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Derivation of Basic Energy Storage Parameters for Future Electric Vehicles

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Abstract- For the engineering of ecologic vehicles the search for adequate energy storage types is currently in the focus. The question for future energy storage technologies is whether they are able to successfully compete against conventional vehicular energy storages like fuel and gas tanks. In the paper a methodology is presented that enables an estimation of required energy storage characteristics for future storage technologies that can be compared to conventional ones. Several showcase calculations are done for a multitude of existing vehicles to get a basis of comparison. As a result necessary energy storage values like energy density and power density are presented and compared to conventional vehicular storage types.

Keywords- Energy storage; energy density; driving cycle; cycle utilization; drive train; fuel consumption; energy consumption; storage characteristics.

1. Introduction

Electromobility and its systems and components are under the top issues of today's and tomorrow's engineers. A special topic is the development of electric vehicles. Novel drive trains with new vehicular components are designed. No component seems to be more under discussion than the energy storage since today's storage technologies allow only a short driving range due to relatively low energy densities.

In both, research and development new ideas, technologies, components and systems have been presented over the last years to improve the energy storage performance for electric vehicles [1]. Lithium ion batteries with different specifications and based on different technologies as lithium iron phosphate seem currently to be a means to an end due to higher energy density. However, electrostatic storage technologies as electric double-layer capacitors are still under discussion especially because of their high power capability [1], [2]. An approach to use the advantages of both technologies, battery and capacitor, is to build a hybrid energy storage system (HESS) consisting of a lithium ion battery and a double-layer capacitor that are linked through a DC converter [3].

No matter what system is chosen the current storage characteristics of all technologies are definitely not competitive compared to a conventional drive train using a gasoline or gas tank. Thus, the aim of this paper is to define a methodology that allows to rate required characteristics of competitive future vehicular energy storages for electric vehicles, to derive the inevitable equations, and calculate some significant exemplary numbers that can be compared to today's conventional drive trains.

2. Methodology

A conventional vehicular fuel or gas tank has an impressive energy density of more than 11000 $^{\mathrm{Wh}}/_{\mathrm{kg}}$. Even though the efficiency of conventional drive trains is not very high (tank-to-wheel utilization under 10 %), conventional drive trains are competitive with more efficient electric drive trains due to the mentioned storage's energy density that leads to an adequate vehicle range. To find out requirements of future electric energy storage characteristics it is essential to compare conventional and alternative drive trains including the respective energy storage. In doing so, efficiencies and cycle utilizations of drive train components are considered and it becomes possible to estimate a specific value of a fuel tank for a particular driving cycle, e.g. the New European Driving Cycle (NEDC). In a second step, it can be derived what characteristic values a future electrical energy storage has to achieve to be competitive.

3. Cycle utilization of conventional drive trains

The chemical power (or chemical energy respectively) of the fuel tank runs through a functional chain within the drive train consisting of the following components that are also shown in Fig. 1:

- Internal combustion engine
- Transmission
- Possible rear-axle differential
- Wheels

The conventional drive trains' cycle utilization ζ_{Conv} is a specific value for how efficient the tank's chemical energy in a particular driving cycle is applied in fact. For its calculation merely three values are necessary:

- Vehicle's total weight m_V in kg
- Vehicle's fuel consumption in a given driving cycle χ_{Cycle} in l
- Velocity-time-characteristics $v_{Cycle}(t)$ of the regarded driving cycle

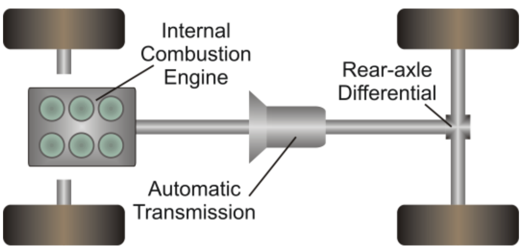

Fig. 1. Typical conventional drive train with components

The cycle utilization ζ_{Conv} is calculated by use of the kinetic energy of a vehicle within a certain driving cycle E_{Cycle} and the chemical energy of the fuel E_{Fuel}, as it is shown in Eq. 1.

$$\zeta_{Conv} = \frac{E_{Cycle}}{E_{Fuel}} = \frac{\frac{1}{2} \cdot m_V \cdot \sum_1^n v_{max,i}^2}{LHV_{Fuel} \cdot \rho_{Fuel} \cdot \chi_{Cycle}} \qquad (1)$$

Eq. 1 additionally contains

- the lower heating value of fuel LHV_{Fuel} (in case of gasoline 41 $^{MJ}/_{kg}$)
- the fuel density ρ_{Fuel} (in case of gasoline 0.72 $^{kg}/_{l}$)

Table 1. Maximum speeds per acceleration phase of New European Driving Cycle (NEDC)

Number *i*	**Speed $v_{max,i}$**
1	15 km/h
2	32 km/h
3	50 km/h
4	15 km/h
5	32 km/h
6	50 km/h
7	15 km/h
8	32 km/h
9	50 km/h
10	15 km/h
11	32 km/h
12	50 km/h
13	70 km/h
14	120 km/h

The value $v_{max,i}$ represents several maximum speed values of a separate acceleration phase within a driving cycle. A single acceleration phase is completed when a deceleration phase (braking) follows. In doing so, the kinetic energy (wheel-road-contact) that a vehicle requires for a particular driving cycle is estimated. For example, the NEDC holds 14 such maximum speed values as it is symbolized by red stars in Fig. 2. The several maximum NEDC speeds are listed in Table I.

Concluding, the sum term of Eq. 1 in the case of NEDC can be simplified according to Eq. 2.

$$\sum_1^n v_{max,i}^2 = \sum_1^{14} v_{max,i}^2 = 2646 \, \frac{m^2}{s^2} \qquad (2)$$

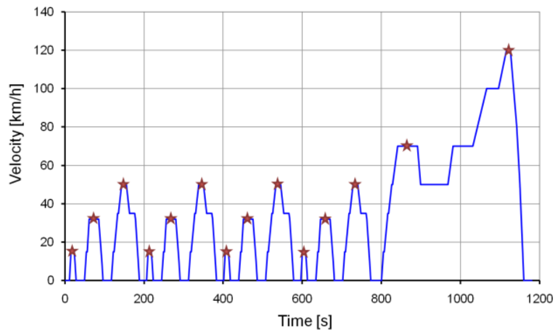

Fig. 2. New European Driving Cycle (NEDC) with maximum speed markers

For the cycle utilization several examples of current series-production vehicles in NEDC have been researched. The results are shown in Table II.

Table 2. NEDC cycle utilization for exemplary vehicles [4] – [10]

Vehicle type	m_V	χ_{NEDC}	ζ_{Conv}
Audi A4 2.0 (155 kW)	1570 kg	0.726 l	9.7 %
BMW 116i	1350 kg	0.671 l	9.0 %
BMW 325i	1505 kg	0.792 l	8.5 %
BMW 550i	1735 kg	1.199 l	6.5 %
BMW 760i	2105 kg	1.419 l	6.6 %
BMW X6 xDrive35i	2145 kg	1.221 l	7.9 %
Citroen C3 (54 kW)	1105 kg	0.660 l	7.5 %
Opel Astra 1.4 (103 kW)	1378 kg	0.649 l	9.5 %
Peugeot 207 (54 kW)	1229 kg	0.693 l	7.9 %
Renault Clio (55 kW)	1055 kg	0.638 l	7.4 %
Renault Mégane (81 kW)	1290 kg	0.781 l	7.4 %
Renault Laguna (103 kW)	1394 kg	0.836 l	7.5 %
VW Golf VI (59 kW)	1217 kg	0.704 l	7.7 %

From these results follows that values for ζ_{Conv} usually amount between 6 % and 10 % (average value = 7.9 %).

4. Corresponding fuel energy density at the wheels

Gasoline has a lower heating value of LHV_{Fuel} = 41 $^{MJ}/_{kg}$. That corresponds with a translated energy density of w_{Fuel} = 11400 $^{Wh}/_{kg}$. As it was mentioned above, in a conventional drive train only a fraction of the tank's chemical energy can be used for the mechanical propulsion. If the cycle utilization ζ_{Conv} is included a corresponding energy density of fuel w^*_{Fuel} will arise, as it is mentioned in Eq. 3.

$$w^*_{Fuel} = w_{Fuel} \cdot \zeta_{Conv} \tag{3}$$

With a mean cycle utilization of ζ_{Conv} = 7.9 % the corresponding energy density of gasoline can be estimated to w^*_{Fuel} = 901 $^{Wh}/_{kg}$. Altogether, this value ranges between 684 $^{Wh}/_{kg}$ and 1140 $^{Wh}/_{kg}$.

5. Cycle utilization of electric drive trains

Also for novel electrical drive trains a cycle utilization ζ_{Elec} can be calculated. The procedure contains appraisals of the included drive train components since only a few reference vehicles exist.

In a pure electric drive train the following components (with average cycle utilization in brackets) are involved as Fig. 3 shows:

- Electrical energy storage (90 %)
- Power electronics / inverter (90 %)
- Electrical machine (75 %)
- Transmission (94 %)
- Wheels (90 %)

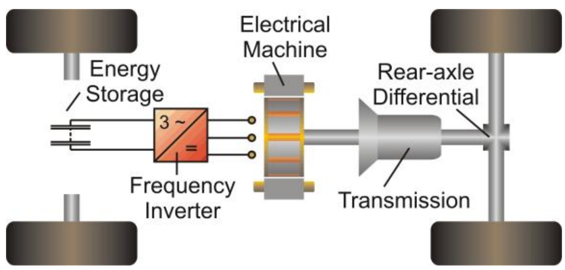

Fig. 3. Typical electrical drive train and components of an electric vehicle

From storage to wheel a total average cycle utilization of the drive train of about ζ_{Elec} = 51 % results. This value is plausibility checked consulting datasheet results of existing electric vehicles.

The vehicle Mini E of BMW has a curb weight of m_V = 1465 kg [11]. From this and using Eq. 1 and 2 a mechanical energy at the wheels during

NEDC of E_{Cycle} = 1938 kJ follows. Furthermore, a range of 240 km (200 – 250 km) is mentioned in the datasheet [11]. The storage's utilizable energy content is about 28 kWh [11]. Consequently, the electric energy consumption χ_{Elec} can be calculated by Eq. 4.

$$\chi_{Elec} = \frac{28\ \text{kWh}}{240\ \text{km}} = 117\ \frac{\text{Wh}}{\text{km}} \tag{4}$$

The electric energy consumption result χ_{Elec} = 117 $^{Wh}/_{km}$ from Eq. 4 may vary between 112 and 140 $^{Wh}/_{km}$. Related to the 11 km long NEDC the electrical energy effort E_{Elec} in Eq. 5 arises for the Mini E.

$$E_{Elec} = 117\ \frac{\text{Wh}}{\text{km}} \cdot 11\ \text{km} = 4633\ \text{kJ} \tag{5}$$

The electrical energy effort E_{Elec} = 4633 kJ from Eq. 5 may vary between 4435 and 5544 kJ.

Finally, the cycle utilization ζ_{Elec} is estimated by dint of the mechanical energy of the driving cycle E_{Cycle} and the electrical energy effort E_{Elec}, as Eq. 6 shows.

$$\zeta_{Elec} = \frac{E_{Cycle}}{E_{Elec}} \tag{6}$$

For the Mini E a cycle utilization of ζ_{Elec} = 42 % results. This value that may vary between 35 % and 44 % shows on the one hand that the utilization of electrical drive trains is much higher than the one of conventional drive trains (see Table II). On the other hand the utilization of the Mini E is relatively low compared to the above supposed value of 51 %. However, it is assumed that the drive trains of novel electrical vehicles are not yet well-engineered and operated. There is still high optimization potential regarding energy efficiency of electrical drive trains. According to that, plausibility of the calculated value of 51 % is given.

6. Derived required energy density of electrical energy storages

With the help of the in Eq. 3 derived corresponding energy density of gasoline w^*_{Fuel} and the cycle utilization of electrical drive trains ζ_{Elec} the required energy density of electrical energy storages (EES) w_{EES} for future electrical vehicles can be estimated using the quotia of both drive train utilizations, as Eq. 7 shows.

$$w_{EES} = w_{Fuel} \cdot \frac{\zeta_{Conv}}{\zeta_{Elec}} = \frac{w^*_{Fuel}}{\zeta_{Elec}} \tag{7}$$

As derived in chapter 4 by use of the researched empirical values from Table II values for w^*_{Fuel} may vary between 684 $^{Wh}/_{kg}$ and 1140 $^{Wh}/_{kg}$.

As derived in chapter 5 values for ζ_{Elec} may vary between 35 % and 44 %.

From this Eq. 8 follows for the scope of the required utilizable energy density w_{EES} of future energy storages to be comparable to conventional drive trains.

$$1555\ \frac{\text{Wh}}{\text{kg}} < w_{EES} < 3257\ \frac{\text{Wh}}{\text{kg}} \tag{8}$$

With the above calculated average values (w^*_{Fuel} = 901 $^{Wh}/_{kg}$; ζ_{Elec} = 42 %) an energy density of about w_{EES} = 2145 $^{Wh}/_{kg}$ arises.

Reaching this specific value the electrical energy storage in an electric drive train was approximately comparable to a fuel tank in a conventional drive train as it is shown in Fig. 4.

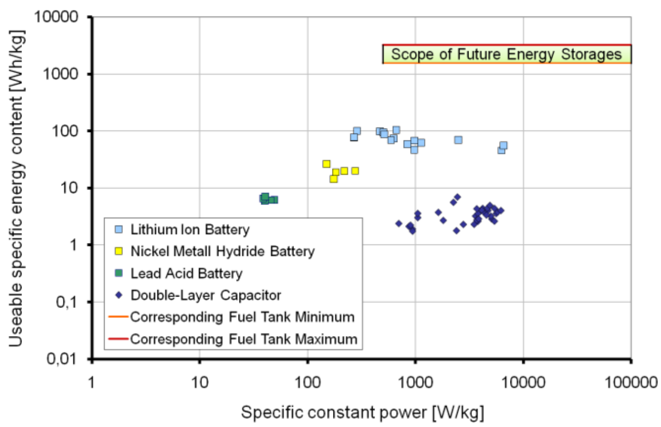

Fig. 4. Ragone plot of today's existing storage technologies and scope for future storages

Consequently, for current storage technologies the following factors result for a required energy density improvement compared to typical today's values:

- Electric double-layer capacitor (350)
- Nickel metal hydride battery (100)
- Power optimized lithium ion battery (40)
- Energy optimized lithium ion battery (20)

7. Conclusion

In the presented paper a methodology for the calculation of future electrical energy storage requirements was introduced. As a result, specific values of current electrical energy storages and drive trains are compared to its conventional counterparts.

Apart from the calculation methodology the paper's main result is the in Eq. 8 and Fig. 4 rated scope of a required utilizable energy density w_{EES} of future energy storages. With a utilizable energy density of about w_{EES} = 2145 $^{Wh}/_{kg}$ a future electrical energy storage (in conjunction with an electrical drive train) would be comparable to today's conventional gasoline tanks (in conjunction with a conventional drive train).

Today's electrical energy storages seem to be far from such a value in the context of energy density. Nonetheless, the energy density improvement over the last years is noticeable and the development of novel energy storage technologies and the optimization of existing energy storage types become more and more important. Today's lithium ion batteries are a factor of 20 away from the abovementioned required energy density value. The step from NiMH batteries to lithium ion batteries with utilizable energy densities of 15 $^{Wh}/_{kg}$ and 110 $^{Wh}/_{kg}$ respectively makes a factor of about 7. This shows that adequate electrical energy storages with competitive characteristics may be not as far away as they seem to be.

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