

Batteries for Electric Road Vehicles

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4.1 INTRODUCTION

The so-called classic accumulator is not yet exhausted concerning development possibilities. The newest trends in research and development indicate that new production methods offer more cost-efficient methods for production of batteries than present production techniques, corresponding with presumptive large production numbers. Even though presently much work is being invested into conventional battery systems, hopes are focusing on new batteries of higher energy content, such as high temperature batteries, e.g. sodium/sulfur and lithium/sulfur batteries. It must be mentioned, however, that even though very good results can be expected, no “magic battery” will be invented by battery development teams or by teams in any other industry.

The traveling range of battery-powered vehicles will always be very limited compared to vehicles featuring combustion engines, if comparing the practically attainable energy contents of batteries (40 to 150 Wh/kg) to the gigantic 12,000 to 13,000 Wh/kg for gasoline, even though the efficiency of electric energy forms is about five times as high.

This chapter gives basic information on existing systems such as the lead-acid battery; other systems under development are described in Chapter 1 and Chapter 10.

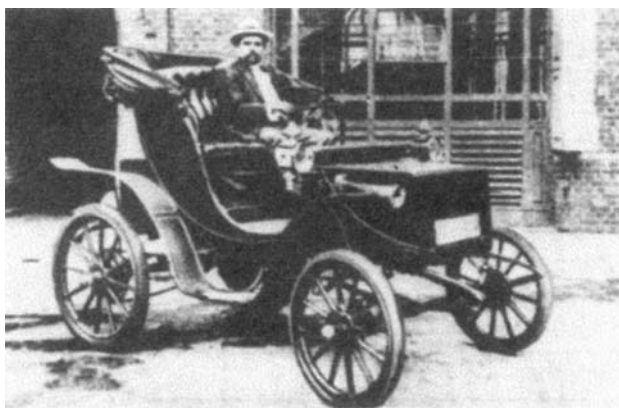


Figure 4.1 The first electric battery-powered car, the Runabout (1890).

The history of industrial production of batteries comprises almost a century; the electric car is of the same age. Adolf Mueller, founder of the AFA (Accumulator-enfabrik Aktiengesellschaft Varta), returned to Germany from a trip to the United States in 1893 with an electrically powered vehicle, the Runabout (see Figure 4.1). He drove this car for many years. Interest of the car manufacturers was very limited but was awakened at the turn of the century when reports of about 15,000 electric cars in operation in the United States reached the country. Very low energy cells and 20 Wh/kg for grid-plate cells were a great step forward. Electric taxis, buses, and trucks sprang up everywhere, and operated profitably. Unfortunately the combustion engine interrupted this development.

After World War II most of the electric vehicles disappeared, and electric industrial trucks, streetcars, and boats and submarines remained the only field of application for traction batteries, mostly lead-acid batteries. England has kept about 40,000 electrically powered trucks in service to this day, mostly for service in rural areas, for milk delivery and the like.

Development in the field of electric fuel cells came to attention in the second half of the 1960s and the 1970s when the oil price shock and later environmental conscience renewed worldwide interest for the electric powered car. First successes in battery development caused euphoria in some places, the electric vehicle becoming a visionary vehicle of the future with power supply by means of nuclear energy seeming limitless. Development problems? These problems could be solved by time and expenditure! So hopes were flying high. Disillusionment and disappointment followed on the one hand, but encouraging reports by the press on the other. What is our situation today?

At the 18th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition in October 2001 in Berlin, Germany, the world's largest event for electric vehicles, under the motto "Clean and efficient mobility for this millennium", development results and real hardware were presented, giving hope for solutions for the market not too far in the future (see *Proceedings EVS 18*).

Arguments for the electrically powered vehicle are still cogent if one accepts the following statements:

- The electric car could be a partial substitute for combustion engine cars at least as a supplement and can take over certain fields of operation.
- As its range is very limited, economic operation can only be maintained for short and medium ranges (100 to 150 km).
- Research and market introduction still needs to be improved.

The following advantages can be listed:

- Electrically powered vehicles are simple to operate and are almost maintenance free.
- Short-range operation poses no problems to the attainable range with the presently available systems.
- Electric power is clean and free of pollution emissions.
- Electric cars offer the same possibilities for exploitation as coal and nuclear power, but with substantially higher grades of efficiency than “artificial” fuels, such as methanol or hydrogen.

As already mentioned, environmental problems, both noise and emissions, and the responsible and expensive primary energy sources, especially crude oil, force us to develop and test alternatives. Most important, large-scale testing of these new technologies is necessary, and is being accomplished in several projects all over the world. Charging, energy distribution, and general operating conditions are only some of a multitude of problems that can presently be handled to a large extent.

4.2 ENERGY AND RAW MATERIALS

Alternative energy forms for future vehicles are synthetic hydrocarbons “artificial gasoline”, liquefied coal, methanol or ethanol, gasses such as hydrogen, and electricity. These so-called secondary energies must be reduced from primary forms of energy such as fossil coals, crude oil, gas, or nuclear power. Calculations of the GES (Gesellschaft für Elektrischen Strassenverkehr) and RWE (Rheinisch-Westfälische Elektrizitätswerke) made more than a decade ago showed that electricity for vehicle propulsion can be produced at about half the expenditure of primary fuels when reduced from different secondary forms of energy compared to powering by synthetic fuels, presumptive equal road performances, of course.

The fundamental question arises: will existing power plants cover such a change to electricity and the involved introduction of a great number of vehicles. This appears possible if, for instance, Germany, had 10% electric road vehicles. In 1980 about 369 billion kWh of electric energy were produced and, from statements from this industry, production of an additional 10 billion kWh presents no problem. 10 billion kWh would power 2 million road vehicles, each covering 10,000 km a year (a calculation easy to follow presuming that each kilometer covered consumes 0.5 kWh of mains electricity). With the generally rising demand of electricity, only 3% of the overall production would be available at any time for powering electric vehicles.

It will be pointed out in the following that for the foreseeable future only lead-acid accumulators will be available for powering vehicles. This of course raises the question whether there is enough lead available to cover such a demand. Newly

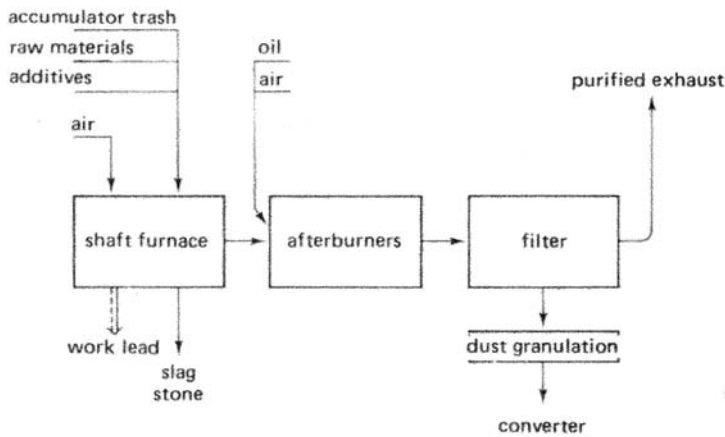


Figure 4.2 Diagram of a recycling procedure of lead batteries (Krautscheid).

developed batteries (see Chapter 10) have to demonstrate reliability in practical use and economy.

If one would start today to produce a stock of, let's say, 500,000 electric cars in Germany over the next 10 years, this would cause a momentous rise in production numbers of cars and batteries. In 10 years from now, an estimated annual production of about 100,000 batteries for new cars and about 30,000 batteries for replacements would be needed. Enough lead for about 30,000 batteries could be recycled by the same low-pollution techniques already practiced today (see Figure 4.2). A 120-V battery with an energy content of 19.2 kWh consumes about 370 kg of lead to the present state of art, resulting in additional 37,000 tons of lead in demand for one year. This is little more than 10% of the amount of lead consumed per annum in Germany. So in a foreseeable starting phase, no shortage of lead would occur, not even if demand were higher. If development of alternative energy accumulators, e.g. lithium/sulfur batteries, succeeds within the near future, the raw material question regarding lead will become obsolete.

Often the amount of primary energy needed for manufacturing a product has to be accounted for; this problem is not too grave since national energy resources, such as fossil coal or nuclear energy, can be exploited for production of electricity, thus lowering the import demand of crude oil to the country in question.

4.3 SOLUTION TO THE RANGE PROBLEM

As mentioned, the problem of a limitless range does not seem solvable with the "classic batteries" within a foreseeable period of time. Battery-powered vehicles thus are regarded as short-range vehicles. As to what is the optimal range, very different opinions are at hand due to the geography of the country in question: 40 to 80 km for European conditions and 150 miles (240 km) would be adequate for American conditions. Let's have a look at the general circumstances in Germany: The following values were found for passenger cars in West Germany in 1979 (these values can still be seen today as representative):

- Average length of one single drive: 12.1 km.
- Average total distance driven per day: 37.87 km.
- Average total distance covered per year: 13 400 km.

It can be derived that a very large number of cars are used for distances smaller than 40 km per day (very precise studies on the type of cars and the people who use them are available). Nonetheless, a great obstacle for the introduction of the electric car is the fear of having a breakdown en route. There is however a very simple way to prolong the range substantially: by recharging during driving breaks by a built-in charging device that enables the battery to be hooked up directly to the AC network current on a domestic wall outlet. Figure 4.3 demonstrates this option. Lines 1, 2, and 3 in the figure represent three different average cruising speeds in urban traffic in a distance/time diagram. The horizontal lines A and B represent the limits for a battery with sufficient capacity for a 40 and 80 km range. The time axis has a range of 14 hours, the time a vehicle should be available per day. The crossing points of the lines give the maximum possible cruising time at constant speed 1, 2, or 3. Generally only a fraction of this maximum cruising time is used and during breaks the cars can be intermediately charged at any power outlet. The diagram also features the values attainable when range prolongation through intermediate charging with 2 or 5 kWh is practiced: the intersections of lines L_1 and L_2 or L_1' and L_2' with the lines 1, 2, and 3.

The average speed of 30 km/h yields the greatest range:

- First case: a battery with about 10.8 kWh and 40 km range; intermediate charging with 2 kW prolongs the range by 125% to 90 km, with 5 kW by 260% to 144 km.
- Second case: a battery with about 21.6 kWh and 80 km range; intermediate charging with 2 kW prolongs range by 56% for 125 km, with 5 kW by 118% to 175 km.

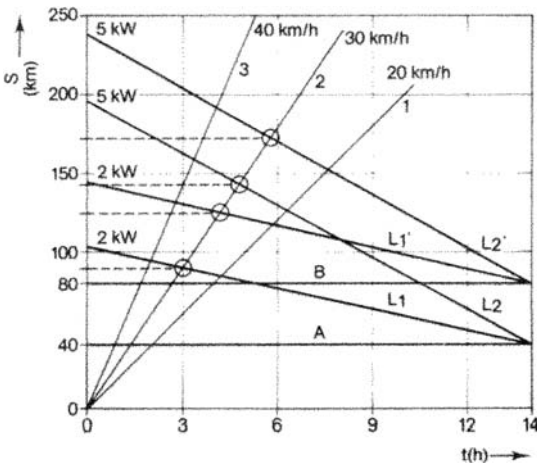


Figure 4.3 Prolongation of the range by built-in charging devices (from a publication of the GES).

This procedure is practicable and is open to optimization depending on how much of the actual stopping period is available for intermediate charging. The batteries' perfect function is not affected by this method. This indicates the following:

1. Service range can be substantially improved without high costs and without fitting a larger battery simply by intermediate charging.
2. Application of a larger battery without the employment of intermediate charging makes electromotive power more expensive (capital and interest rates).
3. Higher energy densities are primarily of interest for lowering battery weight and only secondarily for improving range.
4. Charging devices and mains adaptors can be incorporated in the vehicles and are state of the art.
5. This application can be used not only for lead-acid batteries, but also for any other secondary battery.

Now as it is evident that there are no arguments against the introduction of the electric car regarding the energy and raw material situation and with the range problem being almost solved, we will examine whether the requirements for the battery itself have been or can be solved.

4.4 BATTERY REQUIREMENTS: CONTRIBUTIONS TO SOLVING THE PROBLEM

The following goals exist for electric road vehicle batteries:

- Making batteries lighter by significantly higher energy and power densities, primarily weight-specific.
- Raising power content, weight-specific.
- As maintenance free as possible without sophisticated peripheral equipment.
- Service life should reach the life span of industrial trucks.
- 1200 cycles 80% C₅ lead-acid batteries.
- 2000 cycles 80% C₅ nickel/iron batteries.
- High efficiency/low charging factor: 1.01 to 1.05.
- No noticeable rise in price through energy consumption during use.
- Same or improved reliability compared to present products.

Furthermore:

- The ability to incorporate the energy-storing device into presently produced cars, raising the competitive situation (especially when only some basic models are produced): modularization.
- Mechanical stability without supporting devices. Solutions that dispense with battery trays (saving cost and weight) are especially advantageous.
- Tightness. Solutions that prevent leakage of electrolyte vapor and charging gasses are especially advantageous.
- Temperature resistance. The upper and lower temperature limits should be penetrable temporarily with no damage done to the battery.
- Long shelf-life and active life even after a long inactive period.
- Ability to withstand overcharging facilitating the charging procedure.

- Ability to withstand exhaustive discharge, preventing failure of the battery following severe strain and reducing exhaustive discharge protection requirements.
- Sustainable fast charging. In many cases recharging times of 10 to 16 hours are sufficient. The ability to sustain fast (0.5 to 1 hour) charging would solve the range problem and would also contribute substantially to making battery interchange superfluous.
- Reparability. Damaged or worn-out parts, such as cells and modules, must be replaced quickly to reduce breakdown periods.
- Easy activation. Expenditure of activation must be as low as possible at highest possible initial power output.
- State-of-charge indicator. This “marginal problem” has not been solved satisfactorily.
- Electrical and mechanical ruggedness regarding shock, vibrations, and crashes.
- Non polluting during operation, manufacturing, and recycling.

With knowledge of these requirements, developments have been carried through to improve the lead-acid, nickel/iron, and high-temperature lithium/sulfur systems to the above standards. Outstanding successes were made that can be regarded as milestones of battery development. The first lead battery systems as they were tested in MAN and Mercedes Benz buses, Volkswagen and Mercedes Benz vans, and other experimental vehicles should be mentioned here:

- Energy and power densities could be essentially improved.
- Parts optimization was carried through to reduce dead weight.
- Fully insulated batteries with 100% gas-tight terminal passes were developed (see Figure 4.4).

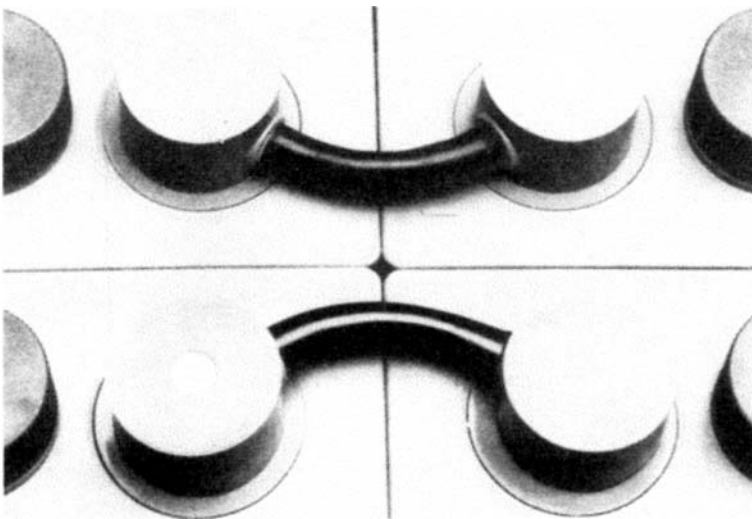


Figure 4.4 Fully insulated flexible connector technique.

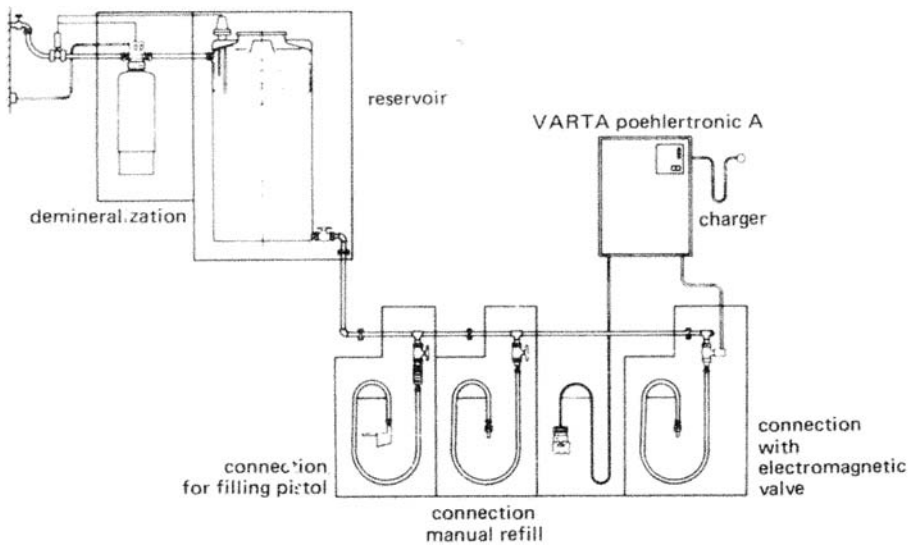


Figure 4.5 Peripheral devices: centralized water replenishing system (Varta aquamatic).

- Service life and reliability were improved coexistent with higher energy density values.
- Peripheral devices such as water replenishing systems, central gas adsorption, cooling systems, charging, and battery controlling equipment have been developed (see Figures 4.5 through 4.8) and have been successfully tested.
- Basic theoretical and experimental research work has yielded a lead-accumulator system.

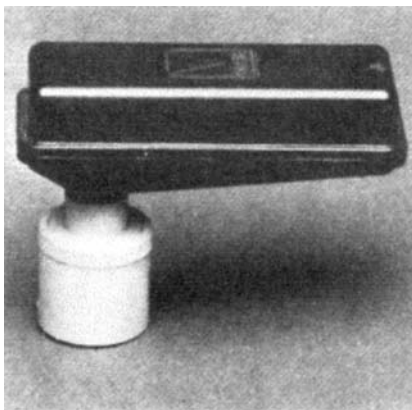


Figure 4.6 Peripheral devices: recombination plug.



Figure 4.7 Peripheral devices: water refill plug.

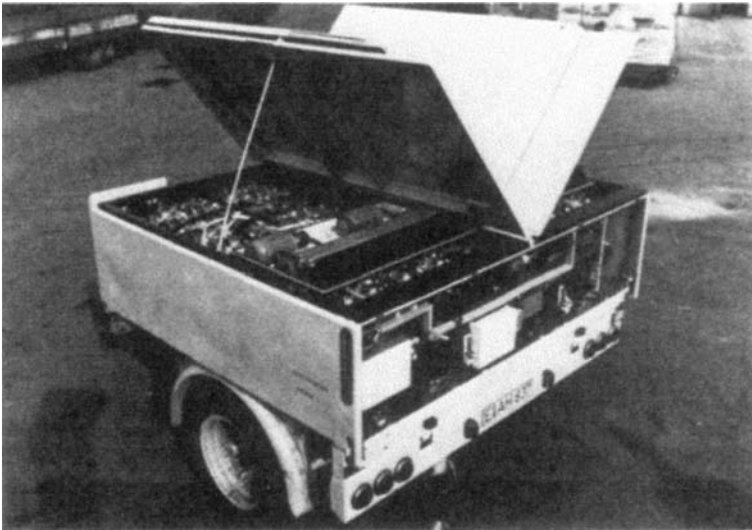


Figure 4.8 Peripheral devices: cooling system for the lead traction battery of an electric bus.

4.5 ALTERNATIVES TO LEAD-ACID SYSTEMS

The experiments that have been carried out with electric vehicles for several years now have shown that many requirements could be fulfilled to a large extent by focused research work. The cost factor regarding further developments shall be discussed later.

It is only natural that problems had to be solved in the course of the experiments; the combustion engine had to be refined over and over again as well before it reached the present high grade of perfection. More than 200 electric vans and over 20 electric buses have been in experimental operation in different cities of Germany. In Stuttgart and Wesel large-scale experiments involved over 20 hybrid

buses and in Esslingen further research was made with “duo-buses”. Three systems have prevailed out of all these experiments with electrically powered vehicles:

- *The battery/electromotor drive.* Exclusively batteries maintain this. A charging station is frequented at certain intervals to recharge or change batteries or intermediate charging is made during stops.
- *Hybrid drives.* This drive also employs batteries, but with a certain change a diesel generator is frequently activated to recharge the batteries during operation. After the craft has departed from areas suffering from heavy pollution, the diesel generator is switched on.
- *Duo drives.* The vehicle runs mainly on battery power and frequent overhead power lines make recharging.

Spectacular advances in the applied battery systems cannot be expected, but surely another rise in energy density, perhaps by 10 to 20%, may be made regarding power density.

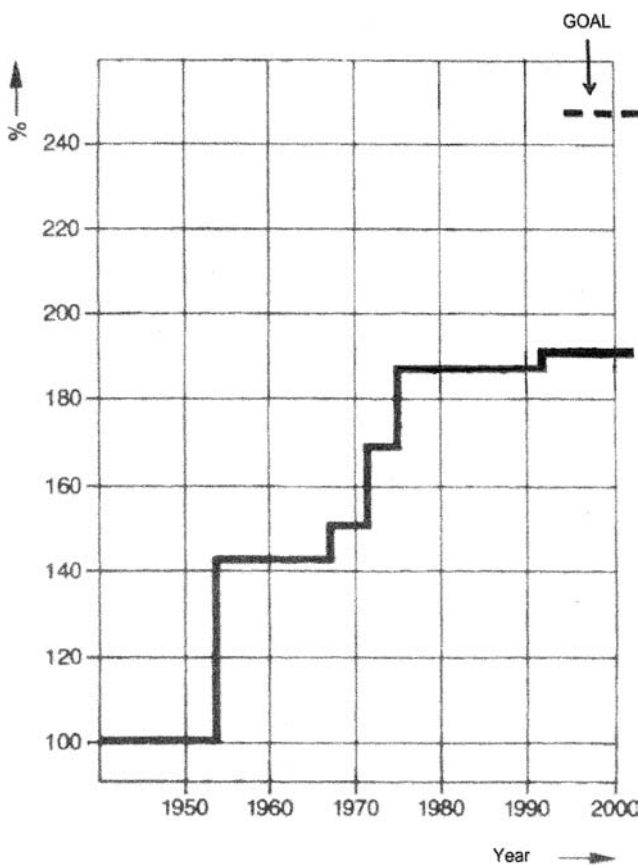


Figure 4.9 Development of energy density (percent Wh/kg) of lead-acid traction cells with future outlook.

Figure 4.9 shows the development of energy density of the lead-acid accumulator since 1945 in percent as well as the goal, which seems attainable presuming research work on improved mass utilization proves successful, e.g. by electrodes that are run through by the electrolyte, a principle presented by the supervisor of the AFA laboratories in Hagen, Carl Liebenow, in his famous experiment in 1895.

A decisive change, especially regarding price and economy can only be brought on by large-scale introduction. At present it is not possible to compare prices and costs of a new technology with those of a mass product. At best an estimation of those costs can be made caused by an actually comparable function and with the same operational parameters, also regarding further price rises for crude oil (see Section 4.6).

The presently available lead-acid batteries consist of cells and modules, with standard sizes for cells having been published in the DIN 43 537 standard. This type of cell is totally electrolyte-tight except for the refill and gas-emission openings for the vent plugs. The connectors are flexible and fully insulated (see Figure 4.10). All cells and modules can be fitted with central water-replenishing systems or with recombining systems (catalytic converters that recombine charging gases to water). The replenishing system is combined with a gas adsorption system. All of the gas produced inside the cells is ventilated to the outside air.

Certain types of cells, such as the HD types, can be fitted with a water-cooling system. This prevents the temperature from rising above a certain limit under heavy load and thereby allows higher loads and currents to be drawn.

Lead-acid cells and modules have attained the highest level of development, especially concerning reliability and attainable service life. The first generation of

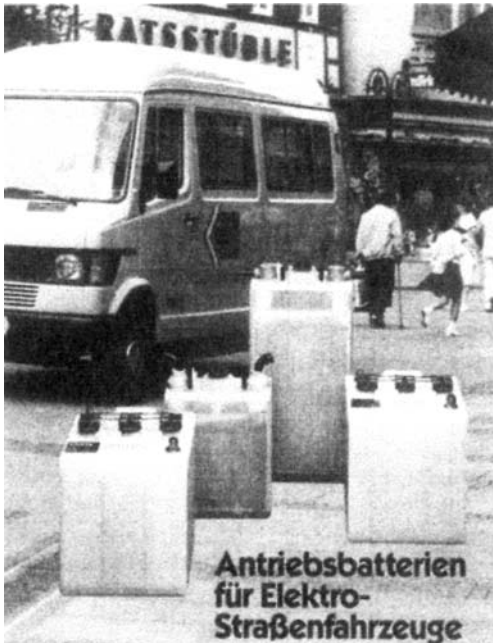
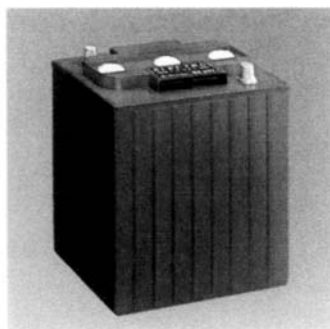
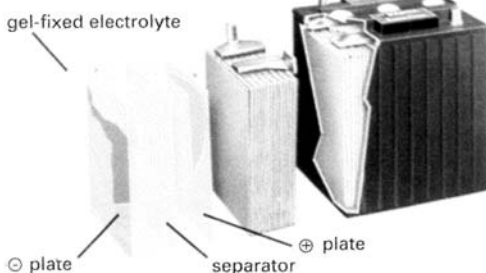


Figure 4.10 Present-state designs of vehicle traction batteries and battery modules.

Varta Electro Power: lead-gel



Lead-acid-battery technologies for electrically powered road vehicles

	Battery with liquid electrolyte	Valve regulated battery gel-type	AGM-type	Advanced developments
Design description	gas output while charging	limited electrolyte volume	limited electrolyte volume	new electrode technology
Plate construction	reinforced grid plate, tubular plate	thin grid plate	thin grid plate	■ lead-free grid ■ thin-foil systems ■ mini tubular cells
Energy density (Wh/kg) 5-hour discharge rate	30	35	35	50
Power density (W/kg) 30 s to 2/3 U ₀	100	up to 150	up to 150	200 and more
Life cycle (80% DOD)	up to 1,500	700	500	600 to 1,500
Maintenance	Automatic water refill once a year	no water refill		
Application	Bus, heavy utility vehicles	Passenger car, light van	Passenger car	
Entirely electric powered v.	+	+	+	
Hybrid electric powered v.	-	-	o	
Development status	Mass Product	Mass Product	Mass Product	Laboratory prototype or pilot production

Legend: + = good o = with reservations - = poor

Figure 4.11 Technology comparison of different types of lead-acid batteries.

batteries for electric vehicles will almost certainly be of the lead-acid battery family as they already fulfill most requirements at present and permit short-range traffic.

Figure 4.11 shows a three-cell monobloc valve-regulated lead-acid battery and a comparison of other lead-acid battery types with an outlook on possible future design.

4.6 BATTERY SYSTEMS OF THE NEAR FUTURE

To answer the question which system is the best alternative to combustion engine drives, it is necessary to look a bit closer at the problems of some experimental battery systems.

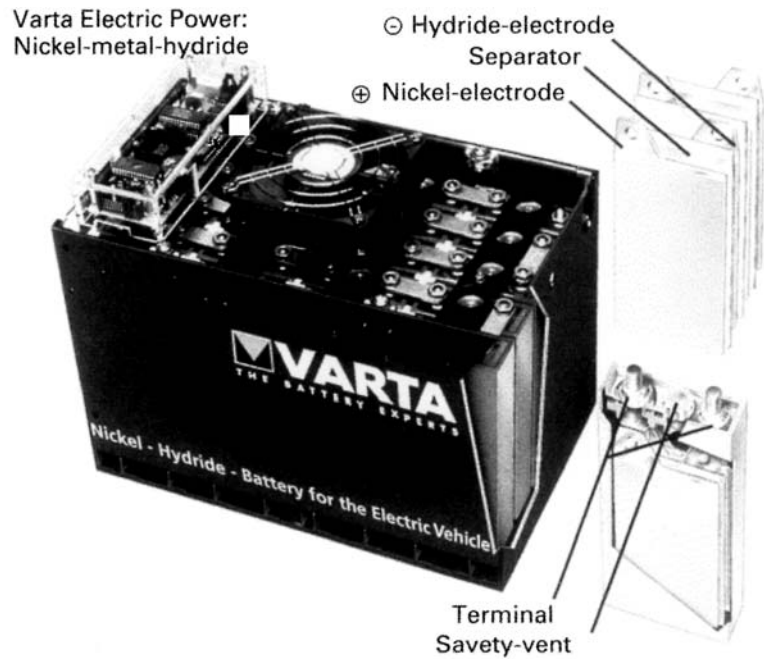
The first systems to be examined are the nickel/iron and the nickel/zinc systems. Values ranging from 60 to 80 kWh/kg seem realizable, without regard to life expectancy. The nickel/iron and nickel/zinc systems will always be more expensive than a comparable lead-acid battery for the following three reasons: the materials involved are more expensive, the production involves more expenditure, which is partly the case because a greater number of cells are required for the same voltage, and more cells are needed because each cell yields less voltage. So to be more

economic these systems must have a longer service life than a lead accumulator. Even so, there are quite a few manufacturers researching the problems of development of the nickel/zinc battery.

In the field of nickel/iron batteries research has not terminated yet, so it is too early to speculate on the subject. Mainly life expectancy is examined by experiments with changing parameters.

The chlorine/zinc battery may also have potential in the near future. It has electrodes with pumped active material. 50 kWh prototypes have been built by Energy Development Associates, an American Gulf & Western Company.

In the mid-1990s several development teams (e.g. Varta) tried to improve the nickel/metal hydride system to make it applicable for electric road vehicles. Figure 4.12 shows a battery module with nickel/metal hydride cells; the given



Technical specifications Nickel-metal-hydride-cells

Specific energy	50 to 80 Wh/kg
Energy density:	150 to 210 Wh/l
Maxim. power:	more than 300 W/kg
Charge time:	80% in 15 minutes
Life-cycle stability:	more than 2,000 cycles



Figure 4.12 Battery module with nickel/metal hydride cells and performance data.



Figure 4.13 Cross-section of battery with nickel/metal hydride monoblocs.



Figure 4.14 Neoplan Metroliner bus.

technical data show the improvement of performance. Figure 4.13 shows a cross-section of the complete battery with the modules shown in Figure 4.12. The battery was under test in a Neoplan Metroliner bus. Figure 4.14 shows the Neoplan Metroliner bus running in the city.

Parallel with the development activities on nickel/metal hydride batteries, the lithium-ion (also called 'lithium swing') system was developed and improved by Varta. Figure 4.15 shows a module with lithium-ion cells and the main technical performance data. The outer look conforms to the battery shown in Figure 4.14. The principle of lithium swing is shown in Figure 4.16. Not yet solved is the problem of cycle life, necessary for an economic use of the system. In portable batteries the system has been in successful use for years as an alternative to nickel/metal hydride batteries. (See Chapter 18.) A marketable system is not to be expected in the near future as some grave problems have not yet been solved, such as the control of the sophisticated peripheral devices; reliability; chlorine corrosion properties; low energy efficiency; shunt currents; the nonuniform dispersion of zinc making periodic total cleaning of the system necessary; and sealing of the cell to prevent chlorine from spilling to name a few.

4.7 HIGH-TEMPERATURE BATTERIES AND FUEL CELLS

The most advanced system of this complex is the sodium/sulfur battery. Cost estimates on high-temperature batteries show that after the development phase has been completed and prototypes tested, these systems may operate well inside economical margins, assuming that mass production starts. In case these vehicles and their batteries are only produced in small numbers, the same problem will be at hand, as already discussed with the lead-acid battery. A deficiency of mass production makes vehicles and batteries artificially expensive.

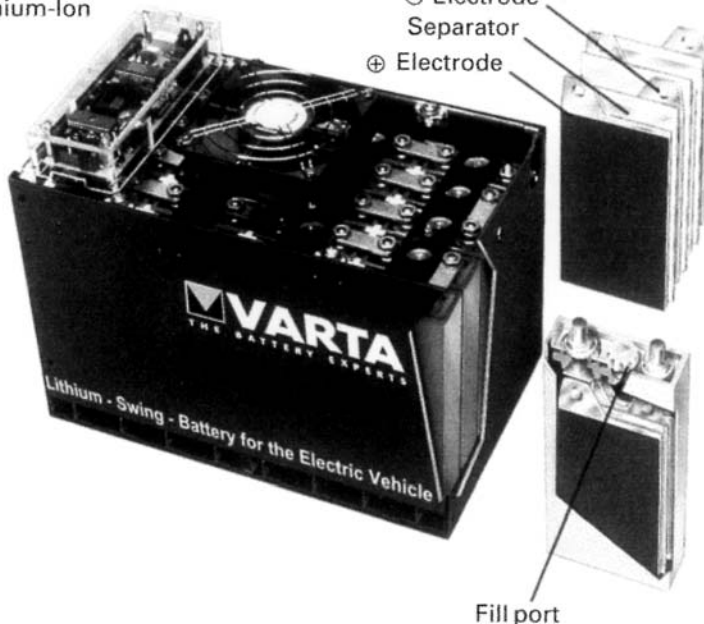
Development of fuel cells also reached a considerable plateau with electrodes that reach service life spans of some 10,000 hours. The great interest for fuel cells remains high. Introduction to the market necessitates the creation of an infrastructure for providing the batteries with the gasses hydrogen and oxygen and their industrial production being state of the art. Much research is invested on making cheaper catalytic materials and electrodes for fuel cells that operate at moderate temperatures (20 to 90 °C) with alkaline electrolytes or at higher temperatures with acidic electrolytes. Yet chances for the future of these systems cannot be evaluated due to this situation. W. Fischer treats the subject of high-energy batteries in Chapter 10.

Figure 4.17, taken from a Varta publication, shows a comparison of the possible range performed by different battery systems by one charge. Presuming a positive result of the development efforts, the estimated values are given for the year 2005.

4.8 ECONOMIC VIABILITY

Economic viability for battery-powered vehicles today is far from realization. Economy can only be reached if electric vehicles, including all their parts and components, are produced in magnitude series. The step to magnitude series is only

Varta Electric Power:
Lithium-Ion



Technical specifications Lithium-ion battery

Specific energy	100 to 120 Wh/kg
Energy density:	200 to 250 Wh/l
Maxim. power:	200 W/kg
Charge time:	4 hours
Life cycle stability:	1,000

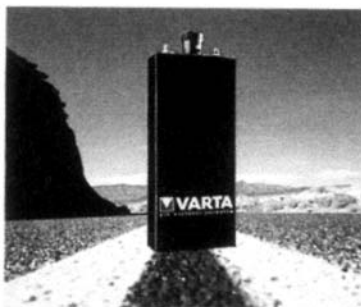


Figure 4.15 Battery module with Varta lithium swing cells.

possible under the condition of general market acceptance for electric road vehicles or if the situation in the field of energy supply changes dramatically by shortage and cost rise of fuel.

Furthermore, three practical examples of application can be named for traction batteries with economic use compared to other propulsion systems:

- The ETA railway coaches with 440-V lead-acid batteries were in service for decades by the German Railways. (Today they are no longer in use because passenger cars are preferred for low distance traffic.)

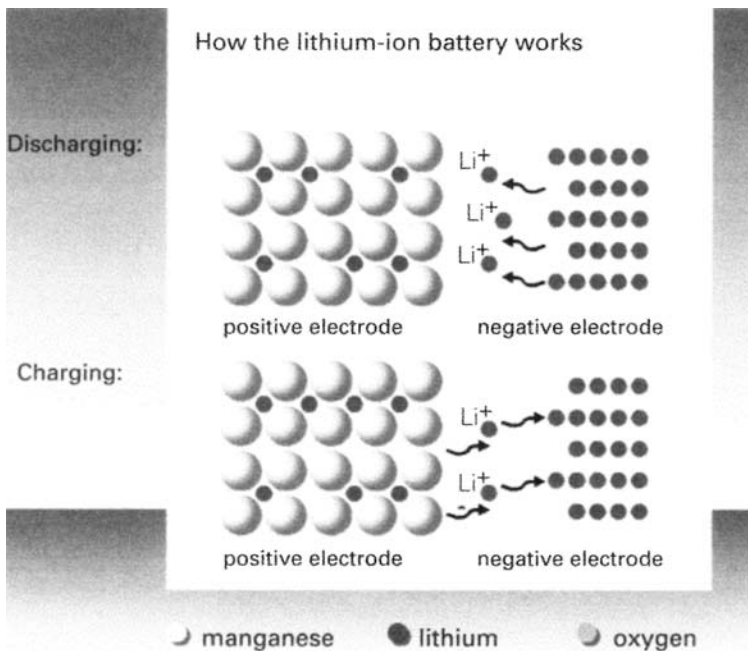


Figure 4.16 Principle of lithium swing.

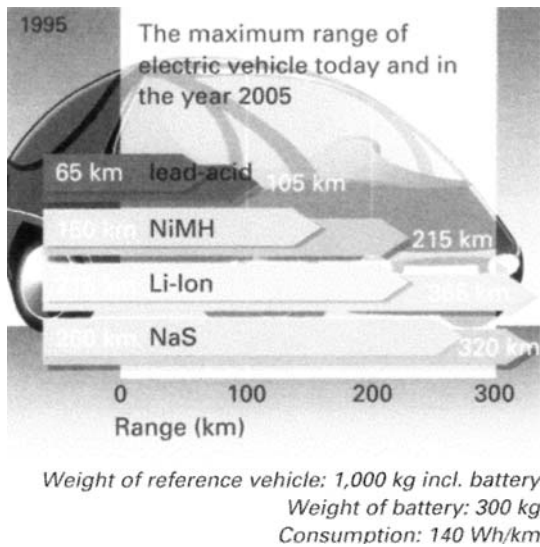


Figure 4.17 Possible ranges performed by different battery systems.

- Battery boats, e.g. for passenger sightseeing transportation on the Königssee.
- Battery-powered forklift trucks.

4.9 OUTLOOK

Despite considerable efforts of countless engaged engineers we are far from market acceptance for electric road vehicles. The technical state of the art is not sufficient. The expectations for possible development work on batteries surely had a level which was too high. Therefore we have to put an eye toward other special applications where battery-powered propulsion fulfills the demands. Progress in traction battery development showed advantages for other kinds of applications. One should not forget that our normal batteries have changed in the last decades in many details. New batteries will need many new parts to enable their employment or to improve their usefulness.

Everybody in Germany who took part in battery development can say, in our country top results could be presented in worldwide competition to realize advanced traction batteries. Expenses amounted to hundreds of millions of deutsch marks in the last 25 years just in West Germany, not to mention governmental fiscal support.

Finally here it will be stated, that all battery systems are “specialists”.

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