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Application Roadmap for Battery Powered Electric Mobility

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***Abstract*— Mobility changes from fossil to renewable energy powered vehicles. Due to high battery weight and costs, only a few applications are currently possible. In this paper, battery weight and amortization times for different means of transport are predicted. It is the goal of this article to analyse, which vehicles are suitable for battery powered electric mobility in the medium-term future.**

Two scenarios with different energy prices and battery developments for the years 2020 and 2030 are analysed. Starting from energy consumption of fossil powered vehicles, the equivalent battery parameters for similar electric vehicles are calculated. The computations show that currently the battery mass is low enough to power short-range electric cars or river ships, but no realistic time-span for amortization can be reached. In 2020, the battery weight will be low enough to power river ships, short and medium range cars. It will be profitable to use battery electric drives for short and medium range cars, city buses and short-range trucks. The projection for the year 2030 shows that all types of commercial land vehicles will be economically driven with batteries. Until 2030, it will be impossible to power transport ships or aircraft using batteries.

It is shown that in the medium term future all land vehicles will be profitable with battery electric drives. The amortization times depend on the chosen scenario. The break-even point for profitable battery powered land vehicles will be between 2020 and 2030. This means that in next decade a big part of fossil powered cars, trucks and buses can be replaced without increasing mobility costs. There is no alternative to chemical fuel for airplanes due to the high battery mass. For ships, the battery costs are too high for amortization. Chemical fuels from fossil or renewable sources will be the only possible power source for these means of transport in the mid-term future.

***Index Terms*—Electric Mobility, Battery technology, Vehicle range**

I. Introduction and Goal of Analysis

It became obvious for mankind that fossil energy resources are restricted and their excessive use lead to air pollution and massive climate problems. Therefore it is very important to reduce the consumption of fossil coal, oil and gas. These resources are too precious to burn them for heat or short range mobility. In our future they will be urgently needed for producing plastics, drugs or powering engines where no other possibilities are.

Currently millions of e-scooters and electric bikes are in the streets around the world. It is estimated that in 2015, the number of e-bikes in China is over 150 millions [1]. They are replacing fossil fuel-powered small city motorcycles. Currently there is also a slow trend for passenger cars toward battery powered electric mobility which is due to higher costs and complexity compared to city e-bikes much more demanding. This can be seen in Germany [2] and also the worldwide prognosis is only 2% electric driven passenger cars in 2020 [3].

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For all other means of transport like airplanes or sea ships it is currently neither technically nor economically possible to replace chemical fuel by battery powered alternatives. With the ongoing battery development, the extent of mobility applications will grow. It is currently unclear in literature, which new battery powered mobility implementations will evolve.

The here published investigation shows projections for battery mobility as an alternative to fossil fuel for the years 2020 and 2030.

All major types of vehicles are analyzed if a conversion from fossil fuel to battery is technically or economically feasible. A possible roadmap for electric mobility regarding battery mass and amortization time is derived from this investigation.

In the next section, the methods and assumptions for this analysis are shown. The means of transport for electric mobility regarding battery mass and costs are analyzed in Section III. The results are discussed in Section IV.

II. Methods and Assumptions for Analysis

Most assumptions could be verified with current values and predictions out of literature. Few assumptions could not be verified with citations and are estimated using values out of practice. From these suppositions, two development perspectives for battery powered electric mobility were calculated. The optimistic scenario estimates an energy price increase like in the past and a battery development like most scientists predict. The pessimistic scenario forecasts a slower energy price rise and a slow battery development.

TABLE I
BATTERY TECHNOLOGY PROJECTION SUMMARY

Year	Today	2020	2030
Technology [9]	LiFePO4	Li-S	Li-Air
ρ_{grav} in kg/kWh	8.3	3.5 ... 4.5	1.5 ... 2.5
ρ_{cost} in €/kWh	1000	300 ... 500	100 ... 200

TABLE II
VEHICLE ASSUMPTIONS FOR CALCULATIONS

Means of Transport	Weight m_{veh}	Energy E_{bat}	Range d/km	Fuel to vehicle mass	total distance per year y/km	Recuperation factor f_{rec}	Efficiency η_{fos}
Car - short dist.	1,200 kg	8 kWh	120	0.033	6,000	1.18	0.16 [20]
Car - med.dist.	1,400 kg	15 kWh	200	0.036	12,000	1.10	0.16 [20]
Car - long dist.	1,600 kg	58 kWh	500	0.038	30,000	1.05	0.20 [20]
Truck - 7.5 tons	7.5 t	132 kWh	300	0.013	40,000	1.20	0.20
Truck - 18 tons	18 t	517 kWh	500	0.022	60,000	1.05	0.30
Truck - 40 tons	40 t	1.09 MWh	850	0.020	100,000	1.00	0.30
City bus	18 t	443 kWh	300	0.011	80,000	1.40	0.30
Overland bus	24 t	1.45 MWh	1,000	0.017	100,000	1.00	0.30
Motorbike	250 kg	12 kWh	160	0.060	4,000	1.18	0.16
Cargo ship - River	2,550 t	18.6 MWh	160	0.005	30,000	1.00	0.50
Cargo ship - Ocean	187,000 t [8]	27.6 GWh	21,000	0.064 [8]	250,000	1.00	0.50
Plane - short dist.	89 t [17]	48 MWh	1,600	0.213 [17]	1,000,000	1.00	0.40 [21]
Plane - long dist.	560 t [18]	1.62 GWh	14,000	0.464 [18]	2,000,000	1.00	0.40 [21]
Helicopter	2,910 kg [19]	2.63 MWh	500	0.172 [19]	30,000	1.00	0.40 [21]

A. *Calculation of Battery Parameters*

The method can be divided into three parts:

- Energy calculation for all vehicles with combustion engines using liquid fossil fuel.
- Transformation to the equivalent electrical energy considering efficiency factor, recuperation and safety reserve.
- Calculating the battery parameters.

The necessary amount of fossil energy E_{fos} is:

$$E_{fos} = d \cdot r_{fos} \cdot \rho_{fos} \quad (1)$$

The vehicle range d without recharging can be seen in Table II. For the volumetric energy densities of fossil fuels ρ_{fos} the reference [4] was considered. The fuel consumption per kilometre r_{fos} is taken out of the vehicles' data sheets [5], [6], [7] and [8].

To calculate the necessary electrical energy E_{el}, the fossil energy E_{fos} has to be adjusted by the efficiencies of the electrical motor η_{el} (which is assumed 90% for all vehicles) and the combustion motor η_{fos} (see Table II):

$$E_{el} = E_{fos} \cdot \frac{\eta_{fos}}{\eta_{el}} \quad (2)$$

The electrical battery energy E_{bat} is calculated with two additional factors:

- Recuperation increases the range by the factor f_{rec} (see Table II).
- Due to deep discharge prevention and safety issues, only the percentage f_{dis} of the maximum battery energy can be used. This is assumed to be 80% for all vehicles.

$$E_{bat} = E_{el} \cdot \frac{f_{dis}}{f_{rec}} \quad (3)$$

The battery energy E_{bat} is used to calculate the required battery mass m_{bat} and costs c_{bat} by using the gravimetric energy density ρ_{grav} and the specific costs ρ_{cost} from Table I.

$$m_{bat} = E_{bat} \cdot \rho_{grav} \quad (4)$$

$$c_{bat} = E_{bat} \cdot \rho_{cost} \quad (5)$$

B. *Projections of Battery Development*

Currently many research groups all over the world develop new battery technologies with higher energy densities. A steady battery improvement with simultaneously decreasing costs can be expected.

The authors analysed several studies, which predict the future battery development. The Fraunhofer Institute for Systems and Innovation Research ISI published a technology roadmap for Lithium-Ion Batteries until the year 2030 [9].

TABLE III
ENERGY COSTS PROJECTION

Year	Today	2020	2030
Gasoline €/l	1.35	1.56 … 1.68	2.03 … 2.55
Diesel €/l	1.27	1.48 … 1.60	1.95 … 2.47
Kerosene €/l	0.60	0.76 … 0.85	1.12 … 1.52
Fuel Oil €/l	0.45	0.57 … 0.64	0.84 … 1.14
El. Energy (private) €/kWh	0.21	0.24 … 0.25	0.30 … 0.34
El. Energy (industry) €/kWh	0.12	0.14 … 0.15	0.16 … 0.19

TABLE IV
BATTERY TO VEHICLE MASS RATIO

Means of Transport	Today	2020	2030
Car - short dist.	0.08	0.04 … 0.05	0.02 … 0.03
Car - med. dist.	0.12	0.05 … 0.06	0.02 … 0.04
Car - long dist.	0.34	0.14 … 0.18	0.06 … 0.10
Truck - 7.5 tons	0.15	0.06 … 0.08	0.03 … 0.05
Truck - 18 tons	0.23	0.10 … 0.12	0.04 … 0.07
Truck - 40 tons	0.23	0.10 … 0.12	0.04 … 0.07
City bus	0.20	0.09 … 0.11	0.04 … 0.06
Overland bus	0.50	0.21 … 0.27	0.09 … 0.15
Motorbike	0.41	0.17 … 0.22	0.07 … 0.12
Cargo ship - River	0.06	0.03	0.01 … 0.02
Cargo ship - Ocean	1.2	0.52 … 0.67	0.22 … 0.37
Plane - short dist.	4.5	1.9 … 2.4	0.81 … 1.3
Plane - long dist.	24	10 … 13	4.3 … 7.2
Helicopter	7.5	3.2 … 4.1	1.4 … 2.3

TABLE V
AMORTIZATION TIME OF BATTERY COSTS IN YEARS

Means of Transport	Today	2020	2030
Car - short dist.	32	7.6 … 14	1.6 … 4.2
Car - med. dist.	29	6.9 … 13	1.5 … 3.8
Car - long dist.	53	12 … 22	2.5 … 6.6
Truck - 7.5 tons	20	4.5 … 8.3	0.9 … 2.5
Truck - 18 tons	54	12 … 23	2.3 … 6.5
Truck - 40 tons	61	14 … 26	2.6 … 7.3
City bus	14	3.3 … 6.1	0.7 … 1.8
Overland bus	72	16 … 30	3.1 … 8.6
Motorbike	64	15 …28	3.3 … 8.4
Cargo ship - River	---	---	---
Cargo ship - Ocean	---	---	---
Plane - short dist.	89	12 … 25	1.2 … 3.8
Plane - long dist.	391	51 … 108	5.1 … 17
Helicopter	930	121 … 258	12 … 39

This roadmap is based upon expert interviews, literature research and market analysis. According to this roadmap by the year 2020 the Lithium- Sulphur-Technology and by the year 2030 the Lithium- Air-Technology will be ready to use.

Another battery investigation states that every five years the battery parameters will be improved by about fifty percent [10].

Other sources estimate similar or higher energy densities for future battery technologies [11], [12] and [13].

Starting with the values of LiFePO4 batteries in the year 2010, the values of LiS batteries in 2020 and Li-Air batteries in 2030 are calculated in Table I. In the optimistic scenario, the development is assumed according to the cited studies. In the pessimistic scenario, a slower increase in battery technology is estimated.

C. Energy Costs

The European average level (EU-28) is taken into account [14], [15] and [16] for estimating the energy costs.

The authors analyse two scenarios with different energy price trends. For the fast rising scenario, the trends from the past are extrapolated. Prices are damped due to new energy sources and changing demand in the slow rising scenario.

The projected price corridors for fossil fuels and electric energy are shown in Table III.

III. ANALYSIS OF VEHICLE TYPES

A. Analysis Assumptions

All analyses are based on the values in Table II. Vehicle parameters are taken out of their data sheets. With the weight values m_{veh} and the associated tank capacities, the fuel to vehicle mass ratios are calculated as references for battery to vehicle mass ratios. Distances per year y are assumed according to used vehicle average values and plausible travel ranges per year. The vehicle range d is the maximal necessary distance to be covered without recharging the battery. The efficiencies of the combustion motor η_{fos} are taken out of general technical data books. For the recuperation factors of cars the new European driving cycle is assumed [22] for short-range electric cars. All other values for long distance cars, trucks and city buses are approximated.

B. Mass Ratio Analysis

For investigating the technical feasibility, the battery weight m_{bat} to vehicle weight m_{veh} analysis m_{rel} is calculated:

$$m_{rel} = \frac{m_{bat}}{m_{veh}} \quad (6)$$

Table IV shows the calculated battery to vehicle mass ratios for all analysed vehicles and the projection years. The ranges of values are due to the two different battery development scenarios.

It can be seen that in 2020, the battery weight has acceptable values for river ships, short and medium range cars. The weight is also in principle possible for city buses, trucks, long distance cars and motorbikes.

In 2030, near all vehicles can be battery powered except ocean ships and aircraft.

When only considering the technical side it can be seen that in the medium future, batteries can supply most land vehicles and short distance ships.

C. Economic Analysis

Besides the technical analysis of battery electric vehicles, also the economic aspect is important mainly due to the high battery costs. For simplification it is assumed, that the higher costs of electrical driven means of transport are just caused by the expensive battery pack. Additional costs for maintenance and repair or interest charges are not taken into account.

The costs of a fossil propulsion per year c_{fos} can be calculated with distance per year y, the consumption rate r_{fos} (see also eq. 1) and the tariff of the fossil fuel p_{fos}:

$$c_{fos} = y \cdot r_{fos} \cdot p_{fos} \tag{7}$$

The operating costs of the electrical propulsion per year c_{el} can be determined with the required energy per kilometre E_{el}/d, the distance per year y and the electricity tariff p_{el}. The amount of energy needed has to be corrected with the recuperation factor f_{rec}.

$$c_{el} = \frac{y \cdot E_{el} \cdot p_{el}}{d \cdot f_{rec}} \tag{8}$$

The savings per year s can be determined with the difference of the operation costs of the vehicle with a conventional c_{fos} and the electrical c_{el} propulsion.

$$s = c_{fos} - c_{el} \tag{9}$$

The payback period t_{pb} for the additional battery costs compared to fuel powered vehicles is calculated:

$$t_{pb} = \frac{c_{pb}}{s} \tag{10}$$

In Table V, the amortization times for all means of transport can be seen for different energy price and battery development scenarios. Currently, no electric powered vehicle has an economically interesting amortization time. In 2020, short and medium range cars, short-range trucks and city buses have acceptable amortization times. In 2030, there will be a clear cost benefit for battery powered land vehicles compared to fossil fuels. Even for aircraft, it would be economically interesting to use batteries instead of fossil fuel. Only for ships battery powering will not be profitable.

IV. Conclusion

Estimations for future battery parameters in connection with different electro-mobile applications are given based on several battery development studies. Derived from literature research, the impacts for different means of transport are analyzed. With these calculations it becomes clear which vehicles can be battery powered in the mid-term future from a technical and economic view.

The break-even point for battery powered land vehicles will be between 2020 and 2030. From this time on, they will be cheaper than fossil powered cars, trucks and buses. A large amount of fossil fuel can be saved, because for these vehicles no fuel from biomass is needed. In the mid-term future, it will be impossible to power long distance air planes mainly due to battery weight restrictions. It also will be uneconomically to power ships due to the high battery costs. For these vehicles, there are no real alternatives to chemical fuels and therefore it is necessary to produce fossil or biomass fuel for these.

From this investigation, it can be seen that all land vehicles can be powered with batteries in the mid-term future. It is possible to save large amounts of fossil and biomass fuel and use these for more important applications like powering aeroplanes, ocean ships and chemical applications.

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