOC 0%-80%	3	3.5	3.5	3

PHEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Charging rate	C (1/h)	SOC 0%-80%	4	5	10	10

Unit: The unit of this parameter is (1/h)

Condition: Continuous charging rate can begin with an empty cell (0% SoC) and end when the upper cell voltage limit is reached (typically around 80% SoC at max continuous C-rate) at +25 °C

Relevance: The higher the charging rate the higher the fast charging capability of the cell. This value is critical in reducing the charging time of BEVs and promoting long distance drivability. For commercial HDVs, the required charge rate is directly related to the length of typical available charging opportunities such as lunch breaks, loading/unloading stops and working shift changes. It is clear that fast charging will affect lifetime of a battery and needs therefore considered when designing new cells technologies.

For example, if a 50 Ah cell can be continuously charged with maximum current of 200 amperes, this cell has a Charging --rate of 200/50 = 4C

Self-Discharge

Definition: Self discharge is the reversible loss in capacity of a cell over time without any external electrical load.
Self-Discharge = Cell capacity loss over time (Ah) / Nominal capacity of the cell (Ah) *100

BEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Self discharge	%	SOC100%, 25°C, 30 days	1	1	1	1

PHEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Self discharge	%	SOC100%, 25°C, 30 days	1	1	1	1

Unit: The unit of this parameter is (%)

Condition: Cell capacity loss measured after 30 days on a fully charged cell (SoC 100%) at +25 °C

Relevance: High self-discharge during vehicle parking, shipping or battery storage will reduce range and performance, and may in severe cases cause irreversible loss to cells. Cells and battery packs are typically shipped at partial SOC lower than 30% and may be stored for up to a year. Hence, the self-discharge must be low enough to avoid too low SOC (10%) and thus enable standard commissioning after storage.

Cycle Lifetime

Definition: Cycle lifetime is the amount of energy (Wh) throughput a cell can undergo through charging and discharging until its end of life (<= 80% SoH)
Cycle lifetime = Sum of energy over charge and discharge (Wh) until end of life of the cell.

BEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Cycle lifetime WLTP for cars Cycle lifetime for truck / bus	Energy throughput MWh	25°C, DOD90% until SOH80%	~20	22 to 24	22 to 24	N/A

PHEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Cycle lifetime WLTP for cars Cycle lifetime for truck / bus	Energy throughput MWh	25°C, DOD90% until SOH80%	~20	15 to 24	N/A	N/A

Unit: The unit of this parameter is (Wh)
Condition: Cell is charged and discharged (typically between 5%SOC and 95%SOC, or as recommended by cell manufacturer) at +25 °C until 80% SOH (or as defined by each OEM)

Relevance: The higher the cycle lifetime the higher the service life under operation. Long cycle life is directly proportional to number of driven kilometres.

Whereas the average annual driving distance for passenger cars is 10 000 to 15 000 km, commercial HDVs are typically driven 50 000 to 150 000 km / year depending on type. Consequently, the cycle life requirement is typically five to ten times higher than for passenger cars.

Fast charging at high power has a detrimental effect on Li-ion battery cycle life as well as insufficient thermal management at extreme temperature operations.

Hazard Level

Definition: Hazard level of cells is the outcome of safety tests performed on the cells and the outcome is classified under the commonly known EUCAR Hazard level table[4].

[4] https://www.rechargebatteries.org/wp-content/uploads/2013/07/Li-ion-safety-July-9-2013-Recharge-.pdf

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 Δ mass < 50%	No venting, fire, or flame*; no rupture; no explosion. Weight loss <50% of electrolyte weight (electrolyte = solvent + salt).
4	Venting Δ mass ≥ 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).

Fig. 3: Various hazard levels defined by EUCAR members for the use of a cell level safety performance in EV

BEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Hazard level	EUCAR safety levels		<=4	<=4	<=4	<=4

PHEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Hazard level	EUCAR safety levels		<=4	<=4	<=4	<=4

Condition: Series of tests conducted according to regional standards such as SAE, GB/T, etc. Details of the testing conditions can be found in the appropriate documentation

Cost

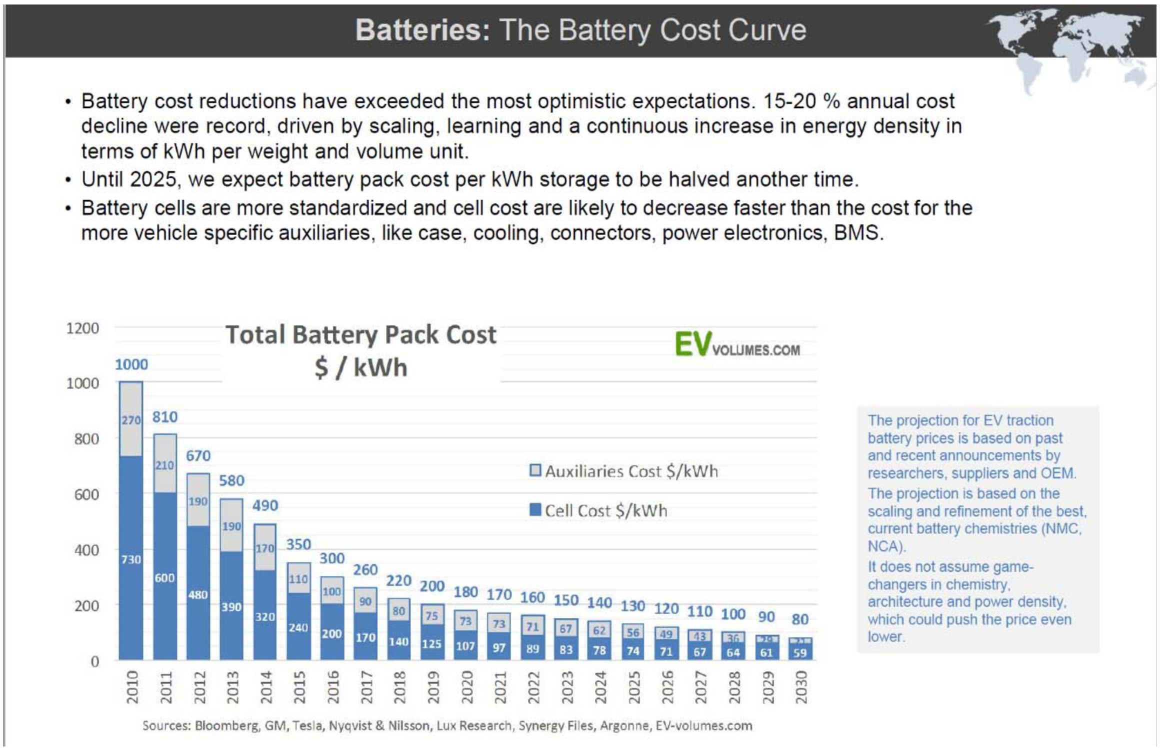

Fig. 4: Example of battery cost development expectation (Source: AABC 2019 EV-volumes.com)

Definition: Cells costs are commonly described in $ or € per kWh (energy content) for BEV applications. The cell costs in $/kWh may be higher for cells used in high power applications due to their lower energy content.

Cost per cell = Total cost per cell ($) / Cell energy content (kWh)

BEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Cost	€ / kWh		220	70	70	70

PHEV - Parameter at CELL level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Cost	€ / kWh		220	100	120	120

Unit: Cost is typically used as $/kWh (or €/kWh)
Condition: Cell energy content is estimated by considering the energy discharged from the cell at 100% SoC to 0% SoC at 25 °C at 1/3 C-rate

Relevance: Cost of cells in a BEV is the largest part in the overall vehicle costs. This indicator is important to understand the commercial viability of new cell technologies. However, in certain heavy-duty applications, the total cost of ownership may be more relevant than simply considering only the cell costs.

Cell Volume per battery pack volume

Definition: A battery pack is considered a closed hard case housing containing multiple cells connected in series and/or parallel along with all the necessary connections and electronic components needed to manage the battery system. The packing ratio determines the total cell volume compared to the overall pack volume. Cell volume x number of cells / outer volume of battery pack x100

Unit: The unit of this parameter is (%)

BEV - Parameter at PACK level	Unit	Condition	State of the art 2019 (approximated average	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Cell volume per battery pack	%		60	75	75	75

PHEV - Parameter at PACK level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Cell volume per battery pack	%		60	70	70	70

Condition: No specific conditions

Relevance: The higher the cell volume per battery pack volume the higher the energy density of the battery system. Given the limited space in vehicles, this indicator is relevant to increase driving range. Innovations in battery construction and integration in vehicle can improve this value.

Cell Weight per battery pack weight

Definition: This weight ratio shows the proportion of the cell weight in comparison to the complete battery pack weight including all the connection and the components as well as the pack housing structure. Cell weight x number of cells / total weight of battery pack x100

Unit: The unit of this parameter is (%)

BEV - Parameter at PACK level	Unit	Condition	State of the art 2019 (approximated average	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Cell weight per battery pack	%		70	80	80	80

PHEV - Parameter at PACK level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Cell weight per battery pack	%		70	75	75	75

Condition: No specific conditions

Relevance: The higher the cell weight per battery pack weight the higher the specific energy of the battery system. Additional weight decreases the efficiency of the vehicle and reduces payload. Innovations in lightweight and functional integration can for example improve this value.

Lifetime expectation

Definition: Lifetime expectation of battery packs is the combined lifespan of the battery system in cycle life as well as calendar life.

Unit: The unit of this parameter is (Years in operation and total kilometres driven)

BEV - Parameter at PACK level	Unit	Condition	State of the art 2019 (approximated average	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Lifetime expectation	Years & km	DOD90%	lifetime of a car 150.000km	lifetime of a car 150.000km	lifetime of a car 150.000km	N/A

PHEV - Parameter at PACK level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Lifetime expectation	Years & km	DOD90%	lifetime of a car 150.000km	lifetime of a car 150.000km	lifetime of a car 150.000km	N/A

Condition: Dependent on individual OEM

Relevance: Lifetime warranty conditions are defined to provide the expected lifetime of the battery system. This is typically aligned with the vehicle lifetime and can be up to two times higher for heavy duty applications compared to passenger cars. Also, this condition depends on the application and environmental conditions.

Battery Pack Cost

Definition: Battery pack costs are commonly described in $ or € per kWh (energy content) for BEV applications. The pack costs in $/kWh may increase for high power or PHEV applications due to their lower energy content.

Battery cost pack = Total cost of battery pack ($) / Battery pack energy content (kWh)

Unit: Cost is typically used as $/kWh (or €/kWh)

BEV - Parameter at PACK level	Unit	Condition	State of the art 2019 (approximated average	Target 2030 Mass market PC low range ~400km	Target 2030 Mass Market PC high range >600km	Target 2030 Mass market Commercial HDV
Cost	€ / kWh		*+30% of cell cost	*+20% of cell cost	*+15% of cell cost	N/A

PHEV - Parameter at PACK level	Unit	Condition	State of the art 2019 (approximated average values)	Target 2030 Mass Market PC PHEV e-mode ~100km	Target 2030 Typical distribution truck e-mode ~70km	Target 2030 Typical long-haul truck e-mode ~150km
Cost	€ / kWh		*+30% of cell cost	*+20% of cell cost	*+15% of cell cost	N/A

Condition: Total pack energy content is estimated by considering the energy discharged from the pack at 100% SoC to 0% SoC of the battery's operational SOC window (which is defined specifically by each OEM) at +25 °C at 1/3 C-rate

Relevance: In BEV the largest part in the overall vehicle cost is the battery pack. This indicator is important to understand the reduction on the costs of the battery system components. However, in certain heavy-duty applications, the total cost of ownership may be more relevant than simply considering only the battery pack costs.

General:

Moreover, thanks to its flexibility in terms of materials and design, Li-ion technology allows for the construction of batteries within a broad range of power to energy ratio (P/E) which enables their use in the entire range of electrified vehicles, from hybrid (HEV, P/E ~ 15), to plug-in hybrid (PHEV, P/E ~ 8), to fully electric (BEV, P/E ~ 3). 2–13 Fig. 1 shows the typical range of specific power and energy for the different types of electrified vehicles, as well as projected target ranges for the next generations of Li-batteries.

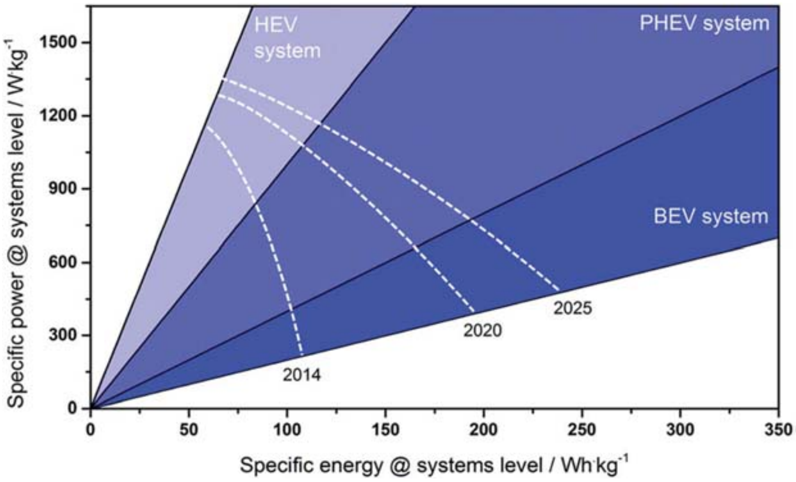

Fig. 5 Specific power and energy roadmap for battery pack for hybrid (HEV), plug-in hybrid (PHEV) and full electric (BEV) vehicles. Source: DOI: 10.1039/c5ta00361j

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ANNEX 1 – Acronyms and basic glossary

Acronym	Meaning
BEV	Battery Electric Vehicle
CCCV	Constant Current Constant Voltage
C-rate	Capacity rate
CV	Commercial Vehicles
DOD	Depth of Discharge
GB/T (standards)	Guobiao (Chinese National Standards)
HDV	Heavy-Duty Vehicle
LTO	Lithium Titanate Oxide
OEM	Original Equipment Manufacturer
PC	Passenger Car
PHEV	Plug-in Hybrid Electric Vehicle
SAE	Society of American Engineers
SI	International System of Units
SoC	State of Charge
SoH	State of Health
V	Voltage
WLTP	Worldwide harmonized Light vehicles Test Procedure

The following list of definitions has been created to explain this document; they indicate the meaning of those physical properties within the boundaries of the EUCAR "Battery requirements for future automotive applications" document.

Current

An electric current is a flow of electric charge. In battery cells this charge is often carried by ions in an electrolyte. The SI unit of electric current is the ampere (A), which is the flow of electric charge across a surface at the rate of one coulomb per second.

Voltage

Voltage is the difference in electric potential between two points. The SI unit of voltage is named volt (V),

Battery capacity

A battery's capacity is the amount of electric charge it can deliver at the rated voltage. The SI measures capacity in amp-hour (Ah).

C-rate

The C-rate is a measure of the rate at which a battery is being charged or discharged. It is defined as the current through the battery divided by the theoretical current draw under which the battery would deliver its nominal rated capacity in one hour. The SI unit for the C-rate is 1/h. C-rate is used as a rating on batteries to indicate the maximum current that a battery can safely deliver on a circuit.

Battery energy

The battery's energy is simply defined by the product of cell capacity in (Ah) * cell average voltage in (V) * the number of cells in a battery pack. The unit of battery energy is typically given in kilowatthours (kWh).

Power

Power is a general measure that is determined by the product of cells actual voltage (V) and the applied current (A). The unit is typically given in kilowatt (kW).

SOC

The state of charge (SOC) is an estimate of the device charge capability expressed as a percentage of the begin of life rated capacity and typically reached by obtaining specified voltages. If 50% of the cells charge carriers haven been discharged from cathode to anode its SOC is 50%.

SOH

SOH is an abbreviation for state of health. It is given in % and determines the battery's health condition which is referred to the actual capacity compared to the initial capacity. If a cell has a capacity of 50Ah after manufacturing and shows a remaining capacity of 40Ah after usage, SOH is calculated by 40Ah/ 50Ah *100 = 80%. 80% is a very important parameter in automotive applications since the end of life of a battery is determined when a cell has lost 20% of its initial capacity.

ANNEX 2 – Rationale for the different calculations in the document

On the energy density

In order to show that the given energy target values are plausible and can be realistically reached this document provides a basic calculation. Therefore, various assumptions for materials and electrode properties need to be fixed. The most important parameters to design a cell are the electrode mixtures, layer thicknesses corresponding to electrode loading and separator thickness and the cell format. For the cathode a ratio of 80 vol-% of nickel-rich layered oxide, 15 vol-% of solid electrolyte and 5 vol-% of binder and carbon black have been assumed. A porosity of 3 vol-% has been introduced to consider remaining porosity from the manufacturing process. The cathode loading was set to 5,8mAh/cm², resulting in a layer thickness <75µm when the aforementioned cathode mixture is applied, and thus in the same order of magnitude compared of today's lithium-ion batteries with liquid electrolyte. The solid separator thickness was set to 15µm. In order to compensate for lithium-ion losses the anode is over-dimensioned about 10% compared to the cathode and is made from 100 vol-% metallic lithium with 0 vol-% porosity.

The calculation has been done for prismatic cells in PHEV2 and BEV4 format and shows specific energies of 450 Wh/kg and 1000 Wh/l with a variation of ~ 5-10% depending on the chosen cell format.

An interesting fact for lithium-ion batteries is that Wh/kg and Wh/l most often show a relation factor of 2,2-2,5, which might be different for non-intercalation based technologies.