



Battery Systems for Multiple Units

Emission-free drives powered by lithium-ion cells

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Executive Summary

The Federal Ministry of Transport and Digital Infrastructure (BMVI) is promoting the development of low-emission drives for local rail passenger transport (SPNV) multiple units. Manufacturers such as Alstom, Bombardier, Siemens Mobility and Stadler are involved by implementing alternative drive concepts, the viability and cost-effectiveness of which need to be demonstrated in practice.

Accumulators for the realization of an alternative emission-free drive form

Supplying the electromotive drive of a train with energy from accumulators represents an attractive, emission-free alternative to diesel engines on non-electrified rail lines. The present VDE study ¹ compares battery technologies and cells that are suitable for use in traction batteries for multiple units and are already on the market or are expected to become available in the coming decade. It incorporates the results of a detailed analysis carried out by VDE on the basis of the requirements and simulations performed in Siemens Mobility GmbH's X-EMU development project. This study is the first in a series of scheduled publications aimed at examining the framework conditions and success factors for multiple units with alternative drive systems from various perspectives.

Special requirements for traction batteries in multiple units

There are highly exacting demands on the reliability and quality of multiple units, as they are expected to provide more or less 24-hour service (usually on a tight schedule) for up to 30 years. Their transport capacity, as expressed in passenger kilometres, is much higher than that of buses or cars. The requirements placed on traction batteries for multiple units are correspondingly stringent, particularly with regard to charging and discharging currents, safety, low-temperature performance, operating time and cycle stability. This considerably reduces the number of suitable cell candidates which are available on the market. Lithium-ion cells with LTO anodes, which are offered as a special technology by a handful of cell manufacturers, offer a safe but costly solution. A significant disadvantage is the relatively low energy density of this technology, which – depending on the specified range – can cause serious weight problems for multiple unit manufacturers.

Pragmatic alternatives to LTO-based battery cells

A further objective of the study was to find out whether and to what extent any of the requirements could be relaxed or compensated with the help of alternative approaches at the system level instead of meeting all requirements at the cell level.

The manufacturers of electric cars have opted for such a pragmatic approach within the framework of the National Platform for Electric Mobility (NPE). They are also relying on a cross-industry generation roadmap that provides information on the development of energy densities and related costs up to the year 2030.

The present study concludes with courses of action and recommendations for possible alternative battery concepts.

¹ VDE – Association for Electrical, Electronic & Information Technologies; <https://www.vde.com/>

1

Introduction and Motivation

Buses, trams and trains operate around the clock in all weathers. They are exposed to wind and rain, heat and cold. Their use is calculated in decades or hundreds of thousands of kilometres. All these requirements far exceed those of most ordinary passenger cars. This difference also applies to battery-powered public transport vehicles. Accordingly, the study is preceded in the present chapter by a detailed analysis of the requirements for the operation of battery-powered multiple units and a comparison of the solution concepts of different manufacturers.

1.1. Environmental and climate requirements

By signing the Paris Agreement, Germany committed itself to reducing its CO₂ emissions by 80 to 95 per cent in comparison to the 1990 levels by 2050. Germany has set itself an interim target of 55 per cent by 2030. Such targets have consequences for industry as well as for private and commercial transport. In recent decades, impressive progress has been made in improving energy efficiency, pollutant emissions and noise levels in combustion engine-based drives. Nevertheless, CO₂ emissions in the transport sector have scarcely decreased since 1994, as increasing numbers of ever more powerful vehicles are to be found on Germany's traffic routes. The emission of climate-damaging gases is a global problem that must be solved at the international and intercontinental level. Road traffic continues to be the cause of problems such as noise or fine dust pollution in the cities which need to be dealt with locally.

In the medium and long term there seems to be no alternative to other, electric motor-based drive systems that are considerably more energy-efficient and quieter than internal combustion engines and, due to their comparatively simple design, consist of considerably fewer components.

1.2. Classification of electric drives and batteries

The electrical power required to operate an electric vehicle is generated and provided in different ways, depending on the type of drive. The electricity can be generated on board by a diesel-powered engine ("power generator") and fed directly to the electric motor. A more environmentally friendly option is to provide electricity from fuel cells that draw their energy from the controlled oxidation of hydrogen. In both cases, the fuel (diesel or hydrogen) must be carried in tanks and regularly replenished.

Alternatively, lithium-ion batteries optimized for vehicle drives are now available which provide the electric current dynamically but can also absorb the current generated during braking. These batteries can be recharged on-board using power generators or fuel cells, or from an external source at charging stations or via a overhead line (where available).

Electric vehicles with combined drive and supply systems are also referred to as hybrid electric vehicles (HEVs). Vehicles in which the traction battery can be charged externally, e.g. at a charging station, are referred to as plug-in hybrid electric vehicles (PHEVs). On the other hand, vehicles which obtain their required drive energy exclusively from a battery that can be charged externally are referred to as battery electric vehicles (BEVs).

In local rail passenger transport, so-called multiple units are used in which the drive technology is not housed in a separate locomotive but in one or more of the two or three carriages of the train (referred to below as 2-car or 3-car trains). Electric multiple units are known as EMUs; diesel multiple units as DMUs. The abbreviation X-EMU is used to denote alternative drive MUs (diesel-electric, fuel cell, battery).

The motors used in electric vehicles today are three-phase asynchronous motors (ASMs), permanently excited synchronous machines (PSMs), hybrid synchronous machines (HSMs) or current-excited synchronous motors (SSMs). What all these machine types have in common is that, during braking, they function as generators which convert the kinetic energy of the vehicle back into electrical energy. This process is also called recuperation. Stored in the traction battery, the recuperated energy is available for the next acceleration phases of the vehicle and thus helps to increase the traction efficiency. For this reason, the use of batteries makes sense in all forms of electric drives, including HEVs. The battery types used in the three drive concepts mentioned (HEV, PHEV, BEV) differ in important aspects. In BEVs, the range is determined by the level of battery capacity, which is why battery cells with optimized (volumetric) energy density are used (→ maximum energy content per volume unit). In HEVs/PHEVs, rapid charging via the alternator of the combustion engine or the recuperation of braking energy is decisive, i.e. here, it is less the level of battery capacity than the ability to quickly draw and release power that is decisive (→ high-current capability, high power density).

1.3. Status quo and areas of application for hybrid multiple units

The German railway network covers about 40,000 kilometres, of which about 23,000 kilometres are electrified with overhead lines. By European standards, this is only a middling figure at 58 per cent [1]. Experts recently demanded complete electrification of the system as an environmentally friendly measure, even if this would cost around EUR 11.5 billion [2]. Implementation of this demand is probably not economically viable, since most of the non-electrified lines are only used to a limited extent. In addition, many of these lines are in areas of natural beauty, where widespread electrification would meet with resistance if overhead lines were perceived as an eyesore.

Up to now, diesel-powered trains have been deployed on the non-electrified railway lines. A total of around 2,900 diesel multiple units are currently in service in Germany, about one third of which are more than 20 years old [3]. The increasing demands on low-emission vehicles suggest that commissioning authorities² are increasingly relying on diesel hybrids or vehicles with alternative propulsion systems based on fuel cells or batteries.

Which drive concepts or hybrid combinations will actually be in demand and will prevail also depends on the parts of the railway network to be covered. In extensive, non-electrified networks such as those in Schleswig-Holstein, the range and the possibility of rapid refuelling or recharging (as appropriate) will be important decision-making criteria. If, on the other hand, it is merely a question of bridging the gaps on routes without catenary between electrified regions, it makes sense to demand hybrid multiple units which are equipped both with pantographs for overhead wires and with alternative drive systems. In this case, drives with batteries that can be recharged on routes with catenary may be useful. Depending on the distances to be bridged, it may even be possible to dispense with charging stations along the lines. If greater distances have to be bridged, it might make more sense to rely on fuel cells which can accommodate longer ranges and the required amount of hydrogen for which can be refuelled in a few minutes.

Similar considerations also apply to the so-called last mile, i.e. the non-electrified section to the destination station where a battery charging station or catenary or an H₂ filling station is provided.

² The term "commissioning authorities" (Aufgabenträger) refers to institutions which are in Germany assigned the planning, organization and financing of local rail passenger transport by law or statute at the state or regional level.

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Requirements for accumulators in battery-powered multiple units

The railway lines which have not yet been electrified with catenary wires are mainly local regional and passenger lines. Since the federal government's present transport infrastructure plan (BVWP) does not provide for any further electrification, only alternative drive technologies can be considered as replacements for older multiple-unit diesel trains, for environmental and climate protection reasons. Pollutant-free emissions can be achieved locally with battery or fuel cell-based drives. Such solutions become climate-neutral when the required electricity or hydrogen is produced using renewable energy.

This study focuses on battery technologies and solutions that are suitable for use in battery-powered multiple units. Similar to the case of battery-powered cars, guaranteeing a certain minimum range is a major challenge. The range of 40 kilometres given for the Talent 3 battery electric multiple unit ³ is quite short and indicates that the energy density of charged traction batteries is very low compared with the fuel capacity of a full diesel tank which yields a range of 1,000 km. Nevertheless, there are powerful arguments in favour of developing battery-powered multiple units. In Germany, two thirds of all lines used by Diesel Multiple Units contain non-electrified gaps shorter than 70 kilometers. A guaranteed range of 80 kilometres would therefore be sufficient on most routes, as long as the battery can be charged via the catenary wire using a pantograph and the amount of time spent connected to the contact wire is sufficient to fully charge it. In this case, the advantages far outweigh those of diesel multiple units: electric motors are more energy-efficient and require less maintenance than internal combustion engines, and the energy generated by the electric motors during braking can be fed back (recuperated) into the traction battery. The battery itself is virtually maintenance-free. Also, this drive system does not emit any hazardous pollutants into the local environment.

Multiple units generally operate more-or-less around the clock every day, throughout the year, in hot and cold temperatures, for up to 30 years. High discharge currents are taken from the traction battery when starting up, accelerating or travelling uphill and it must absorb very high charging currents during braking and additionally when charging via the contact wire. All these different loads affect the life of the battery. Choosing the best technology and the appropriate dimensioning of the battery capacity for a multiple unit is an optimization task in which what is technically feasible has to be reconciled with what makes economic and ecological sense. The following sections of this chapter are taken up with defining the technical requirements. Economic and ecological aspects follow later in the study.

2.1. Operational load profiles

The starting point for specifying an appropriate alternative drive concept is simulating the operational usage, power requirement and energy consumption of the configured multiple unit in realistically modelled route profiles which include stops and electrification islands at varying intervals. Such simulations are commonly used in the industry when designing trains and their components.

³ See Section 2.6 Bombardier

Siemens Mobility GmbH has provided operational usage profile files for this VDE study, dividing the operation into normal or high loads. 95 % to 5 % was assumed for the temporal relation between normal and high-load operation. In the simulations, the traction battery is charged with an output of 2.3 megawatts from the overhead line. In addition, the electric motors contribute up to 1.5 megawatts of recuperation power to charging during braking.

→ Figure 1 shows charging-discharging patterns over a period of 100 minutes when the battery is discharged under normal load, partially recharged during braking through recuperation and then supplied with energy from the overhead contact line until it is fully recharged after a longer phase connected to the catenary. Average discharge currents of 0.3 to 0.6C are shown. In high-load operation, on the other hand, the traction battery is discharged with currents of 0.9 to 1.3C, as shown in → Figure 2. The traction battery is charged at 3C in both load cases.

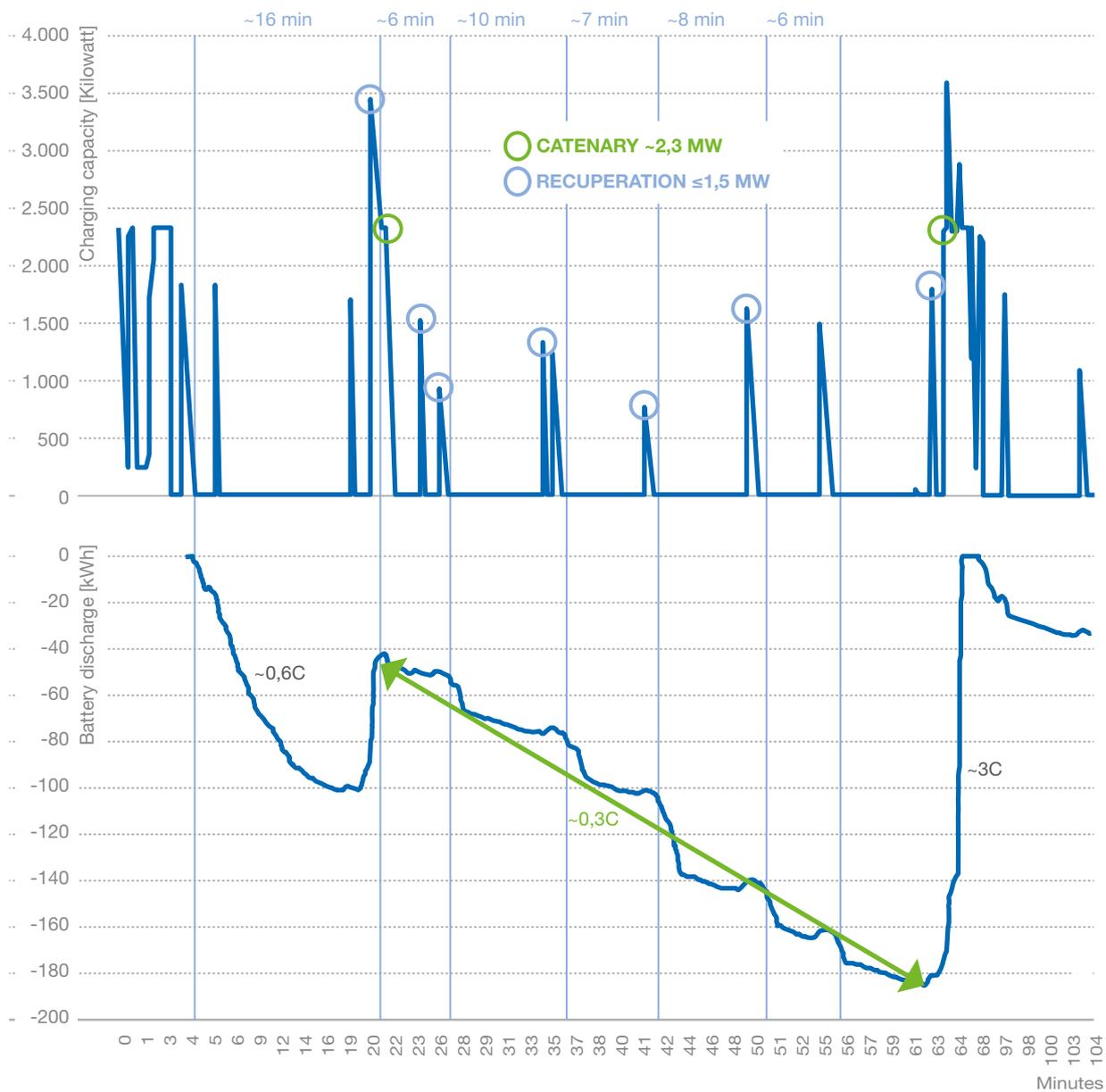


Fig 01 Simulation of normal load operation of a battery-powered multiple unit (detail)

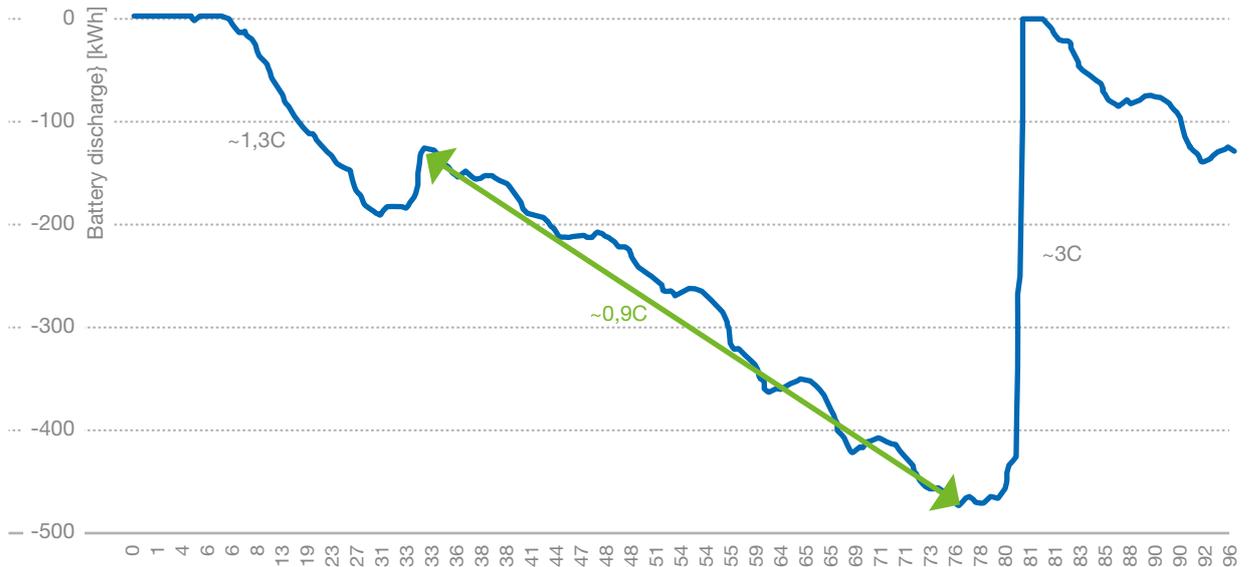


Fig 02 Simulation of high load operation of a battery-powered multiple unit (detail)

2.2. Range and battery capacity

In high-load operation – i.e. in 5 % of operation – the battery discharges more than 450 kWh in the relevant time frame before the train reaches the next charging point. The usable energy content of the battery should therefore not be less than this value in order to cover all normal and high load operating eventualities. Assuming an average energy requirement of 6 kWh/km as shown in the simulations, the calculated range is 80 kilometres.

The nominal capacity of the battery – its maximum energy content at the beginning of life (BoL) – must in practice be considerably higher than the usable energy content, since each discharge results in a slight reduction in capacity. Once this falls below 80 % of the nominal capacity, the battery is considered to be flat, i.e. it has reached its end of life (EoL). Discharging to a state of charge (SoC) close to 0 % and charging to a SoC of close to 100 % (i.e. a depth of discharge (DoD) of 100 %) is particularly stressful for a cell. The service life of the cell is essentially determined by the frequency of such occurrences. According to expert estimates, the SoC window should be between 10 and 90 % for a useful life of 15 years, i.e. the DoD should be limited to a maximum of 80 %. Based on that, a battery-driven multiple unit accumulator should have a nominal capacity of at least 700 kWh.

2.3. Weight and volume requirements

Once a particular lithium-ion cell type has been chosen, the ideal nominal capacity of 700 kWh and a realistic assumed battery voltage of 1 kV can be used to estimate the total weight and volume requirements of the battery modules on the roof or floor of the multiple unit. As an example, a high-energy SCiB cell from Toshiba is chosen which, according to its specifications, has a capacity of 23 Ah and a nominal voltage of 2.3 volts. In total, around 13,000 cells of this type would be required to achieve a total capacity of 700 kWh. The minimum volume and weight of the battery would therefore be 3.5 m³ and 7.3 t respectively. In addition, the weight and volume of the required module housings, cooling plates and associated cables, wiring and data bus, components of the battery management system and other components must also be taken into account. The entire battery system would weigh about 10 t, which would correspond to a gravimetric energy density of approx. 70 Wh/kg.

2.4. Fast charging capability

The speed at which a battery can be charged or discharged is measured in C rates. The C rate stands for the change in the energy content of a battery per unit of time in relation to its nominal capacity. It is a relative quantity: during discharging, the C rate describes the discharge power [in kW] in relation to the nominal capacity of the battery [in kWh]. During charging it provides a measure of the ability of the battery to achieve a defined change in the charge level [in kWh] from the given charging power, i.e. the ability to absorb the charge current supplied.

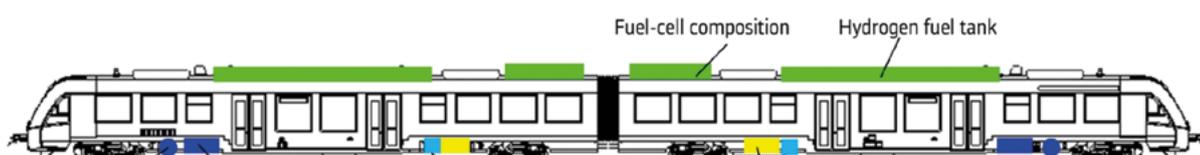
In practice, the C rate is a continuously changing variable while charging and discharging of a multiple unit traction battery during operation: it reflects the charging power currently being supplied or the discharging power being used. The simulated operation profiles show that under normal and high load conditions, a C rate of around 4.5 to 5C can be expected during charging, and around 3.5C during discharging, but only within a few seconds (momentary). Averaged over 3 minutes, the C rates are significantly lower: 3C during charging, 1C or 2C during discharging in normal/high load operation.

2.5. Low-temperature suitability

Like all other vehicle equipment, the traction battery of the battery-powered multiple unit must function as specified at external air temperatures between -25 °C and +40 °C. This corresponds to class T1 according to EN 50125-1⁴ or class 5K2 according to EN 60721-3-5. In fact, the given temperature range refers to the air surrounding the train. The temperatures which actually occur in the battery containers and inside the individual battery cells are not known.

2.6. Hybrid solutions from the manufacturers

The business opportunities presented by the expected demand for hybrid multiple units have prompted renowned manufacturers of locomotives and multiple units (such as Bombardier, Alstom, Siemens and Stadler) to develop their own solutions, in some cases with public subsidies. The different approaches are outlined below and the performance data of the batteries (where available) are summarized in a table.



Alstom

As part of the BethHy and BethHy2 projects sponsored by the German Federal Ministry of Transport and Digital Infrastructure (BMVI), Alstom is developing a hybrid multiple unit with fuel cell propulsion using its Coradia LINT multiple unit platform [4]. The new name is "Coradia iLINT". The train was tested with passengers on the route between Buxtehude and Bremerhaven in the first half of 2018 and received approval from the Federal Railway Authority (EBA) in July 2018 for use in the German passenger rail traffic network [5]. According to Alstom, Coradia iLINT is the world's first low-floor passenger train to generate its electrical power from two 200 kW H₂ fuel cell packs⁵. This multiple unit, with a specified range of 1,000 km, is used as a replacement for diesel-electric multiple units [6].

⁴ EN 50125-1: Railway applications - Environmental conditions for equipment

⁵ The manufacturer is the Canadian company Hydrogenics.



Fig 03 Coradia iLINT on special trip to Frankfurt-Höchst (13 April 2018)

On 13 April 2018, the public was given the opportunity to take a special trip on the Coradia iLINT from Wiesbaden Central to Höchst, 37 kilometres away. Large quantities of hydrogen are produced in the Höchst industrial park as waste gas in the manufacturing processes. Up to now this unused hydrogen has been burned or mixed with natural gas. The fuel cell train allows this hydrogen – which is not generated in a climate-neutral fashion – to be used in an environmentally friendly way. The advantage of Höchst as a location is that all the relevant non-electrified rail lines in State of Hesse pass through there, allowing regular hydrogen refuelling to take place without detours. According to Alstom, the energy consumption of the prototype train is roughly $300 \text{ g-H}_2/\text{km}$ [$\approx 10 \text{ kWh/km}$]. Since the tanks can carry a maximum of 160 kilograms of hydrogen, the range is currently just over 500 kilometres.

Alstom has also incorporated a liquid-cooled dynamic battery system from the Darmstadt-based manufacturer AKASOL in order to achieve the driving dynamics required for operating the train and also to make use of the recuperation energy generated by the electric motor during braking. This system includes two 800 volt battery packs, each with 110 kWh capacity. Each of these packs consists of three Akastem 18 AKM NMC-NANO battery modules connected in parallel, with a nominal capacity of 36.8 kWh each [7]. The battery system can be continuously charged at 2C according to the manufacturer's specifications, and at 4C in pulse mode (40 seconds). It is designed for operation in an ambient temperature range of -25°C to $+45^\circ\text{C}$ [8]. A weight of 425 kg and a volume of $\approx 0.3 \text{ m}^3$ is given for each individual module. This corresponds to a comparatively low gravimetric energy density of $\approx 86 \text{ Wh/kg}$ or a volumetric density of $\approx 123 \text{ Wh/l}$.

The cells installed in the modules are based on NMC-NANO, a Kokam technology which combines the properties of the familiar electrode materials NCM (=NMC), LFP and LTO in such a way that allows high C rates to be achieved for charging/discharging and operation in a wide temperature range while ensuring high safety levels against thermal runaway [9].



Fig 04 TALENT 3 BEMU at Bombardier plant, Hennigsdorf (2018)

Bombardier

Supported by the German Federal Ministry of Transport and Digital Infrastructure (BMVI), Bombardier has been developing a battery-powered multiple unit based on its own “TALENT 3” platform (BEMU project)⁶ [10] since 2016. This train is scheduled to go into operation in 2018/2019.

According to Bombardier, a battery pack solution (MITRAC) developed by Primove [11] for tram and light rail applications is used. This is an optimized version of the “PRIMOVE Battery 50” [12]. It consists of a battery system composed of two parallel packs – each pack is equipped with its own battery management system (BMS) and the system has a common thermal conditioning unit (TCU). The two battery packs each contain 12 battery modules.

According to the data sheet, the capacity of the battery pack is 49 kWh – at a nominal voltage of 532 volts. The weight (including TCU) is 837 kg, the volume is $\approx 0.9 \text{ m}^3$.⁷ The service life of the battery is given as 10 years. According to Bombardier, the lithium-ion cell type used is based on performance-optimized NCM/graphite technology.

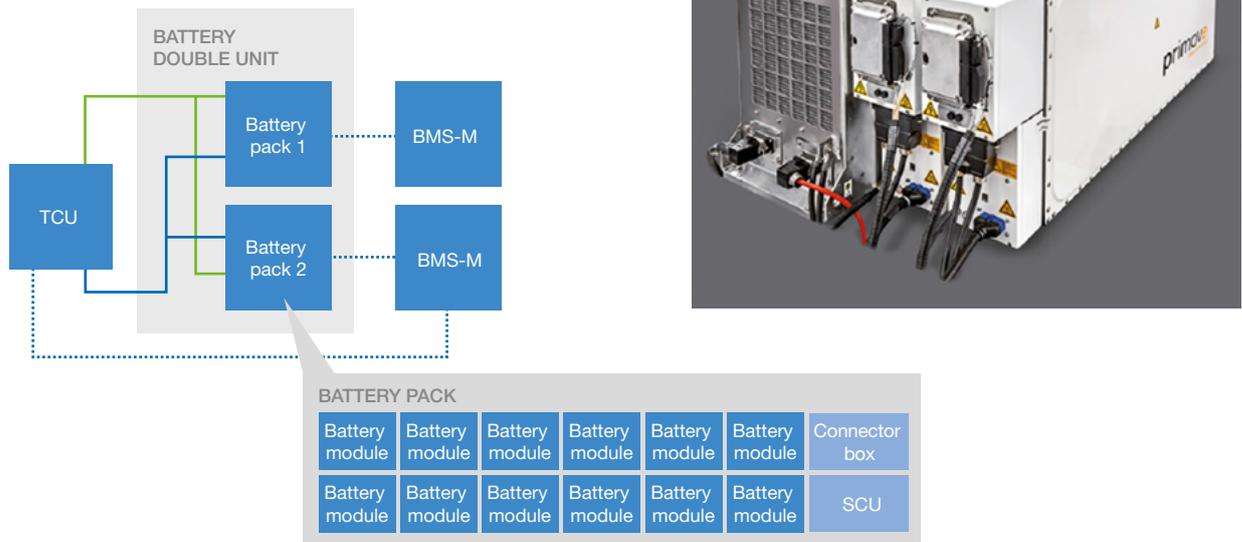
In designing the battery system for BEMU, Bombardier assumed that two-thirds of the distances travelled by the diesel multiple units were shorter than 70 kilometres, and that over a quarter were less than 40 kilometres [13]. In the project, Bombardier opted for battery capacities of either 300 kWh or 440 kWh in order to be able to guarantee a range of 40 to 100 kilometres at a consumption level of 4 to 8 kWh/km. These figures do not take into account the fact that the depth of discharge (DoD) should be well below 100 % for optimum battery life, i.e. only part of the battery capacity should be used.



⁶ Battery Electric Multiple Unit

⁷ This corresponds to a system energy density (incl. cooling) of approx. 60 Wh/kg or 55 Wh/l.

Fig 05 PRIMOVE Battery 50 – battery pack solution [12]



Siemens Mobility

Also supported by BMVI, Siemens Mobility GmbH is developing a hydrogen fuel cell based drive that will be used in Mireo multiple units from 2019. For fuel cells, Siemens Mobility is relying on the next generation of Ballard cells. These deliver twice as much power for the same installation space while yielding considerably more operating hours than the previous generation. The fuel cells ensure long ranges in this drive concept ($\approx 15\text{--}30 \text{ kg-H}_2/100 \text{ km}$). The lithium-ion battery provides the required dynamics for starting and accelerating the train. It also serves as a reservoir for the recuperation energy generated by the electric motors during all braking processes. No further data is currently available on this battery.

A special feature of the Siemens concept is that the Mireo platform is used as a modular traction system. At the same time, Siemens Mobility is developing a purely battery-operated drive system, the lithium-ion battery modules of which are distributed over two to four containers for fuel cells and dynamic batteries on the roof or in the floor of the multiple unit. According to Siemens Mobility, a battery capacity of 600 to 700 kWh is planned for the two-car multiple unit variant, which will provide a guaranteed range of 80 kilometres.



Fig 06 Mireo multiple unit platform from Siemens Mobility GmbH



Stadler

The Swiss manufacturer Stadler is currently developing an emission-free variant on its two-car multiple unit WINK (“Wandelbarer Innovativer Nahverkehrs-Kurzzug” = “Convertible Innovative Commuter Short Train”) platform.

The central part of the train, known as the “PowerPack”, contains the components for power generation, traction and the auxiliary systems. The new trains for Arriva Netherlands will be powered by a diesel engine running on hydro-treated vegetable oil (HVO). Batteries are also provided to store the braking energy. In the event of longer standing times in railway stations, the diesel engine of the multiple unit will be switched off in future, and the required energy taken from the battery. This “bi-modal” multiple unit WINK train will be operated in the Netherlands on the Leeuwarden-Groningen line and in the provinces of Friesland and Groningen. The diesel engines are to be replaced by batteries from 2025. The system will operate on 1.5 kV DC voltage [14]. No detailed information on the technology and capacity of the batteries is currently available.

CRRC (China)

In partnership with the Railway Vehicle Corporation in Tangshan, the National Rail Transit Electrification and Automation Engineering Technology Research Center (NEEC) in Chengdu has developed a fuel cell-powered three-car, low-floor tram. Two fuel cell modules from the Canadian manufacturer Ballard Power provide a total output of 300 kW which drives eight 46.6 kW electric traction motors.

To deliver the specified range of 40 km, 10 kg of hydrogen compressed to 350 bar is carried in a tank on the roof. A 20 kWh lithium-ion battery in combination with a supercapacitor (which has a voltage of 528 volts and a capacity of 45 farad and contributes around 1.7 kWh) serves as a dynamic energy storage device. This tram is designed for 180 passengers and the first successful demonstrations were carried out in May 2016. [15]



Fig 07 Fuel cell tram in China [16]

In March 2017, the China Railway Rolling Stock Corporation (CRRC) Qingdao Sifang signed an agreement to supply eight fuel cell-powered trams to the southern Chinese city of Foshan for use on the 17.4 km Gaoming line from 2018. The tram is based on Škoda's licensed ForCity 15T model and uses Ballard's FCveloCity fuel cell system. It is designed for speeds up to 70 km/h. Seven of these trams have been operating successfully in the city of Qingdao since 2016 on an 8.8 km line with 12 stops. This means that China is now probably the world leader in fuel cell-powered trams, both in terms of the number and length of lines.

Overview of battery designs

→ Table 1 shows the different designs that manufacturers have chosen for the lithium-ion batteries required for their multiple units running on alternative drive systems. The only information currently available from Stadler is that a dynamic battery is envisaged in their bi-modal multiple-unit train concept. No technical data is given. For this reason, no separate column has been included in the table for Stadler.

Tab 01 Specifications of multiple unit batteries from different manufacturers

Train manufacturer	Alstom	Bombardier	Siemens	Siemens
Name	Coradia iLINT	Talent 3 battery MU	Mireo hybrid MU	Mireo battery MU
Type	Fuel cell + dynamic battery	Battery MU with pantograph	Fuel cell + dynamic battery	Battery MU with pantograph
Battery type	Akaystem 18 AKM NMC-NANO	PRIMOVE Battery 50	Actia special development	Actia special development
Battery manufacturer	AKASOL	PRIMOVE (Bombardier)	Cell manufacturer Toshiba	Cell manufacturer Toshiba
Battery technology	NMC-NANO	NCM/C	NCM/LTO	NCM/LTO
Traction battery - total capacity	220 kWh	300/440 kWh	~200 kWh	~700 kWh
Traction battery - total weight	~2.6 t	7.5 t	~9 t (FC+batt)	9.5 t
DTE (distance to empty)	600–1,000 km	40–100 km	600–1,000 km	80–120 km

3

Technology overview of lithium-ion cells and supercaps

There are exacting technical requirements for batteries in multiple units, as can be seen in Chapter 2. Toshiba's lithium-ion cell (SCiB 23 Ah) is a special component whose properties have been optimized for use in traction batteries for buses, trams, locomotives and multiple units. One consequence of this optimization is that the cell has a relatively low gravimetric energy density, i.e. its vehicle range and battery weight are disproportionate to each other.

Section 3.1 below provides an overview of the battery technologies available today that are suitable for use in the traction system of a battery-powered vehicle, in particular battery-powered multiple units. Key characteristics for evaluating the technologies include:

- Energy density (gravimetric, volumetric), i.e. the electrical energy [in Wh] which the cell can store and release per kilogram weight [in Wh/kg] or litre volume [in Wh/l]
- Power density (gravimetric, volumetric), i.e. the electrical power [W] that a cell can provide per kilogram weight [W/kg] or litre volume [W/l];
- Safety arising from measures taken to stabilize the lithium-ion cell, e.g. against thermal runaway in the event of overload;
- Cycle stability and calendar life;
- Usability at temperatures below 0 °C.

These parameters depend not only on the selection of active materials, but also on the design of the cell and the additives used.

Section 3.2 gives a technological overview of supercapacitors (also known as supercaps). These are already used in some electric vehicles because of their power densities, cycle rates and service lives, which far exceed those of today's lithium-ion cells. However, since their energy densities are far below those of lithium-ion cells, they are only described here for the sake of completeness and will not be considered in the following chapters. If progress is made in significantly improving their energy densities in the future, supercaps could become a viable alternative.

3.1. Lithium-ion cells

3.1.1. Structure of a cell

Each lithium-ion cell (see → Figure 8 [17]) consists of a negative and a positive electrode, an ion-conductive electrolyte that enables the charge exchange between the electrodes, and a separator that electrically separates the two. The following convention exists regarding the names of the electrodes: the electrode on which the active material (e.g. the transition metal cobalt) is chemically reduced during discharge is called the **cathode** of the cell. The other electrode, correspondingly, is called the **anode** because its active material (e.g. graphite) is oxidized during discharge.

The following materials were used as cell components when the lithium-ion technology was commercialized by SONY in 1991:

- Lithium cobalt oxide as cathode material
- Graphite as anode material
- Mixture of organic carbonates (including ethylene carbonate) as electrolyte

These cells had a nominal voltage of 3.7 volts and an energy density of approx. 200 Wh/l or 80 Wh/kg. Today's commercial cells reach volumetric energy densities of more than 500 Wh/l. Special cells have been developed to meet one or more of the above requirements for different applications.

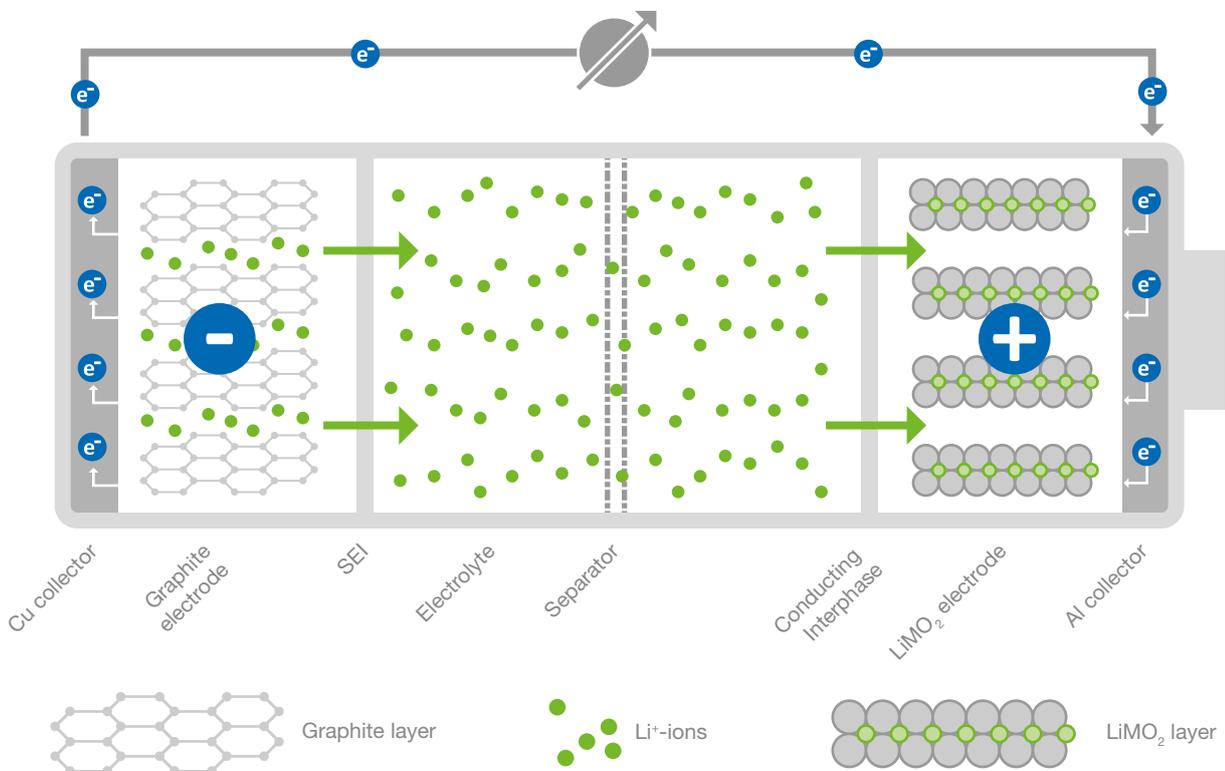


Fig 08 Structure and function of a lithium-ion cell during discharge [17]

3.1.2. Cathodes

Lithium transition metal oxides (LCO, NCA, NCM)

Lithium transition metal oxides are arranged in a so-called layered R-3m structure. → Figure 9 shows this structure using LiCoO_2 as an example.

(a) Lithium cobalt oxide, LiCoO_2 (LCO)

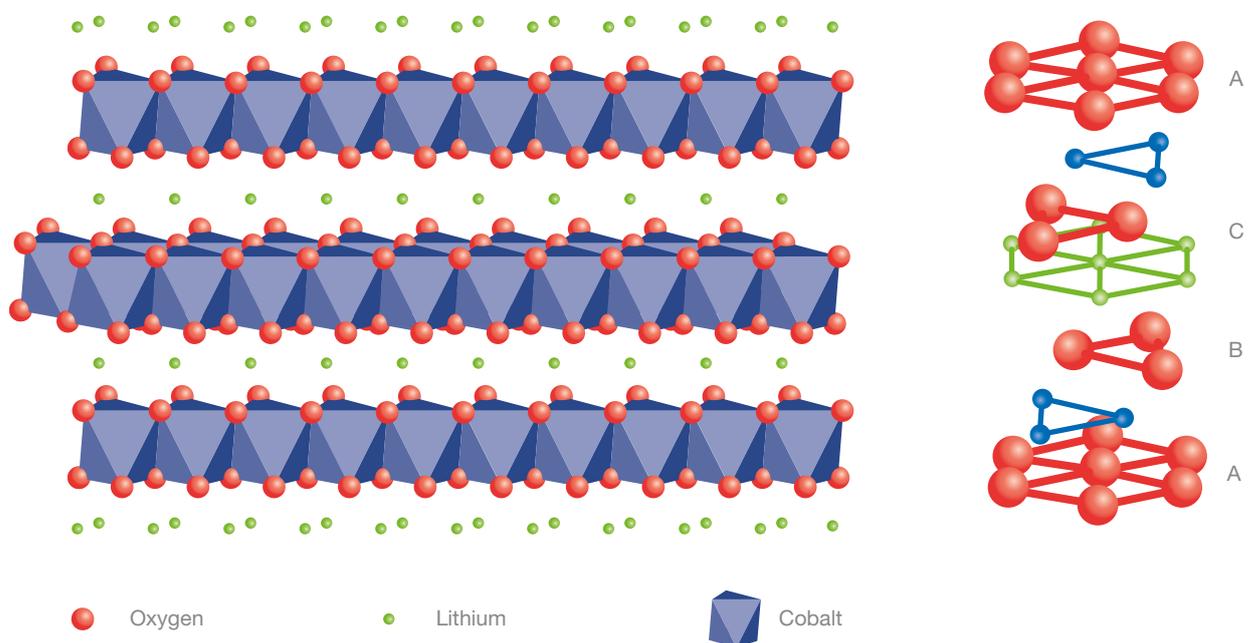


Fig 09 Layered R-3m LiCoO_2 structure [18]

LCO was the first cathode material to be used in lithium-ion cells. Due to the good balance between its capacity, power density and material processability, LCO is still the most commonly used cathode material for cells in consumer electronics [19]. A disadvantage of LCO is its relatively low thermal stability, because thermal decay of the charged LCO (Li_xCoO_2 , $x < 1$) begins even at temperatures below $150\text{ }^\circ\text{C}$. The reaction is exothermic, and gaseous oxygen (O_2) is formed which is responsible for electrolyte combustion (“thermal runaway”). Another disadvantage is the high price of cobalt as a raw material: at approx. 75 €/kg cobalt is currently over seven times more expensive than nickel, for example.

Optimization measures on the basis of LCO: The cobalt content of the cathode material can be reduced by using alternative metals. For example, partial replacement of cobalt by nickel gives the cathode even greater capacity. However, this results in deterioration of both the thermal and structural stability. For this reason, a third metal which is electrochemically inactive in the given crystal structure is added to stabilize the active material. Aluminium or manganese are generally used for this purpose.

The following two alternative cathode materials were developed on this basis:

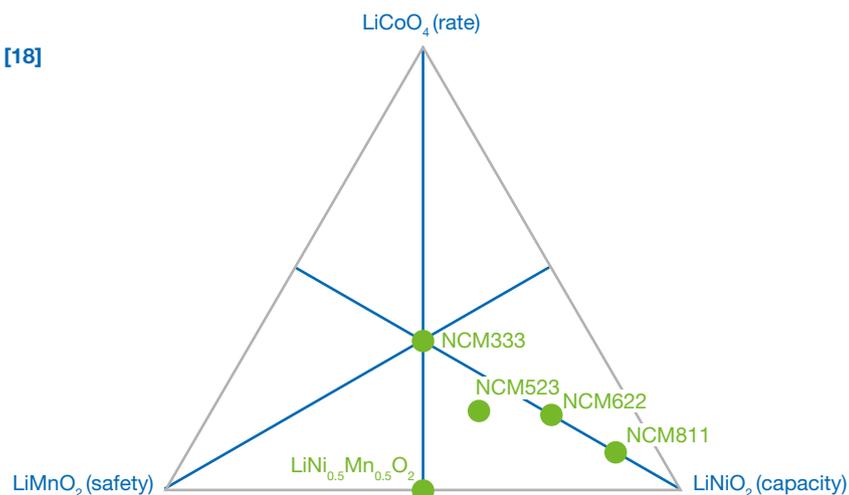
b) Lithium nickel cobalt aluminium oxide, $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$ (NCA)

Replacing cobalt with nickel, in the ratio given in the formula $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$ (NCA), causes the capacity of the cathode material to increase from 140 mAh/g to almost 200 mAh/g. The addition of aluminium (Al < 1.5 % weight of the active material) provides the necessary stability of the crystal structure which roughly corresponds to that of LCO. The power density is slightly lower. NCA is combined with graphite as the anode in the round cells of Panasonic's NCR series. At over 240 Wh/kg, these cells currently have the highest gravimetric energy density among commercially available lithium-ion cells. This is one reason why Tesla uses them in its electric cars.

c) Lithium nickel cobalt manganese oxide, $\text{LiNi}_{1-x-y}\text{Co}_x\text{Mn}_y\text{O}_2$ (NCM or NMC)

By combining the three transition metals ⁸ nickel, cobalt and manganese to form ternary materials – formally described by the mixture formula $\text{Li}[\text{Ni}_{1-x-y}\text{Co}_x\text{Mn}_y]\text{O}_2$ – cathode materials can be “designed” with properties which derive from the mixture ratio of the three metals. The spectrum of all theoretically possible combinations can be represented as a triangle of the three transition metal oxides LiCoO_2 (LCO), LiNiO_2 (LNO) and LiMnO_2 (LMO), with one of the three metals not occurring in each of which (see → Figure 10). LCO, LNO and LMO have been extensively studied for their suitability as cathode materials: each is deemed to have its own specific advantages and disadvantages. The roles that the transition metals actually play in the ternary material mixtures can be characterized by specific characteristics: Nickel increases capacity and cobalt improves the rate capability. Manganese increases safety: manganese is electrochemically inactive in the NCM crystal structure, i.e. its oxidation state remains unchanged at +4 during charging and discharging. This “manganese(IV)” stabilizes the structure and improves the material safety. However, the manganese content reduces the capacity of the cathode. To a small extent, manganese can also contribute to cell aging, as Mn+4 ions can be reduced to Mn+2 which, at low cell voltage, dissolves in the electrolyte and thus changes the crystal structure.

Fig 10 Phase diagram of mixtures of the transition metals Ni, Co, Mn [18]



⁸ Transition metals are elements with the atomic numbers 21-30, 39-48, 57-80 and 89-112. Ni, Co and Mn belong to the first group.

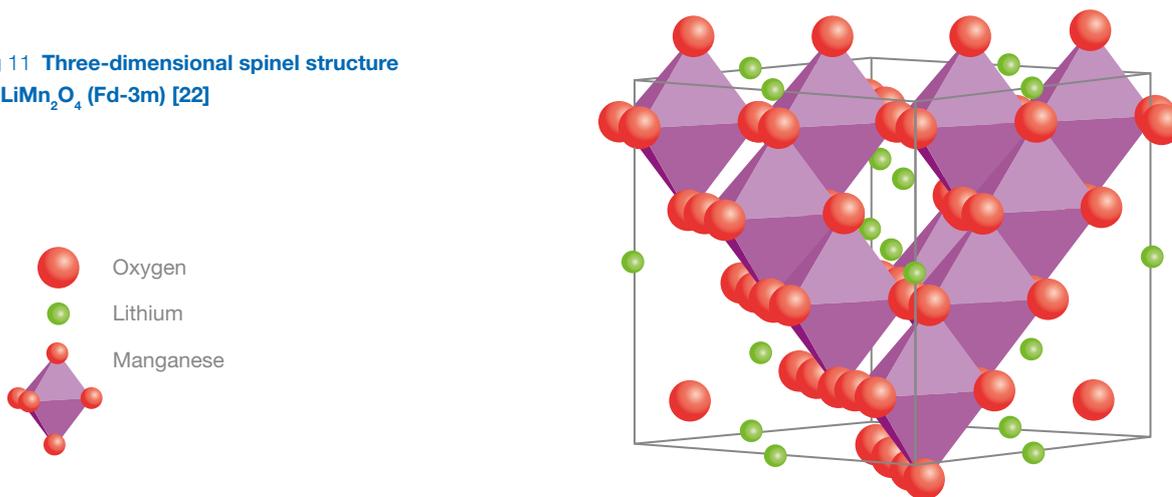
Any shift in the proportions in favour of one metal is at the expense of the other characteristics. For example, a nickel-rich material such as $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.01}\text{O}_2$ (NCM811) has disadvantages in terms of power density, cycle capability and safety: in the long term, the nickel content causes the crystal structure of the material to decompose and thus a loss of capacity. In addition, the thermal stability is no better than that of LCO. Other relevant mixtures essentially line up along the line of compromise between “rate” and “safety”.

In practice, $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$ (NCM333) has established itself for the time being as a good compromise in the NCM group with regard to energy density, cycle stability and safety. The lower cobalt content makes this material cheaper than LCO or NCA. In addition, NCM is thermally more stable than these: decay of the charged NCM cathode and the resulting release of oxygen only starts at 300 °C [20]. At 160 mAh/g, the specific capacity of NCM333 is similar to that of LCO. However, the lower electrode potential reduces the cell voltage, thus resulting in a lower energy density [21].

Lithium manganese oxide spinel (LMO-s)

The lithium manganese oxide spinel, LiMn_2O_4 (LMO-s), differs from other lithium transition metal oxides by its crystal structure (see → Figure 11). The spinel structure (Fd-3m) of the material permits the diffusion of lithium ions in all three dimensions. This property yields higher currents and a high power density, see → Table 02. For this reason, cells with LMO-s cathodes are used above all in power tools.

Fig 11 Three-dimensional spinel structure of LiMn_2O_4 (Fd-3m) [22]

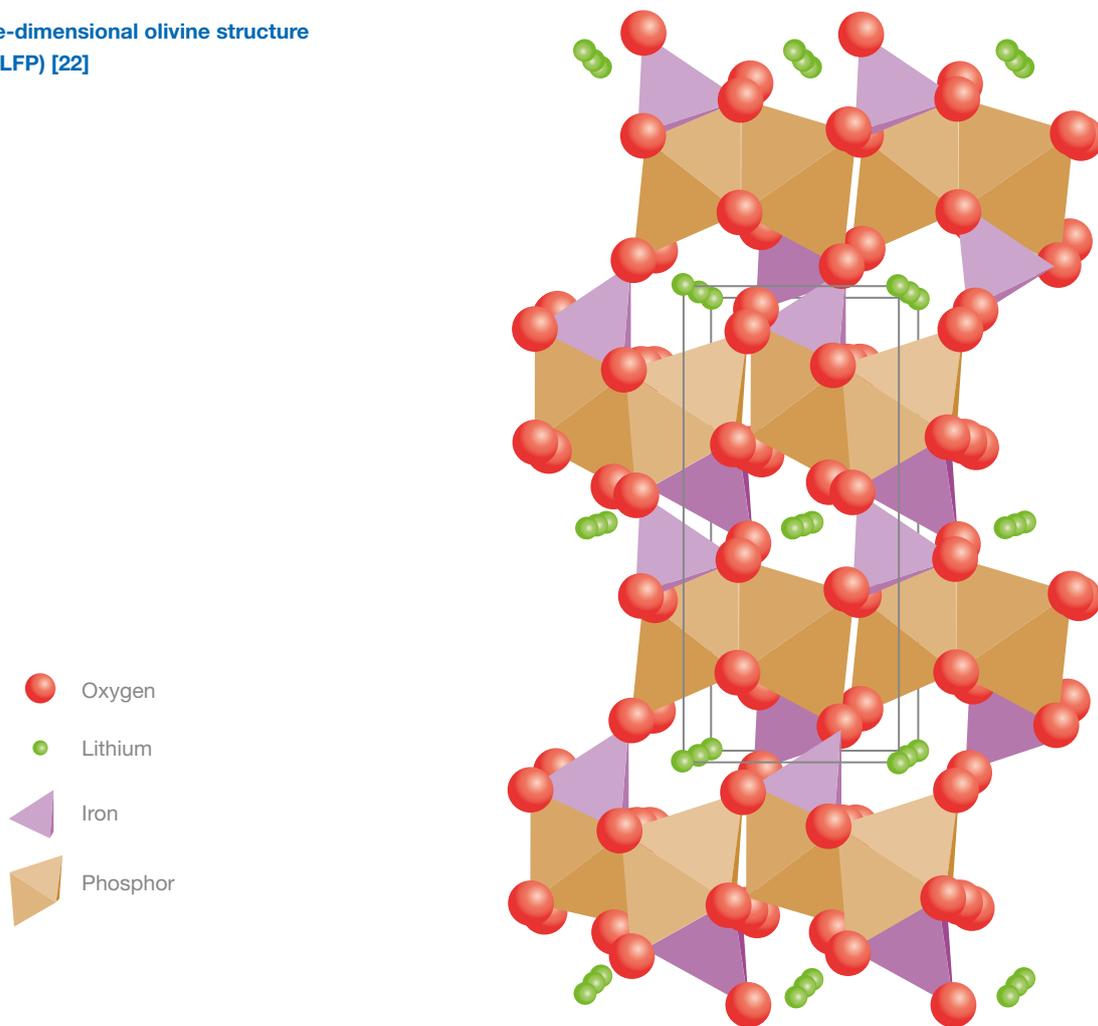


At 120 mAh/g, the specific capacity of the LMO-s material is very low compared to other cathode materials. A further disadvantage is the rapid aging with continuous cyclization which is accompanied by a significant loss of capacity. The thermal stability of an LMO-s cathode is comparable to that of NCM. The lower price of manganese compared to cobalt and nickel is an important advantage.

Tab 02 Power densities and maximum currents with LMO-s versus NCM

Comparison	Technology	Energy density	Power density	Max. current
Moli-IMR-18650	LMO-s	127 Wh/kg	1,700 W/kg	20 A
Panasonic CGR 18650CH	NCM	184 Wh/kg	820 W/kg	10 A

Fig 12 Three-dimensional olivine structure of LiFePO_4 (LFP) [22]



Lithium iron phosphate (LFP)

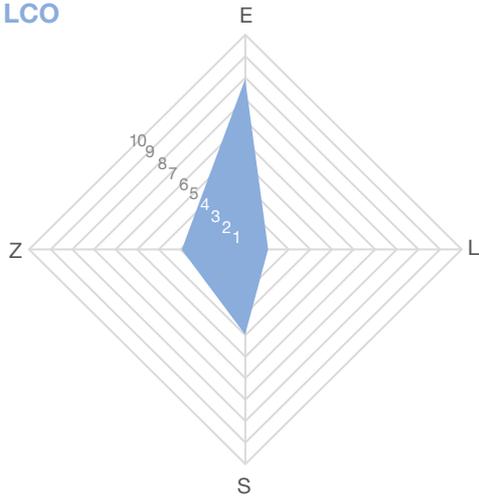
Lithium iron phosphate, LiFePO_4 (LFP), has long been regarded as a safe alternative to transition metal oxides while delivering maximum power density. When LFP decays at elevated temperatures, no oxygen is formed. Nor is there any decomposition of the electrolyte because of the lower cell voltage. The lower cost of the necessary raw materials is another advantage of this material.

At 160 mAh/g, the specific capacity of LFP is roughly the same as that of the transition metal oxides LCO or NCM. However, the lower cathode potential of LFP and the associated lower cell voltage result in a significantly lower energy density.

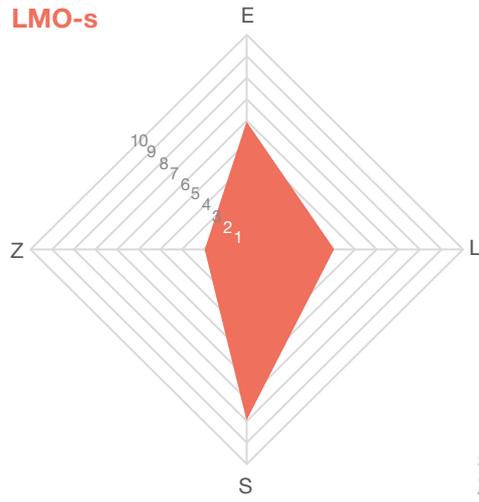
Comparison of cathode materials

The choice of a suitable cathode material is usually a compromise between the parameters energy density (volumetric/gravimetric), power density (vol./grav.), cycle stability and safety. → Figure 13 charts these parameters as criteria for evaluation of the cathode materials LCO, LMO-s, NCM, NCA and LFP [23].

LCO

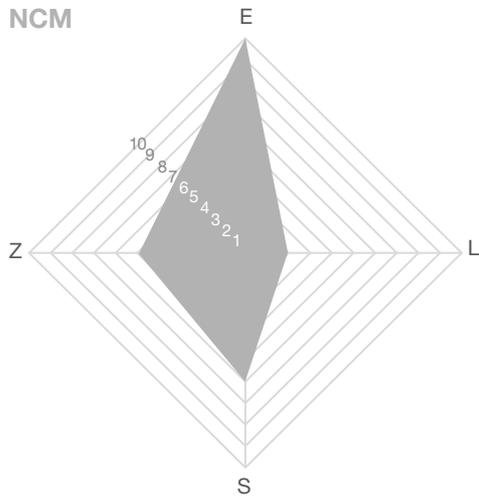


LMO-s

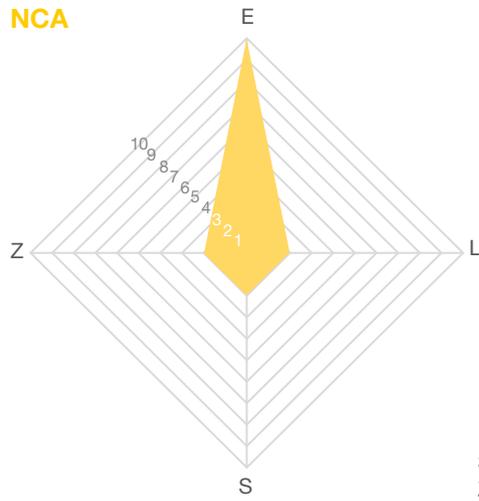


E Energy density
L Power density
S Safety
Z Cycle stability

NCM

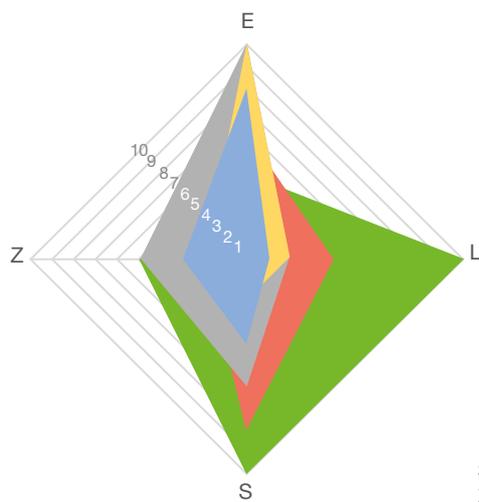
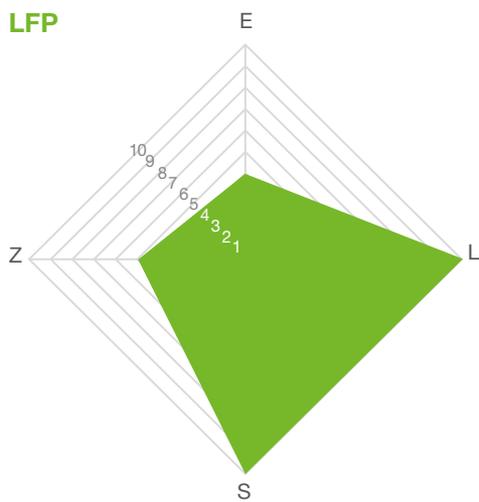


NCA



E Energy density
L Power density
S Safety
Z Cycle stability

LFP



E Energy density
L Power density
S Safety
Z Cycle stability

Fig 13 Qualitative comparison of the properties of LCO, LMO-s, NCM, NCA, LFP

Another important criterion in selecting the cathode material is its electrode potential, which in lithium-ion batteries is usually related to the potential of the Li/Li⁺ reference electrode. The open-circuit voltage of a lithium-ion cell is the difference between the electrode potentials of the cathode and anode. Alongside the properties of the active materials, it is decisive for determining the energy density level which can be achieved by the cell. → Figure 14 gives an overview of the electrode potentials of different materials [24].

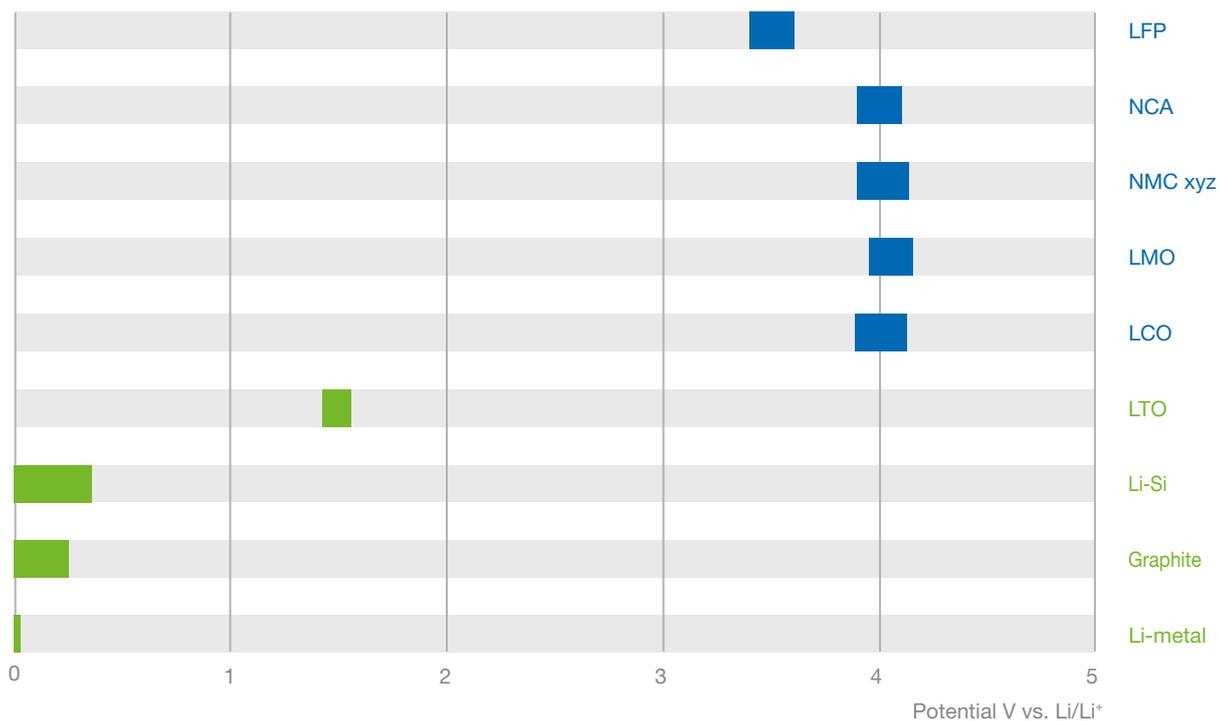


Fig 14 Electrode potentials of (blue) “cathode” and (green) “anode” materials

3.1.3. Anodes

In contrast to the range of cathode materials which are commercially available, the selection of anodes is relatively small. New, more powerful technologies (such as silicon anodes) are not yet market-ready and do not represent a viable alternative at the present time.

Carbon

The anode consists of graphite (100 % carbon) in the vast majority of lithium-ion cells today. Its low electrode potential of +0.2 volts and high specific capacity of about 350 mAh/g are important prerequisites for the creation of high energy density cells. Good electrical conductivity and low material prices are further advantages over other possible anode materials.

The low potential of graphite anodes also gives rise to a number of problems:

1. metallic lithium is deposited on the anode at higher currents, high charge levels or low temperatures. Over time, this forms sharp, needle-like structures – so-called dendrites – which impair the capacity of the cell and in extreme cases can lead to internal short circuits.
2. The graphite potential contributes to the electrochemical reduction of the electrolyte, which is accompanied by the formation of flammable gases. This undesirable reaction between graphite and electrolyte is normally inhibited by the formation of an insulating top layer, the so-called SEI (solid electrolyte interphase). At higher temperatures, however, this protective layer becomes unstable: its decay is often the beginning of thermal runaway in the cell. The SEI is required for safety reasons: it increases the impedance of the cell and thus limits the power density and prevents higher C rates.
3. Cells with graphite anodes can also be used at temperatures below 0 °C, albeit with limited power density. In addition, the cells age faster under these conditions. Lithium-ion cells with graphite anodes are therefore only partially suitable for high-performance applications at low temperatures.
4. For the cathode, aluminium can be used as a light and inexpensive collector material. For the anode, this is not possible with graphite, since lithium forms alloys with aluminium as a result of the potential of graphite. Here, higher-priced copper must be used instead, raising the weight and price of the cell.

Lithium titanate, $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (LTO)

The only commercially available alternative material to graphite is lithium titanate (LTO). Compared to Li/Li^+ , its electrode potential of +1.5 V compensates for the above safety and power density disadvantages of graphite; see also → Figure 15.

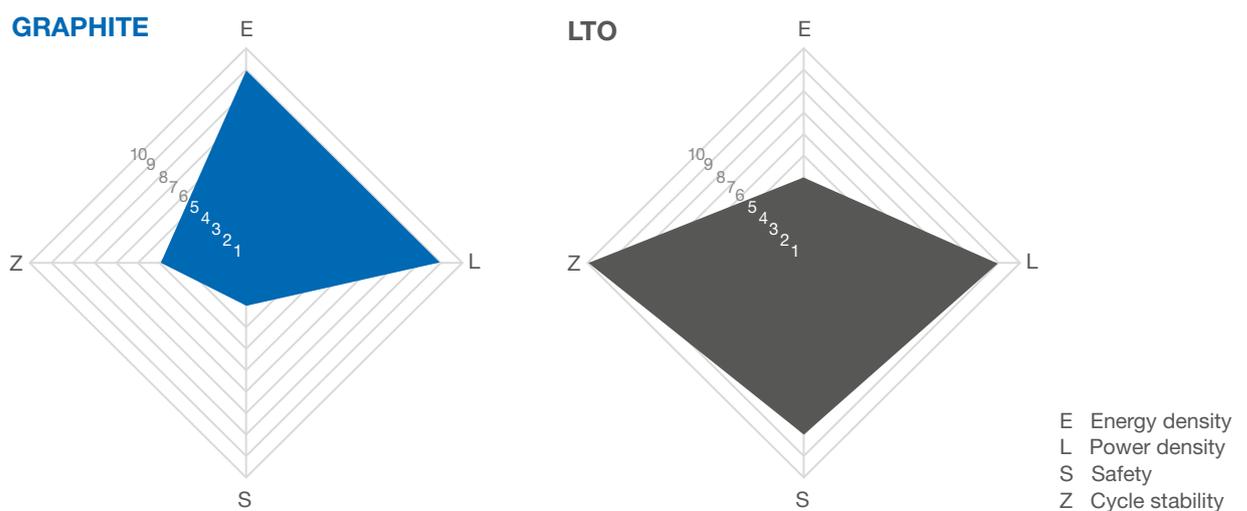


Fig 15 Qualitative comparison of the properties of graphite and LTO

Since the anode potential is higher and the specific capacity of 180 mAh/g is considerably lower than in graphite, the achievable energy density of an LTO anode is relatively low: lithium-ion cells with NCM-LTO electrode combinations achieve a gravimetric energy density of only 80-100 Wh/kg.

On the other hand, lithium-ion cells of this type are among the safest. Since SEI protective layers only form at anode potentials of less than +1.2 volts [25], the disadvantage of increased impedance does not apply here. This advantage is complemented by the higher diffusion mobility of the Li⁺ ions in the three-dimensional crystal structure of the LTO material, enabling excellent power densities and cycle rates. The higher anode potential of LTO also allows the use of aluminium instead of copper as the collector material [26].

In contrast to graphite, LTO can also be used at low temperatures: cells with an LMO-s cathode and LTO anode passed cold start tests at -30 °C [27].

3.2. Supercapacitors (supercaps)

Until a few years ago electrolytic capacitors were rarely considered for energy storage due to their low energy density – and if they were, only in combination with other technologies. Recent developments, however, open up the possibility of using so-called supercapacitors (or supercaps) in purely capacitor-based storage systems.

In contrast to electrolytic capacitors, supercapacitors consist of two mechanically separated electrodes which are ionically connected by an electrolyte. There are two possible principles for storing electrical energy in supercaps: charge separation in Helmholtz double layers for electrostatic storage in a double layer capacitor, or Faraday charge exchange through redox reactions for electrochemical storage in a pseudocapacitor. Both principles are asymmetrically combined in a hybrid capacitor in which an electrode with high double layer capacitance is combined with an electrode with high pseudo-capacitance.

The various mechanisms are described in more detail below and evaluated with regard to their relevance for possible use in vehicles with alternative drive systems.

3.2.1. Electrostatic double layer capacitance

Supercapacitors which operate on the electrical double-layer capacitor (EDLC) principle use an energy storage effect familiar from lithium-ion batteries: a double layer of charged particles is formed at the interface between the surface of a conductive, chemically inert electrode and the electrolyte, in which moving positive and negative charge carriers are dissolved. These are separated from each other by a single layer of solvent molecules – the “inner Helmholtz plane”. Such a double layer forms on each of both electrodes in the capacitor. Positive ions are involved in the case of the negatively charged electrode (anode); negative ions are involved in the case of the positively charged electrode (cathode).

The capacitance of an EDLC supercapacitor can be calculated using the plate capacitor formula, $C = \epsilon \cdot A / d$. Here, A is the size of the effective surface of the electrode (mostly graphite-based), d is the “plate” distance of the electrodes and ϵ is the dielectric conductivity (permittivity). Since the plate spacing is only a few atomic diameters, the capacitance of such a capacitor is much greater than that of electrolytic capacitors in which the electrolyte acts only as a dielectric. → Table 03 shows the theoretically possible capacitance of certain electrode materials; see also [28], [29], [30].

The speed at which an EDLC supercapacitor can be charged or discharged depends on the mobility of the ions in the electrolyte. Since this is higher in water-based than in anhydrous systems, higher power densities can also be achieved with water-based electrolytes. The disadvantage is that the voltage is limited to approx. 1.23 volts due to the low electrolysis potential of water, while systems based on organic solvents can be operated at voltages of 3 to 5 volts [28].

Tab 03 **Theoretically achievable capacity of different electrode materials**

Materials	Spec. capacity [F/g]	Spec. capacity [mAh/g V]
Graphite paper	0.13	0.0364
Cellulose-based foamed carbons	70–180	20–50
Activated carbon	250	70
Graphene	550	154

Since the charging and discharging of EDLC supercapacitors is not based on chemical reactions, the reaction time constant τ is considerably shorter than that of batteries, thereby making power densities of up to 10 kW/kg possible. There is no change in the volume of the active material due to the intercalation of ions. Cycle numbers of more than 500,000 can therefore be achieved [31]. A wide temperature range from -40 °C to +85 °C can be used, depending on the electrolyte deployed. Since the energy in the EDLC supercapacitor is only stored in the double layer, the currently achievable energy densities of up to 10 Wh/kg are still low.

3.2.2. Electrochemical pseudo-capacitance

A pseudo-capacitive effect occurs when ions from the electrolyte penetrate the double layer and are intercalated in the electrode material as the result of a reversible redox process. The absorbed ions do not react chemically with the electrode material; there is merely a charge transfer between the electrolyte and the electrode. With batteries, on the other hand, the charge transfer is part of an electrochemical process which results in much longer reaction times and also leads to aging of the cell.

Pseudocapacitive effects occur when metal oxides are doped into the mostly graphite-based electrode material.

→ Table 04 provides an overview of suitable doping materials.

Tab 04 **Suitable doping materials for the realization of pseudo-capacities**

Material	Spec. capacity [F/g]	Spec. capacity [mAh/g V]
Polymers	400–500	100–150
Ruthenium oxide (RuO ₂)	380	100
RuO ₂ hydrate	760–1,340	210–380
Nickel cobaltite (NiCo ₂ O ₄)	330–2,680	90–750

During the reversible intercalation of ions in the electrodes, volume changes take place which contaminate the material. For this reason, the cycle numbers of supercapacitors which exploit the pseudocapacitive effect are lower than those of EDLC supercapacitors. With sulphuric acid as the electrolyte, pseudocapacitive supercapacitors can achieve energy densities of up to 26.7 Wh/kg [32]. Laboratory tests have shown that this system can be used to obtain energy densities of up to 38 Wh/kg and power densities of up to 128 kW/kg [33] using graphene⁹ electrodes.

⁹ Graphene is an artificially produced modification of carbon that is very similar in structure to graphite: at room temperature graphene has a greater electrical conductivity than silver and is a very good thermal conductor.

3.2.3. Hybrid supercapacitors

Hybrid supercapacitors use asymmetric electrodes in which one electrode stores energy based on the double-layer principle, while the other electrode exploits the pseudocapacitive effect. Lithium-ion supercapacitors are a good example of this. Commercially available supercaps of this type achieve energy densities of 30 to 50 Wh/kg and power densities of 5 to 10 kW/kg, with a service life of >100,000 cycles in the temperature range -40 °C to +85 °C [34].

There are few reliable sources on the safety performance of commercial lithium-ion supercapacitors, but according to some manufacturers (e.g. [35]), standard safety tests conducted on lithium-ion technology based on UL standards and UN guidelines revealed no explosions or fires.

In laboratory tests, hybrid supercapacitors were used to measure energy densities of up to 148 Wh/kg and power densities of up to 41 kW/kg with a service life of over 10,000 cycles [36]. Hybrid lithium-ion supercapacitors with typical energy densities for conventional nickel-metal hydride batteries, i.e. 60–120 Wh/kg, are expected to become commercially available in the next 5 years.

3.3. Summary

→ Table 05 lists the key characteristic values of commercially available lithium-ion cells and supercapacitors.

Tab 05 **Key characteristics of Li-ion cells and supercapacitors**

Property	Lithium-ion cell	Supercapacitor
Energy density	120–280 Wh/kg	13–50 Wh/kg
Power density	0.5–1.5 kW/kg	5–10 kW/kg
Safety	depends on anode material	comparable with LTO
Cycle stability	10 ³ up to 10 ⁴ cycles	up to 10 ⁵ cycles
Low-temperature performance	0 °C (graphite) -30 °C (LTO)	-40 °C

4 Lithium-ion cells for use in battery-powered multiple units

On the basis of the requirements set out in Chapter 2 based on operational load profiles, the VDE examined the technical data of a selection of commercially available lithium-ion cells and evaluated their suitability for use in battery-powered multiple units (or hybrid multiple units). As mentioned in Chapter 3, the possibility of using supercaps instead of lithium-ion cells is not considered, since a purely supercap-based storage system would currently be at least twice as heavy for multiple units with the same range due to the low energy density.

4.1. Target parameters for the selection of available lithium ion cells

The selection of lithium ion cells available on the market was based on the requirements covered in Chapter 2 for energy density and capacity, weight and range, dynamics and fast charging capability, cycle stability and service life, as well as performance at low temperatures down to -25 °C. The corresponding data can be found as references in the first line of → Table 06, → Table 07 and → Table 08 in the section below.

With regard to service life, low-temperature performance or charge/discharge currents, no precise cut-off points can be set for the exclusion of cell candidates, since these properties are ultimately determined by the actual use in operation and can in part be improved at the system level.

4.2. Technical data of selected lithium-ion cells

Tab 06 Cells by C rate for discharging/charging

Manufacturer	Model	Discharge C rate			Charge C rate		
		Cont.	Peak	Time (peak)	Cont.	Peak	Time (peak)
Load specifications from operational load profiles:		2–3	4	10 s	3–5	5	10 s
XALT	F900-0001	6	10	10 s	3	–	–
	F940-0001	8	16	10 s	4	–	–
	F920-0006	8	20	10 s	5	–	–
Kokam	SLPB98188216P	20	30	10 s	4	8	10 s
	SLPB130255255N	4	8	10 s	4	8	10 s
	SLPB130255255P	8	15	10 s	4	8	10 s
Toshiba	SCiB 20 Ah	5	10	10 s	5	10	10 s
		4	9	10 s	4	9	10 s
Lishen	LP27148134-40Ah	4	5	30 s	3	4	30 s
LG	JP1 27 Ah	3	4	10 s	3	4	10 s
A123	20 Ah Ultra-Phosphate	3	4	–	2	–	–

Tab 07 Cells by cell chemistry, type, nominal voltage, capacity, cycles, min. temperature

Manufacturer	Model	Cell chemistry	Cell type	Nominal voltage [V]	Capacity [Ah]	Cycles@100 % DOD	Min. temp (charge)	Min. temp (discharge)
Specifications from MU operation:		N/A	N/A	N/A	N/A	16.5k @1 C	-25 °C	-25 °C
XALT	F900-0001	NCM / C		3.7	75	>6.5k @1 C	5 °C	-10 °C
	F940-0001	NCM / C	Pouch	3.7	37	>5k @1 C	5 °C	-10 °C
	F920-0006	NCM / LTO		2.2	60	40k @1 C	-30 °C	-30 °C
Kokam	SLPB98188216P	NCM / C		3.7	30	10k @1 C	0 °C	-20 °C
	SLPB130255255N	NCM / LTO	Pouch	2.3	65	20k @1 C	0.5 °C	-30 °C
	SLPB130255255P	NCM / C		3.7	75	>6k @1 C	0 °C	-20 °C
Toshiba	SCiB 20 Ah	NCM / LTO	Prism.	2.3	20	15k @3C	-30 °C	-30 °C
	SCiB 23 Ah	NCM / LTO	Prism.	2.3	23	15k @3C	-30 °C	-30 °C
Lishen	LP27148134-40Ah	LFP / C	Prism.	3.2	40	>2k @1 C	0 °C	-20 °C
LG	JP1 27 Ah	NCM / C	Pouch	3.7	27	5k @1 C	-10 °C	-10 °C
A123	20 Ah U. -Phosp.	LFP / C	Pouch	3.3	20	2k @1 C	-	-30 °C

Tab 08 Cells by energy content, volume, weight and energy density

Manufacturer	Model	Energy [Wh]	Volume [l]	Weight [kg]	Vol. energy density [Wh/l]	Grav. energy density [Wh/kg]
Spec's derived from Chapter 2:		N/A	N/A	N/A	> 200	> 100
XALT	F900-0001	278	0.89	1.75	310	160
	F940-0001	137	0.49	1.00	280	140
	F920-0006	132	0.90	1.75	150	80
Kokam	SLPB98188216P	111	0.43	0.87	260	130
	SLPB130255255N	150	0.96	1.85	160	80
	SLPB130255255P	278	0.97	1.83	290	152
Toshiba	SCiB 20 Ah	46	0.27	0.52	170	90
	SCiB 23 Ah	53	0.27	0.6	196	96
Lishen	LP27148134-40Ah	128	0.54	1.03	240	125
LG	JP1 27 Ah	99	0.33	0.64	300	150
A123	20 Ah Ultra-Phosphate	65	0.31	0.52	210	125

4.3. Evaluation of cells by different criteria

None of the cells in the above → tables meets all the requirements. In general, the properties of a cell represent a compromise between energy density, power density, low-temperature resistance and service life. The latter three parameters are fulfilled much better by LTO-based cells than by cells with graphite anodes. However, LTO cells have much lower energy densities due to their low cell voltage.

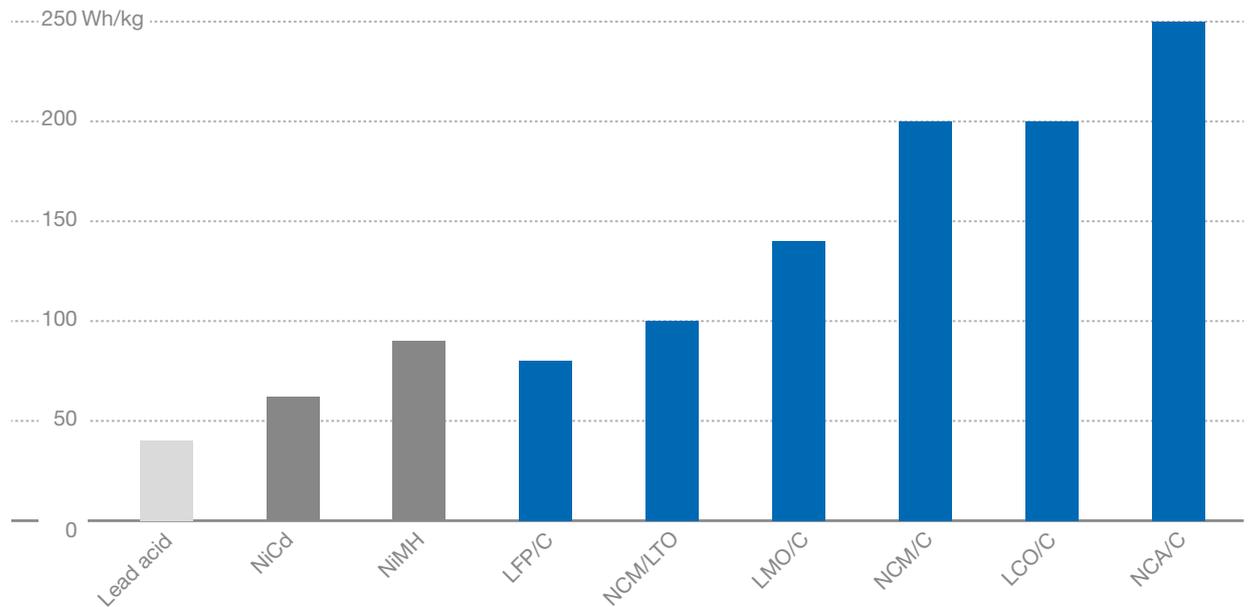


Fig 16 Typical energy densities of lead, nickel and lithium-based batteries [37]

4.3.1. Energy density

The energy density values shown in → Table 08 are the product of the nominal voltage and nominal capacity given in → Table 07 and → Table 08, divided by the mass or volume of the cell (all four parameters are manufacturers' specified values). The nominal voltage and capacity values are measured by the manufacturers under their own standard conditions (usually 0.2C discharge current) and not e.g. for maximum current. At higher charging currents, the cell voltage and thus the usable capacity decreases.

The energy densities of the cells are essentially determined by their cell chemistry. Graphite anodes allow higher energy densities than LTO anodes, NCM cathodes higher energy densities than LFP cathodes. Higher energy densities are possible with NCA than with LCO or NCM; see also → Figure 16.

Using the example of type SLPB1xxxP (NCM/C) or SLPB1xxxN (NCM/LTO) Kokam cells, → Table 08 shows that replacing graphite with LTO results in a 45 per cent reduction in energy density, i.e. 290 → 160 Wh/l or 152 → 80 Wh/kg.

Another factor which determines the energy density of a cell is its design: prismatic and cylindrical cells are heavier and larger than pouch cells due to their metal housing, and therefore have lower energy densities (both gravimetric and volumetric).

4.3.2. Power density

The power density [in W/kg] is rarely stated in manufacturers' data sheets. The maximum C rate generally serves as a measure of the power density. The indicated C rates differ from capacity and voltage data in that they are not based on an objective measurement method, but have a qualitative character instead. After coordinating concrete application cases with the system manufacturer or battery assembler, some manufacturers allow the maximum currents to be extended.

Most high performance cells allow continuous charging currents from 3 to 4C. The disadvantage of cells that continuously tolerate 5C is that their energy density is significantly lower than 100 Wh/kg. Increasing the charge/discharge currents to C rates outside the values specified by the cell manufacturers is basically possible if suitable cooling systems are used. However, such use is at the expense of the cell life or its available capacity.

4.3.3. Service life and cycle stability

The service life of a lithium ion cell (see section 2.2 for definition) is a non-linear function of a number of parameters. Three of the most important parameters with otherwise identical conditions are the operating temperature, the charging and discharging currents (C rates) and the SoC¹⁰ window used.

Studies such as [38] and [39] show that restricting the SoC range by avoiding charging statuses of near 0 % SoC and 100 % SoC significantly reduces the capacity loss over the service life of the battery. The smaller the SoC window selected (e.g. 80 %), the more full cycles¹¹ are possible, i.e. the cycle stability of the battery increases.¹²

Some studies such as [40], [41] and [42] also provide evidence of the influence of the operating temperature on the service life of the cell. The optimum operating temperature for many cell types is between 18 and 25 °C. The use of high C rates within a wide operating temperature range has a negative effect on the service life. Manufacturer's service life specifications generally refer to currents of 1C at room temperature, unless otherwise specified. The comparatively long service life of cells with LTO anodes is due to the relatively low volume change of the LTO material during the intercalation of lithium ions (0.1–0.3 %). In addition, no lithium dendrites which would reduce the capacity are produced here.

The specified service life of multiple units is 30 years. In the case of battery-operated trains, if it is assumed that only one complete battery change is undertaken during this period, the required service life of the battery system is at least 15 years. Such a time specification cannot be taken directly from the data sheets of the cell manufacturers, but must be derived from the indicated maximum number of full cycles. Assuming that the accumulator of a battery-powered multiple unit undergoes three complete charging and discharging cycles per day, this results in a total of 16,500 cycles over 15 years:

$$n_{\text{cycles}} = 15 \text{ a} \times 365 \text{ d / a} \times 3 \text{ cycles / d} \approx 16,500 \text{ cycles}$$

The cycle numbers given by the manufacturers for the cells examined (cf → Table 07) are based on different operating and boundary conditions for determining the service life. In all cases, the figures give the maximum number of cycles at discharge depths (DoDs) of 100 %, i.e. the number of "real" full cycles. → Figure 17 shows the expected cycle lifetimes of the cells examined in comparison to the given figure.

¹⁰ SoC = State of Charge (%)

¹¹ A full cycle corresponds to complete discharge and recharge of the battery within the SoC window. Successive partial cycles with the total energy throughput of a full cycle count as one full cycle.

¹² The cause of the capacity loss due to aging is the constant volume changes of the active materials during reversible intercalation of lithium and the associated material stress.

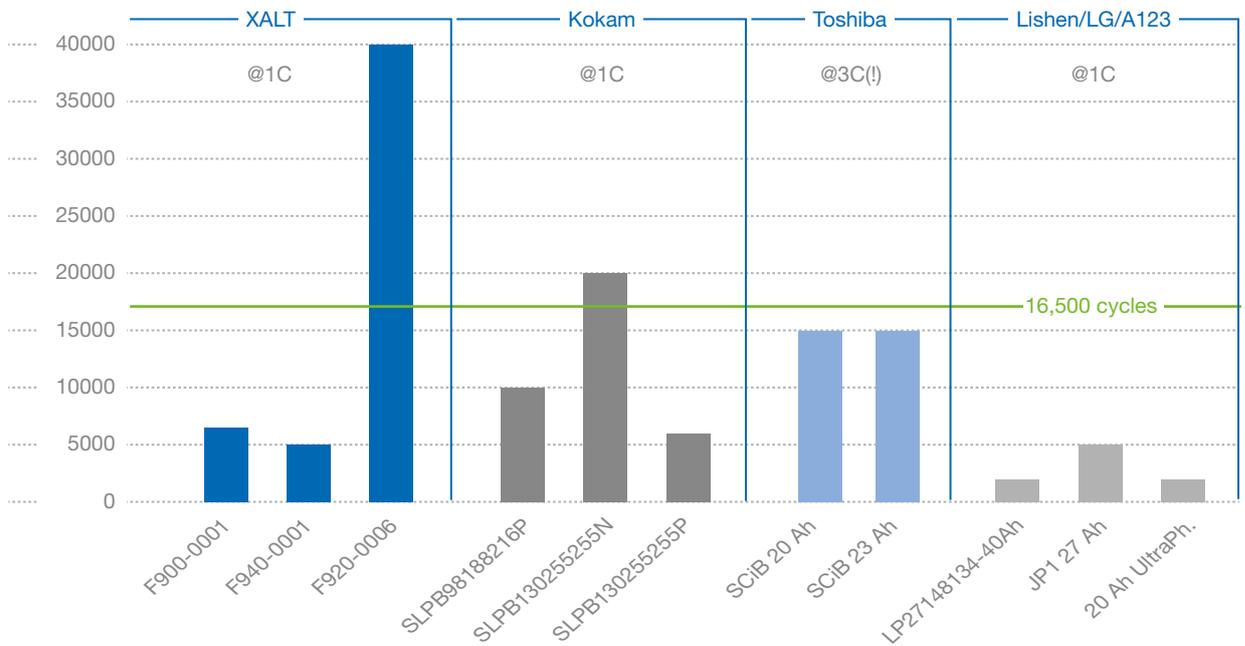


Fig 17 Cycle life at 100 % DoD versus specification (here 16,500 cycles)

4.3.4. Use at low temperatures

The choice of suitable anode and cathode or electrolyte materials for lithium-ion batteries also depends on the ambient temperatures at which they are to be used. These are usually around $20^{\circ} \pm 10^{\circ} \text{C}$. Charging at temperatures below 0°C is critical for lithium-ion cells with graphite anodes. Some manufacturers even recommend a minimum charging temperature of $+5^{\circ} \text{C}$ (cf → Table 07). The lower the lithium-ion battery's ambient temperature, the lower is the energy available during discharging or supplied during charging, respectively. → Figure 18 shows how the discharge performance of e.g. the NCR 18650 round cell from Panasonic (NCA/graphite) can change with temperature (e.g. at 2C) [43].

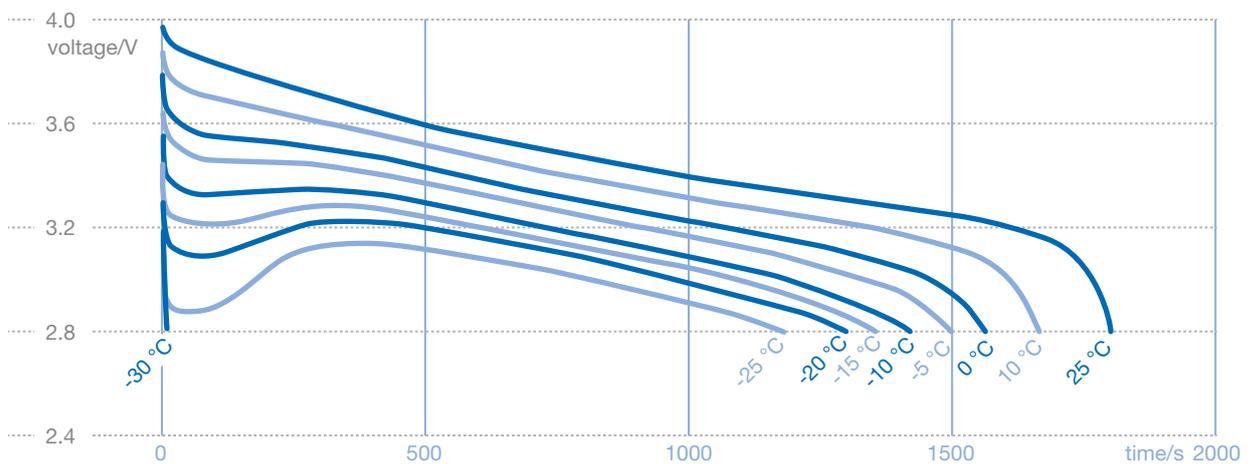


Fig 18 2C discharge curves of a Li-ion round cell at different temperatures

The literature cites the following possible reasons for the loss of performance at low temperatures:

1. Deterioration of the ion conductivity of the electrolyte
2. Deterioration of the conductivity of the SEI film between anode and electrolyte
3. Deterioration of the diffusion coefficient for Li^+ ions in the anode material

In practice, all three reasons are relevant. Avoiding cell types with a graphite anode is a possible consequence of the required ambient temperature. Choosing a cell technology with LTO anode, which has been proven to provide consistent performance even at low temperatures, is a possible technical solution to the problem.

4.4. Summary

→ Figure 19 shows a comparison of the cells based on the five most important selection criteria. The horizontal line in the diagram represents the desired cell properties. The maximum C rate for discharging is not given because all cells evaluated in this report meet the relevant requirement.

The cells with graphite anodes have the highest energy densities. However, they do not meet any of the other requirements. In particular, the number of cycles and the specified minimum charging temperature deviate from the specification in the case of graphite-based cells.

On the other hand, cells with LTO anodes promise longer service lives (more cycles), a wide operating temperature range and higher charging currents. In the case of Toshiba's NCM/LTO (SCiB) cells, the energy density is close to the required minimum energy density. The XALT and Kokam NCM/LTO cells meet all requirements except for energy density (75 Wh/kg).

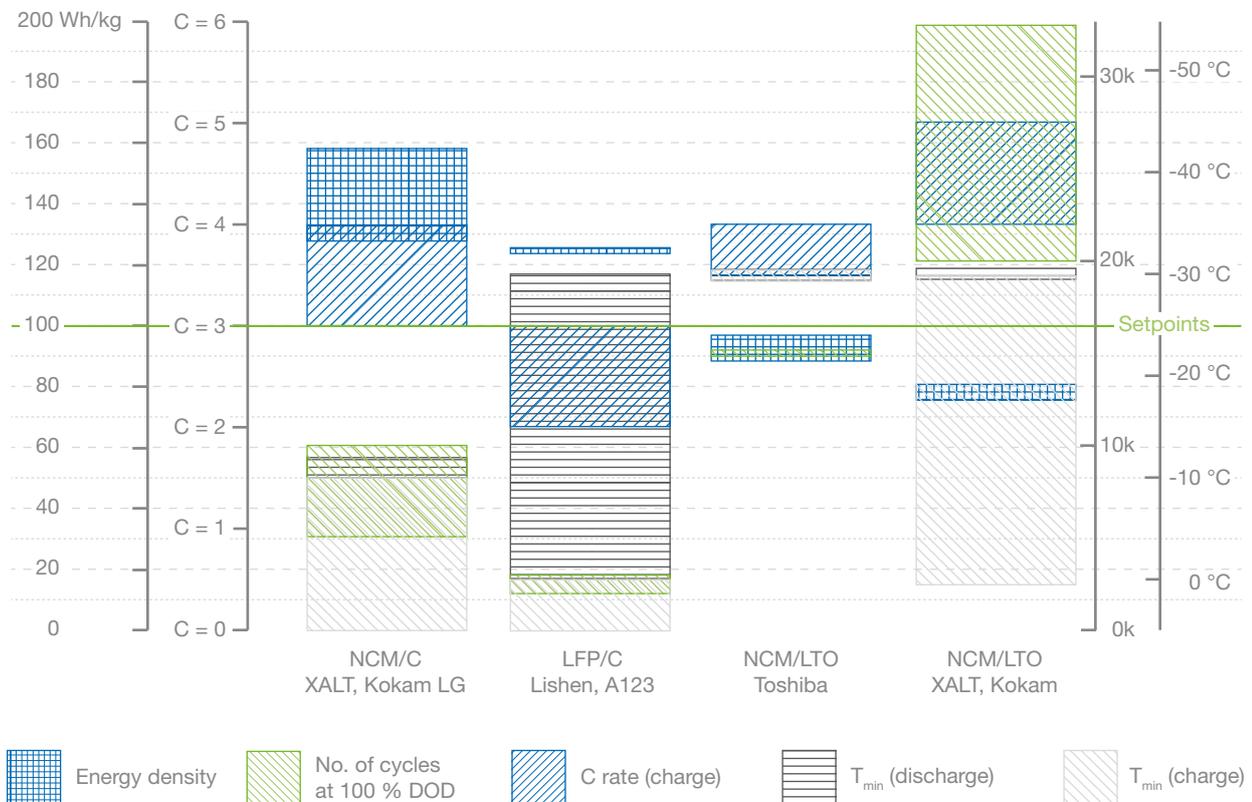


Fig 19 Comparison of investigated cells, arranged by cell chemistry

5

Potential routes of technological development up to 2030+

During the development of a battery-powered multiple unit, a technological decision must be made which may be of long-term importance in view of the normal service life of 30 years for multiple units, especially since it can be assumed that at least one battery replacement will be required during this long period. It is therefore necessary to clarify at an early stage the expected battery life, the long-term availability of the selected cell type, how cell costs will develop or whether more powerful versions of the cell or alternative cells with the same dimensions can be expected in the coming decades.

In order to assess these possibilities, it is necessary to look at cells and technologies that may still be at the research and development stage today or are only available as prototypes.

5.1. Generation Roadmap

Energy and power density, low-temperature performance and safety, service life and cycle stability – these are the key performance parameters for evaluating traction batteries. These characteristics result not only from the properties of the active materials used in the cells, but are also influenced by non-active components and their arrangement, as well as the actual design of the battery system and the resulting thermal and battery management. The range of possible research and development activities is wide indeed: it extends from new and evolutionary further developments through to possible disruptive innovation leaps at various levels [44].

Working Group 2 of the National Platform for Electric Mobility (NPE AG2) published a report [45] in January 2016 containing a development roadmap which had been coordinated with the vehicle manufacturers and in which the battery technologies suitable for electric vehicles (in particular pure BEVs) are listed by generation. The period considered is 2015 to 2030. This “generation roadmap” clearly meets a definite need because it is often quoted in publications and is also used as a basis for cell production research to ensure that future production processes are available in good time [46]. This roadmap could be extended to include technologies for traction batteries, which today are subject to stricter requirements in terms of C rates, cycle stability, safety, low-temperature performance and service life in battery-powered buses, trams, locomotives or multiple units. The (extended) characteristics of the roadmap generations can be summarized as follows:

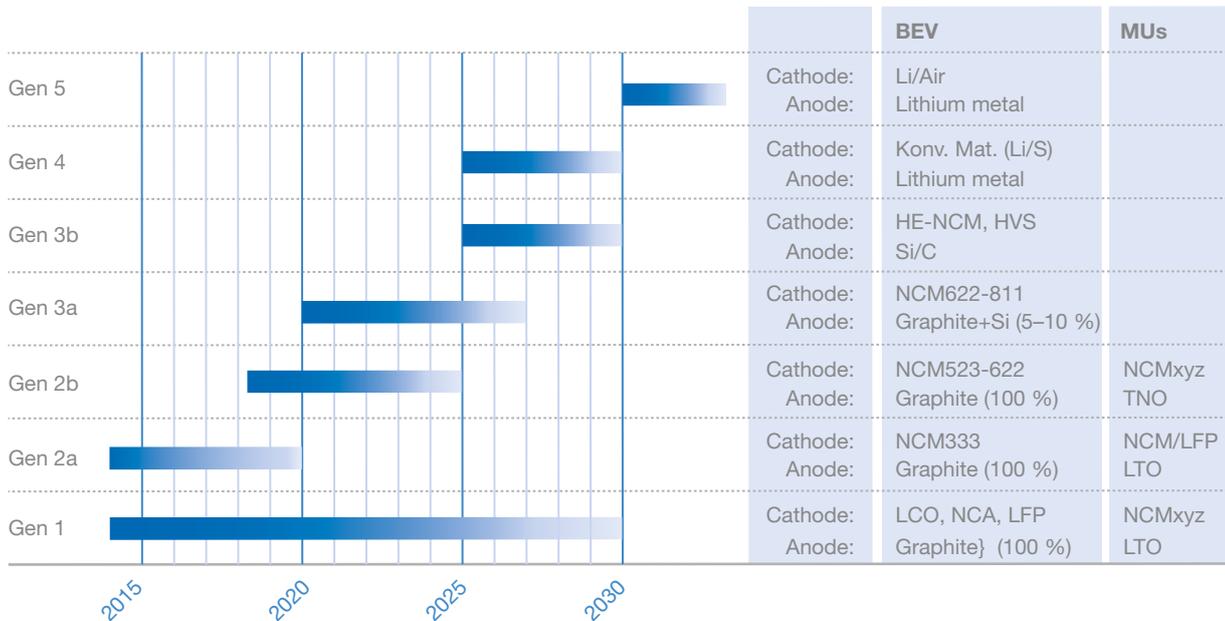


Fig 20 Development roadmap of cell technologies up to 2030 (according to NPE AG2)

Generation 1: Use in BEVs today Generation 1 includes lithium-ion cells in which lithium manganese oxide (LMO), lithium iron phosphate (LFP) or lithium nickel cobalt aluminium oxide (NCA) is used as the material for the cathode, and graphite for the anode.

Generation 2a: Use in BEVs today until ≈2020 Generation 2a includes lithium-ion cells in which a ternary lithium mixed oxide of the transition metals nickel, cobalt and manganese (NCM) is used in a mixture ratio of 1:1:1 as cathode material (so-called NCM333). Here, too, the anode is made of graphite.

In our opinion, cells with an NCM cathode and LTO anode, as offered by manufacturers such as XALT, Kokam, Toshiba or Saft, belong to generation 2a, as does Kokam's NMC-NANO technology, in which NCM (= NMC) and LFP are blended in such a way to meet special customer requirements. The latter also uses LTO for the anode.

Generation 2b: Use in BEVs today until ≈2025 According to NPE, generation 2b includes enhanced lithium-ion cells with the nickel-rich cathode variants NCM523 to NCM622 and graphite as anode material.

In terms of technological development, the innovation of the SCiB cell with lithium titanium niobium oxide (TNO) announced by Toshiba as a new type of anode material should be mentioned here [47].

Generation 3a: Use in BEVs from 2020 to ≈2027 Generation 3a includes lithium-ion cells with nickel-rich cathode variants NCM622 to NCM811 and graphite anodes with a 5 to 10 % silicon content (so-called Si/C composites).

Generation 3a also focuses on achieving higher energy densities for greater "range" without improving power density.

From today's perspective, it therefore offers no improvement for use in multiple units.

Generation 3b: Use in BEVs from 2025 to ≈2030 Generation 3b includes lithium-ion cells with cathodes optimized for high energy density (high-energy NCM) or high cell voltage (high-voltage spinel, HVS). A silicon-carbon mixture optimized for energy density is used as the anode material.

Generation 4: Use in BEVs from ≈2025 to ≈2030 Generation 4 includes all solid state cells with anodes made of lithium metal, and cathodes made of conversion materials (e.g. lithium sulphur) and solid electrolytes.

Generation 5: Use in BEVs from ≈2030 Generation 5 includes so-called "open" cells with a lithium air/O₂ cathode.

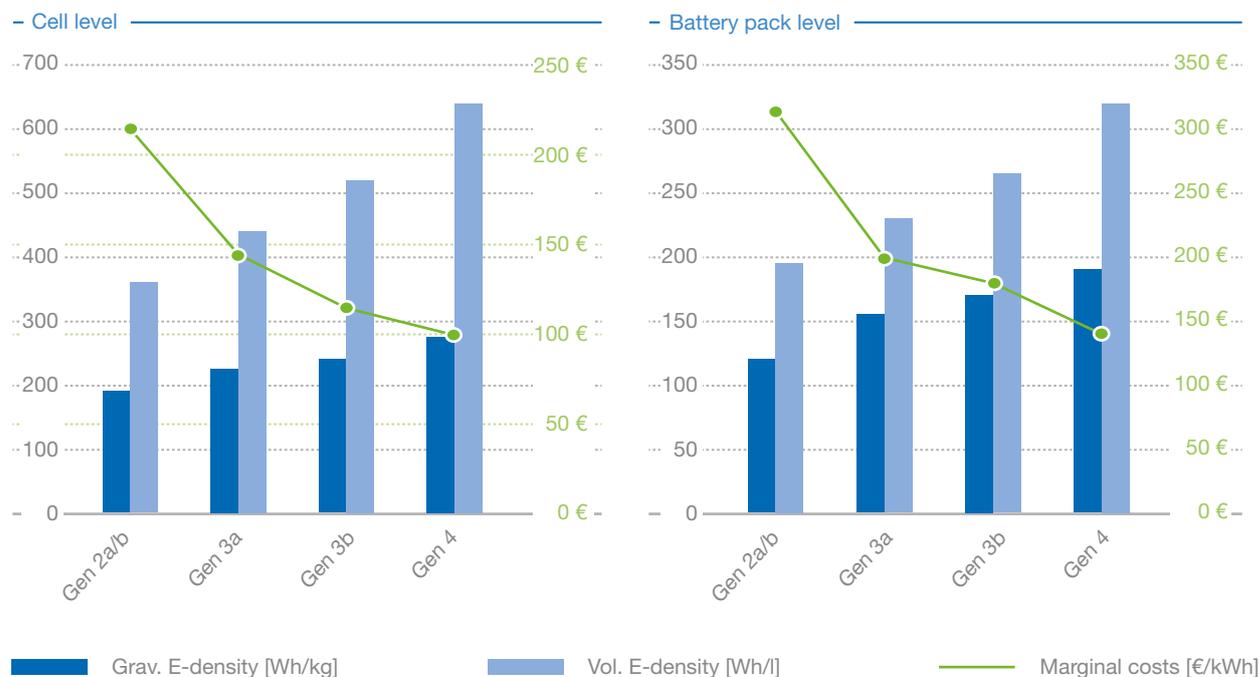


Fig 21 Expected development of energy density and marginal costs (according to NPE)

The main emphasis of the NPE AG2 roadmap is on the continuous increase of energy density [in Wh/l or Wh/kg] for a better range value and the reduction of marginal costs [in €/kWh], both at the cell and battery pack level. → Figure 21 provides an overview. The roadmap assumes that the gravimetric energy density at the cell level can be increased over the generations from 190 to 280 Wh/kg, i.e. almost 50 %, by 2025. The volumetric energy density is expected to increase by almost 80 % from 360 to 640 Wh/l by 2025. At the same time, the marginal costs are expected to fall from 215 to 100 €/kWh.

At the battery pack level¹³ the NPE expects an increase in gravimetric energy density from 120 to 190 Wh/kg, and in volumetric energy density from 200 to 320 Wh/l. At the same time, the marginal costs will fall from 300 €/kWh to less than 150 €/kWh.

The other equally important requirements of the BEV manufacturers regarding charge currents (fast charging to 80 % within minutes), discharge currents (peak power and cold start power in W/kg), safety (EUCAR level) and cycle stability (service life in years) were set so high from the outset that they would probably only be met from generation 4. The corresponding data is presented in → Table 09.

Tab 09 NPE specifications for C rates, safety and service life (according to NPE)

Criterion	Cell level	Pack level	Note
Fast charging	80 % in 20 min	80 % in 20 min	≈ 3 C charge
Peak power	1,050 W/kg	650 W/kg	≈ 3 C discharge
Cold start power	310 W/kg	155 W/kg	≈ 1 C discharge
Safety (level)	EUCAR-4	EUCAR-3	
Service life	10 years	10 years	

¹³ A battery capacity of 80 kWh was assumed.

Fast charging in 20 minutes to 80 % of nominal capacity, i.e. charging at 3C, is apparently considered sufficient by the NPE. It holds to the required power density of 1 kW/kg (peak) or 300 W/kg for cold starts across the generations. It defines EUCAR¹⁴ level 3¹⁵ as the hazard class at the battery pack level and EUCAR level 4¹⁶ at the cell level. Notably, a battery life of “only” 10 years is assumed.

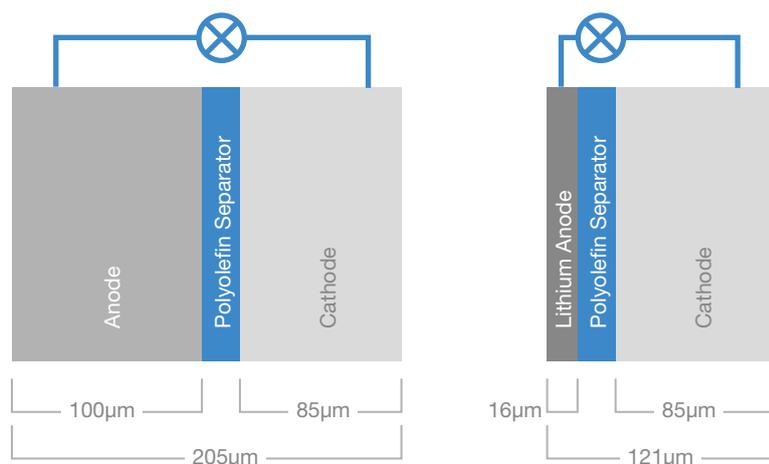
The question arises as to the relevance of the findings and the expectations formulated in conjunction with the customers and manufacturers of electric cars with regard to the requirements for traction batteries for buses, trams, locomotives or multiple units. Can manufacturers and customers also expect optimization, further developments or even disruptive innovation leaps here?

5.2. Optimization of energy density at cell level

Section 3.1.2(c) described options for increasing the energy density of lithium ion cells by using particularly nickel-rich NCM cathodes [NCM622, NCM811] - but at the expense of cell safety and service life. A further, more conservative, option is to increase electrode capacity by optimizing the active material without changing the volume or weight of the electrode. Reducing the size of the electrodes without changing their capacity would have the same effect. This approach is characteristic of the current research and development work on technologies and cell structures. → Figure 22 gives an example where both optimization options are deployed simultaneously.

Alternative combinations of electrode materials which yield advantageous electrode potential values would help obtain the highest possible cell voltages and thus higher energy densities. One way to achieve this is to use a high-voltage spinel as the cathode material. Nickel-doped lithium manganese oxide with cubic spinel structure, for example, belongs to the class of “5V” materials. As a cathode material, $\text{LiMn}_{1.5}\text{Ni}_{0.5}\text{O}_4$ has an electrode potential of +4.8 volt against Li/Li^+ , i.e. when using graphite or lithium metal on the anode side the cell voltage is close to 5 volts. The specific capacity of the high-voltage spinel is approximately 140 mAh/g. A challenge here is that state-of-the-art carbonate-based electrolytes become unstable against Li/Li^+ at electrode potentials above 4.5 V and thus limit the service life of the cell.

Fig 22 **Higher energy density through reduction of anode size (here Li-metal) [48]**



14 EUCAR = European Council for Automotive R&D

15 3 = Possible risk of leakage with slight loss of mass (< 50 % weight loss)

16 4 = Possible hazard from gas discharge with high mass loss (> 50 % weight loss)

Cells with LFP cathodes are characterized by their good power density and long service life. Their energy density is relatively low at 80–100 Wh/kg, i.e. the level of NiMH cells. MuRata is currently developing an LFP-based cell that will achieve an energy density of 120 Wh/kg with the same power density and service life. The low-temperature performance is also being improved: at -20 °C it still offers half capacity.

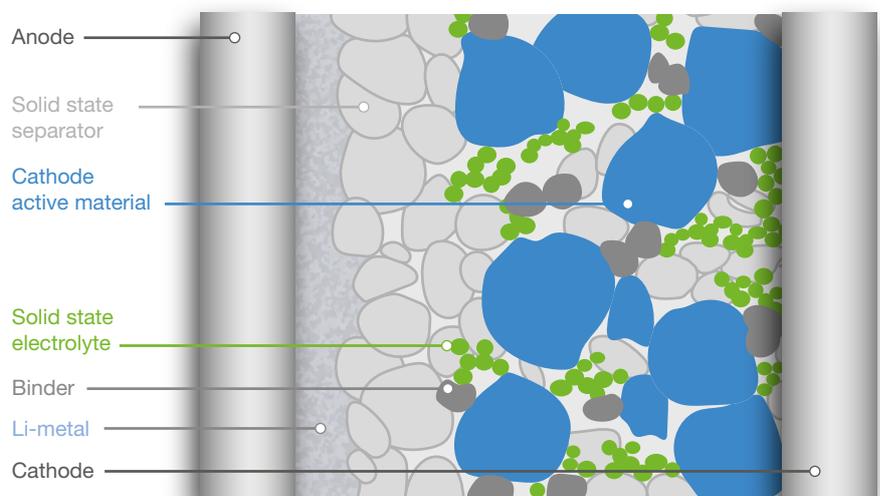
Cells with LTO anodes, such as Toshiba's SCiB, perform excellently across all parameters – with the exception of energy density. At almost 100 Wh/kg, this is scarcely higher than that of LFP- or NiMH-based cells. To compensate for this technological disadvantage, Toshiba is currently developing a SCiB variant with lithium titanium niobium oxide (TNO) as an alternative anode material. At around 350 mAh/g, the specific capacity of TNO should be twice as high as that of LTO [47]. Combined with a lithium-rich NCM622 cathode in the format of a pouch cell, an energy density of 138 Wh/kg or 350 Wh/l can be achieved according to [49].

Because of the formation of dendrites at high charging rates and its tendency to self-discharge, metallic lithium can currently only be used as an anode material to increase the energy density in combination with solid electrolytes, cf → Figure 23.

Recent developments focussing on lithium sulphur and Li air/O₂ are also aimed at increasing energy density. In theory, enormously high gravimetric energy densities can be achieved with these combinations. However, it is now assumed that this technology will not become established in electric vehicles due to a wide variety of technological challenges.

The capacity of a cell is determined by the intercalation of lithium ions into the electrode material. An alternative is so-called “conversion”. Here, instead of intercalation, there is a transfer of charge to conversion materials (transition metal oxides containing traces of iron, nickel, manganese, cobalt or chromium). “Conversion” anodes achieve specific capacities of up to 1,000 mAh/g. However, these materials are still far from being commercialized. Conversion cathodes are currently still at the basic research stage.

Fig 23 **Lithium-metal anode with solid electrolyte (all-solid-state cell) [48]**



5.3. Increasing the power density

Increasing the power density of a cell depends, firstly, on the choice of suitable active materials. In addition, it must be ensured that the ohmic heat generated by the high currents (high C rates) is always effectively dissipated in order to counteract the thermal effects which reduce the service life and cycle stability.

Increasing the reactive surface raises the power density, if the surface area can be accommodated within the same volume by reducing the layer thicknesses. As a rule, the electrolyte must be adapted and compromises made with regard to the requirements for service life and cycle stability. Adaptation of the cell geometry also results in a modest improvement of the power density. A topical example of this is the enlargement of the standard round cell from 18650 to 21700 [50].

It should be noted that the power density of batteries is evaluated almost exclusively at the cell level and without cooling. By adapting the thermal and battery management, the power density of a battery system can also be increased beyond the values specified in the data sheet without curtailing the service life of the cells.

5.4. Thermal and battery management

At the battery system level, optimum use of the total capacity is a key concern. It is also important to prevent premature aging and deterioration of the electrical properties at the cell level. The thermal management required for this is a challenge which is currently being addressed in the research and development departments. A central requirement is to optimize the service life of the battery system at high C rates. Another is to homogenize the temperature in the battery system to ensure the same operating conditions in each cell.¹⁷

The basic task of a battery management system (BMS) is to optimize the service life, reliability, safety and economic efficiency of the battery system, with the aim of giving the battery the necessary “intelligence”. Good BMS design is another challenge to be addressed by research and development. The temperature, voltage and current values measured at the module level must be recorded, evaluated and controlled centrally. The required sensors as well as data and control cables must be designed to be as space-saving as possible in order to minimize any reduction of the resulting (effective) energy density.

¹⁷ In the case of large cells, temperature gradients can also occur within the cell body at high C rates, causing different cell zones to age differently. This effect must also be reduced by suitable thermal or battery management.

6

Courses of action and recommendations

In this section the authors highlight the options for a battery solution for multiple units which meet the relevant technical and economic criteria.

6.1. Meet temperature requirements at system level

The outdoor air temperature range of -25 °C to +40 °C applicable to multiple units according to EN 50125-1 and EN 60721-3-5 is also set out as a requirement in most specifications of traction batteries for battery trains. In fact, at the cell level the outside temperature is scarcely noticeable during operation, since the temperature within the cell environment is usually regulated to a suitable value by a thermal management system.

More critical are cases when the train is parked and switched off in a very cold environment for a longer period of time, e.g. overnight. Under these circumstances, the temperature inside the battery pack could also drop low enough for the integrated cells to enter a state of very low power density in which they would not be able to handle high charging currents. In practice, however, cells, modules and packs are encased in housings and materials that are so solid and tight in order to meet crash safety and applicable IP protection classes that they also provide a degree of thermal insulation from the outside air.

Many batteries are equipped with sensors that detect any critical temperatures. An undercooled battery could first be preheated with a low charging current, e.g. 0.2C, until it reaches a temperature at the cell level at which the charging and discharging currents required for operation can be applied. Alternatively, the existing cooling units could be designed as combination units and used to preheat the batteries. As part of battery pack development, it would be desirable to verify the actual temperatures occurring inside a battery container or in the modules and cells, for example by measuring sample batteries cooled to defined temperature values in a climatic chamber.

If technical measures at the system level succeed in guaranteeing cell temperatures of at least +5 °C, cell types with significantly higher energy densities can also be used for traction batteries in multiple-unit trains that were previously excluded because of their graphite anodes. Possible weight or space problems associated with the battery system could then be resolved without compromising capacity and thus range.

6.2. Assess charging current requirements depending on the situation

Analyses of the load simulations described in Section 2.1 call into question the hard charging current requirement of up to 5C, as this value is obtained by superimposing the charging power obtained from the overhead contact line on the recuperation power generated during braking. The requirement could be relaxed, for example, by charging only from the generated recuperation energy during the braking phases, i.e. deactivating charging from the overhead contact line, as appropriate. Limiting the charging current to 3C would considerably increase the variety of cells suitable for multiple units.

6.3. Exploit technological advantages in hybrid arrangements

High power density is a special requirement of traction batteries. It allows the energy required for starting and accelerating the vehicle to be provided quickly. In the other operation phases of a multiple unit, the more moderate discharging currents serve primarily to extend the range. An alternative (hybrid) concept is therefore conceivable in which the entire battery system is divided into two parallel strands.

- The first part comprises a battery with high energy density, designed for example for 500 kWh to guarantee the desired range. Its power density requirement, or C rate performance, is moderate, by contrast.
- The other part fulfils the function of a dynamic battery as required e.g. in a fuel cell train, e.g. delivering 200 kWh. This is characterized by its high power density and C rate performance. Its contribution to range is of secondary importance. It stores the recuperation energy generated during braking, which is then used for acceleration processes during operation.

A dynamic traction battery system with a long range could be implemented at low cost using such a battery constellation. The load separation should also have a positive effect on the service life of the hybrid system. However, significant amounts of additional hardware and software would be needed for control. The effort required e.g. in the Mireo modular concept for realizing the fuel cell drive would conceivably be incurred anyway: the fuel cells would take the place of the long-range battery; the dynamic battery and its control could presumably be taken over in unchanged form.

6.4. Ensure long-term economy using standard technologies

Answering the question of how prices for traction batteries will develop in the future is akin to looking into a crystal ball, especially when it comes to identifying batteries which are suitable for multiple units, trams or buses. In battery-operated cars, the expectations of the BEV manufacturers regarding the development of marginal costs for battery cells and packs are summarized in the form of a roadmap covering the period up to 2030 – see Section 5.1.

Concrete information on the possible price development of batteries with LTO technology in €/kWh is as hard to find in the literature as that on the associated energy density trends. LTO is classified as a special technology with limited scope and relatively low demand. A significant drop in prices is hardly to be expected in the coming 10 to 15 years, even if competition from manufacturers such as Toshiba, XALT, Kokam or Saft is currently growing. The technological innovation involving TNO anodes announced by Toshiba promises significantly higher energy densities, but puts the competitive situation for special technologies into perspective. More favourable is the use of standard cell chemistries such as NCA/C (e.g. from Panasonic), NCM/C (e.g. from Samsung) or LFP/C (e.g. from BYD).

→ Figure 24 provides an overview of the projected costs of lithium-ion batteries up to 2030. The Fraunhofer Institute for Systems and Innovation Research (ISI) has compiled this on the basis of the literature and market studies and published it in its updated energy storage roadmap [44]. The development of costs in €/kWh is broken down into

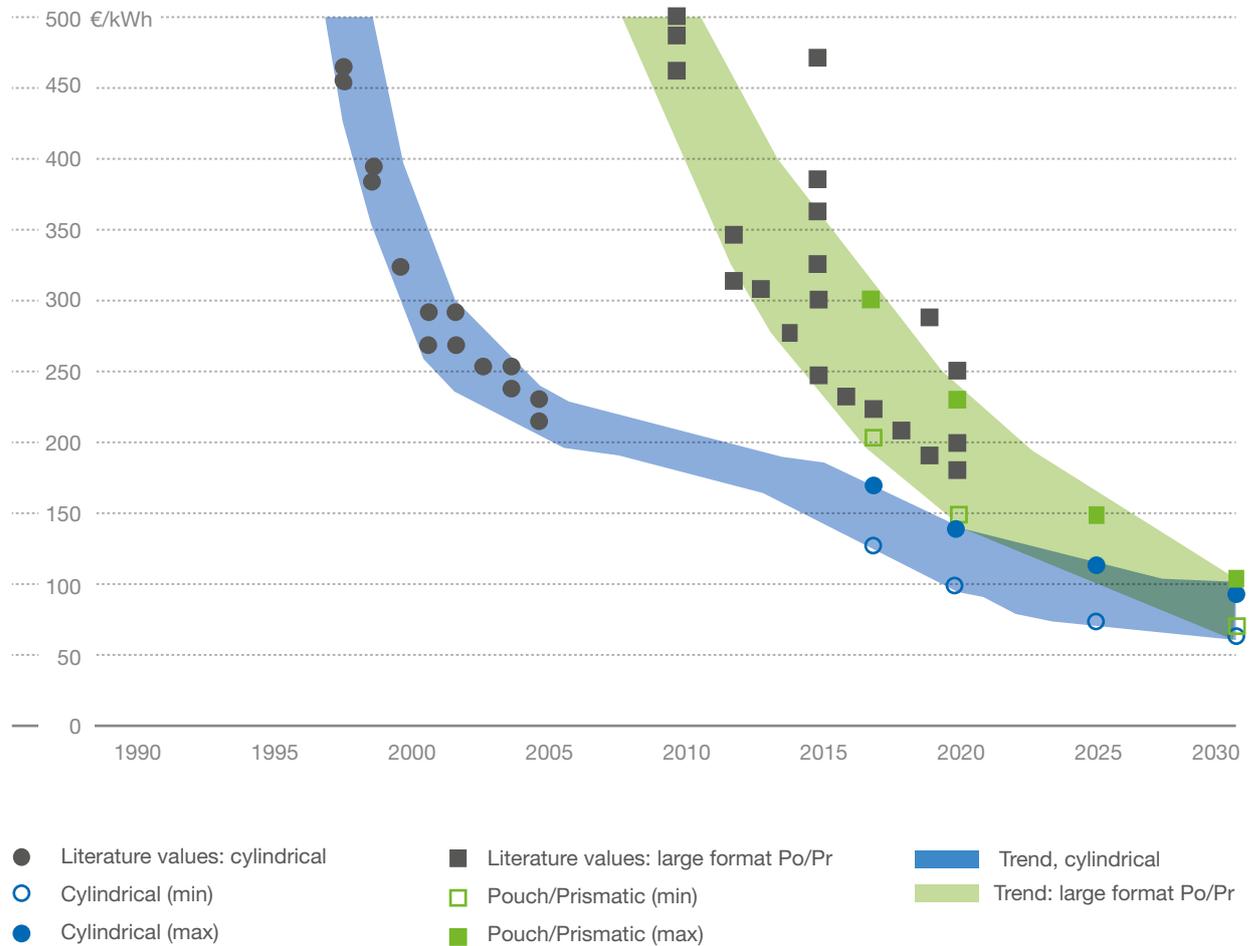


Fig 24 Cost development of LIB cells by cell format (according to [44])

large-format pouch or prismatic cells (green) and cylindrical cells (blue). According to these figures, round cells are now considerably less expensive than all other cell formats. The cost differences based on the cell formats will gradually be eliminated over the next 10 years. The general trend in (marginal) costs at the cell level is towards <100 €/kWh.

It is to be expected that manufacturers of LTO (or TNO) cells will come under pressure in the long term if they are unable to offer their customers favourable price developments, especially if suitable technical measures allow cells with standard technologies to be used in battery-powered buses, trams and multiple units in the future.

6.5. Trust in the future of NCM cathode material

The choice of a cell technology that is particularly suitable for use in multiple units is a question of optimization in which power density, energy density, cycle stability, charge/discharge currents or even costs per kWh etc. are the parameters that need to be taken into account. Long-term availability, competition among suppliers, quality and cost-optimized cell production as well as constant improvements in technologies are further aspects.

The cathode material NCM described in Section 3.1.2(c) – $\text{Li}[\text{Ni}_{1-x-y}\text{Co}_x\text{Mn}_y]\text{O}_2$ – is impressive in terms of the predictability of its improvements and optimizations, in particular in view of the large number of cell manufacturers participating worldwide. It offers the possibility of obtaining higher energy density levels, more or less regardless of the selected anode. According to [49], Toshiba, for example, is supplementing the HD-TNO (high-density TiNb2O7), announced as an LTO successor, with the nickel-rich cathode material NCM622 ($\text{LiNi}_{0.6}\text{Co}_{0.2}\text{Mn}_{0.2}\text{O}_2$).

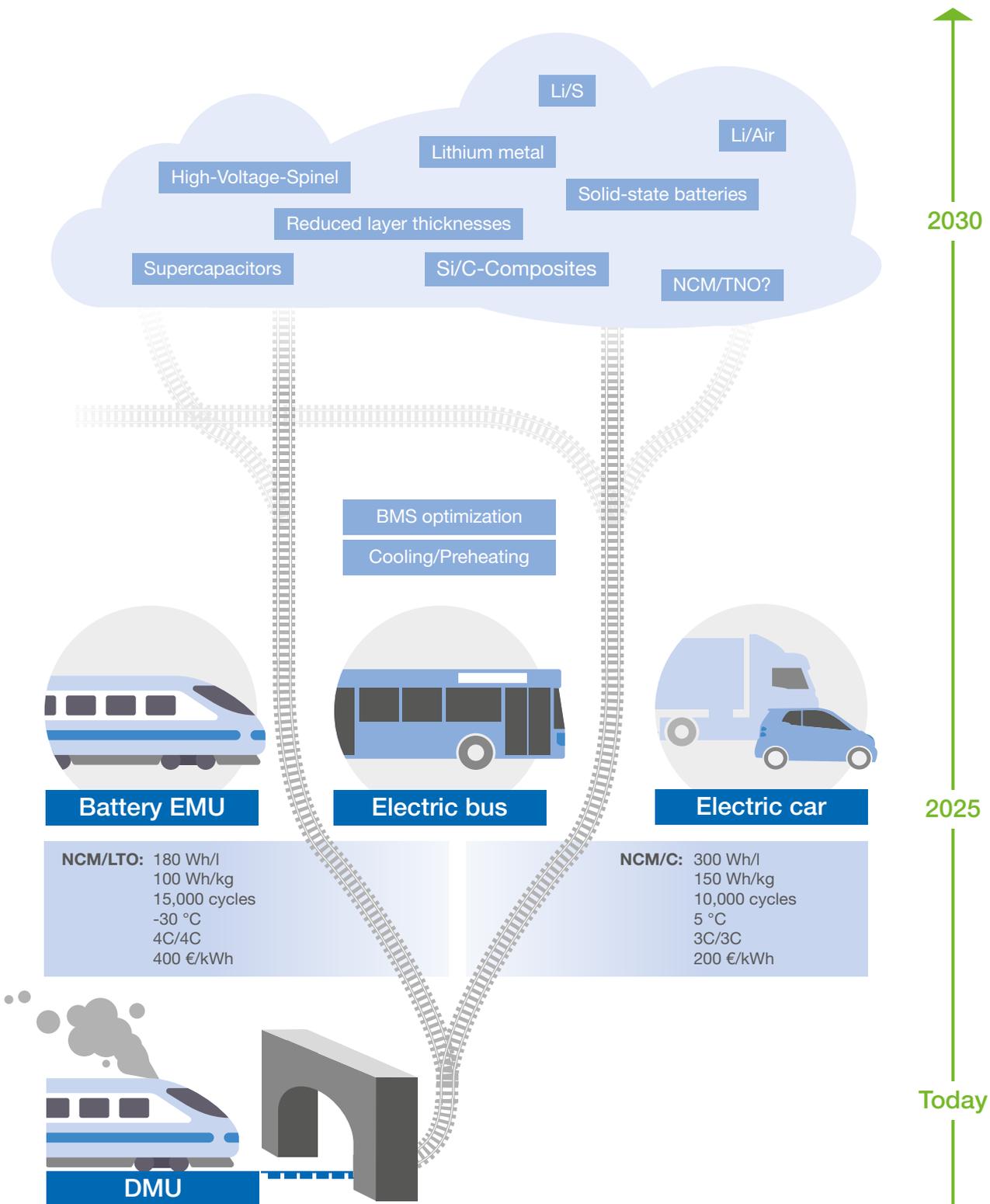


Fig 25 Possible implications of battery decision for multiple units

The choice of which battery solution for multiple units to opt for is ultimately analogous to making a decision at points on a line that lead to two separate technology tracks, NCM/C or NCM/LTO. Put simply, the decision is between **long range at minimum cost** versus **maximum performance with high reliability**. → Figure 25 illustrates the ramifications of the decision and gives an overview of technical data.

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Acronyms

BEV	Battery Electric Vehicle
BMS	Battery Management System
BoL	Beginning of Life
C	Carbon
C rate	Discharge rate relative to nominal capacity
CRRC	China Railway Rolling Stock Corporation
DoD	Depth of Discharge
EDLC	Electric Double-Layer Capacitor
EMU	Electric Multiple Unit
EoL	End of Life
EUCAR	European Council for Automotive R&D
HEV	Hybrid Electric Vehicle
HVS	High Voltage Spinel
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
LMO-s	Lithium Manganese Oxide Spinel
LTO	Lithium Titanate Oxide M
MU	Multiple Unit
NCA	Lithium Nickel Cobalt Aluminium Oxide
NCM, NMC	Lithium Nickel Cobalt Manganese Oxide
NEEC	National Rail Transit Electrification and Automation Engineering Technology Research Center
NiMH	Nickel Metal Hydride
NPE	German National Platform for Electric Mobility
PHEV	Plug-in Hybrid Electric Vehicles
SEI	Solid Electrolyte Interphase
SoC	State of Charge
SPNV	schienengebundener Personennahverkehr (rail-based local passenger transport system)
TCO	Total Cost of Ownership
TCU	Thermal Conditioning Unit
TNO	(Lithium) Titanium Niobium Oxide (also LTN)
X-EMU	Hybrid Electric Multiple Unit

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