Applicability of energy storage units to electric transport

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Abstract. The paper analyzes the possibility for replacement hydrocarbon fuels by energy storage devices in transport. The technical characteristics of the modern batteries and ultracapacitors are presented, their specific parameters are estimated. Energy and power requirements for various driving styles of the vehicles are estimated. The determination of requirements for energy storage devices and the evaluation of applicability of energy storage units are demonstrated in the article.

1 Introduction

The generation and consumption of energy can be divided in time by energy storage device. The electrical energy, to date, does not accumulate in large quantities. The use of energy storage devices will make it possible to equalize the load schedule of power plants, i.e. focus them on the average consumption, and make the process of electricity generation more efficient and profitable [1–7].

At present, the development of higher energy density devices includes the participation of vehicle manufacturers. The idea of replacing hydrocarbon fuel with electric energy has been existing for a long time. It is assumed that the embodiment of this idea will not only make the city's air purer, but also will increase the efficiency of using energy resources for the transport movement [8–17].

The information concerning modern energy storage devices as well as the conducted analysis of their specific energy and power parameters allows us to determine the level of the technology development [33-37]. Due to the increasing interest towards electric vehicles, the possibility of using energy storage devices in transport is discussed [38-41].

2 Methodology

To assess the applicability of energy storage units to electric transport, the data were collected on the technical characteristics of two types of storage devices: a lithium-ion battery and an ultracapacitors (or an electrochemical capacitor). Lithium-ion batteries offer a larger value

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for EMF and specific capacity than other. Therefore, this type of battery, at present, is widely used. Ultracapacitors are considered as devices capable to combine the positive characteristics of accumulators and capacitors. The data of currently produced energy storage devices are presented in Table 1.

Table 1. Battery products. The manufacturers' data.

№	Company	Product	Nominal Capacity, A*h	Nominal Voltage, V	Max Discharge Current, A	Nominal Discharge Current, A	Max Charge Current, A	Nominal Charge Current, A	Cycle Life (to 80% initial capacity), $*10^3$	Weight, kg
1	Altair Nano	LTO battery cell	66.8	2.2	500	2C	500	2C	25^3	1.81
2	Samsung SDI	NCM 111 battery cell	94	3.68	94	0.3C	47	0.3C	3.2	2.06
3	BYD	B-Plus 2.5(LFP)	50	51.2		0.5C		0.5C	6	38
4	LG chem	RESU6.5 NMC	126	51.8	81					52
5	Victron energy	LFP-Smart 12,8/300	300	12.8	2C	1C	2.5C	0.5C	5	51
6	BJEV	LFP-80	80					1C		
7	BJEV	NCM 42	42					1.2C		
8	CATL	LFP 120	120	3.2	2C	1C	1C	1C		2.8
9	CATL	LFP 50	50	3.2	3C		5.2C		1.5	
10	CATL	LFP92	92	3.2	1.5C		3.2C			
11	CATL		86	19	1C					15
12	CATL		86	28	1C					22
13	CATL	NCM 37	37	3.65	3C		1C			
14	CATL	NCM 72	72	3.65	2C		1.5C			
15	CATL	NCM 43	43	3.66	4C		4C			
16	CATL	LFP 120	120	3.2	2C	1C	1C	1C		2.8
17	A123 Systems	22S3P NMC	78	80.3		465		150		42.4
18	Liotech	LT-LFP 270	270	3.2	3C	0.2C	2C	0.2C	3	9.5
19	Liotech	LT–LFP 770P	770	3.2	3C	0.5C	3C	0.5C	3	26.5
20	Tesla	Powerwall								125

Table 1. Battery products. The manufacturers' data. (cont.)

№	Price, €.	Energy, W*h	Specific Energy, W*h/kg	Energy Density, W*h/L	Power, W	Specific Power, W/kg (discharge/charge)	Power Density, W/L (discharge/charge)	Dimensions (WxDxH), mm
1		148[1]	51.8[1]	174[1]	2330 /4580	1290 /2350[2]	2740 /5390[2]	256x12.6x263
2		350			1102[4]			173x45x125
3	1265	2450			2500			483x490x130
4	3675	6500			4200			452x120x654
5	3830	3840						265x425x347
6			127	297				
7			180	415				
8								180x180x50
9			240					
10								
11		1650						343x176x178
12		2470						460x177x176
13								
14								
15			180	415				
16								180x180x50
17		6350						592x165x242
18	370							160x106x337
19	740		93	154,2				289x163x337
20		13500			5000			755x155x1150

Compiled from [12, 13, 18 – 27].
[1]70A discharge, 25^0C. Testing done using a rated capacity of 70 A*h.
[2]10 sec pulse, 50% SOC (State of Charge), 25^0C
[3]cycle life at 2C charge and 2C discharge, 100% DOD (Depth of Discharge), 25^0C
[4]30 sec pulse, 90% SOC (State of Charge), 25^0C

As it can be seen from the Table 1, manufacturers present different technical characteristics. For this reason, the calculation of the specific parameters of storage devices was carried out.

Based on Table 1.

Stored energy in a battery is defined as:

$$W_{bat} = q * U \tag{1}$$

Where q is the nominal capacity (A*h) and U (V) is the voltage of battery.

Equations (2, 3) present the specific energy and energy density.

$$w_{m\_bat} = \frac{W_{bat}}{m_{bat}} \tag{2}$$

$$w_{v\_bat} = \frac{W_{bat}}{V_{bat}} \tag{3}$$

The power of battery is defined as:

$$P_{bat} = U * I_{max} \quad (4)$$

Where Imax (A) is the maximum (or standard) battery discharge current.

Equations (5, 6) present the specific power and power density.

$$p_{m\_bat} = \frac{P_{\text{bat}}}{m_{bat}} \quad (5)$$

$$p_{v\_bat} = \frac{P_{bat}}{V_{bat}} \quad (6)$$

Where m_{bat} (kg) is weight, V_{bat} (L) is volume of battery.

Table 2. Battery products. Specific parameters.

№	Company	Energy, W*h	Specific Energy, W*h/kg	Energy Density, W*h/L	Power, W	Specific Power, W/kg	Power Density, W/L
1	Altair Nano	146.96	81.19	173.23	1100.00	607.73	1296.66
2	Samsung SDI	345.92	167.92	355.47	345.92	167.92	355.47
3	BYD	2560.00	67.37	83.21	1280.00	33.68	41.60
4	LG chem	6526.80	125.52	183.99	4200.00	80.77	118.40
5	Victron energy	3840.00	75.29	98.26	7680.00	150.59	196.52
6	BJEV						
7	BJEV						
8	CATL	384.00	137.14	237.04	768.00	274.29	474.07
9	CATL	160.00			480.00		
10	CATL	294.40			441.60		
11	CATL	1634.00	108.93	152.06	1634.00	108.93	152.06
12	CATL	2408.00	109.45	168.04	2408.00	109.45	168.04
13	CATL	135.05			405.15		
14	CATL	262.80			525.60		
15	CATL	157.38			629.52		
16	CATL	384.00	137.14	237.04	768.00	274.29	474.07
17	A123 Systems	6263.40	147.72	264.97	37339.50	880.65	1579.60
18	Liotech	864.00	90.95	151.17	2592.00	272.84	453.50
19	Liotech	2464.00	92.98	155.21	7392.00	278.94	465.64
20	Tesla	13500.00	108.00	100.31	5000.00	40.00	37.15

It should be noted that the data of battery modules and cells are presented in tables (1, 2, 3). Several modules include, in addition to cells, a cooling system, a monitoring and control system. Therefore, dividing by the total volume and mass of the accumulator, specific parameters were diminished. However, obtained distribution demonstrates, in general, the level of the energy parameters, due to the consideration of a large number of models from different manufacturers.

The characteristics of ultracapacitors are presented in Table 3.

Table 3. Ultracapacitors. Manufacturers' data.

No	Company	Product	Nominal Capacitance, F	Nominal Voltage, V	Maximum Continuous Current, A	Standard Continuous Current, A	Cycle Life, *10^3	Dimensions (WxDxH), mm	Weight, kg
1	Maxwell	K2 2.7V Series	3000	2.7	210	130	1000	π60.4x138	0.51
2	Maxwell	K2 2.85V	3400	2.85	211	131	1000	π60.4x138	0.52
3	Maxwell	K2 3.0V	3000	3	210	130	1000	π60.4x138	0.52
4	NESSCAP	3.0V	3400	3	225	140	1000	π60.3x138	0.5
5	EATON	XL60	3000	2.7		143		π60.3x138	0.52
6	SKELCAP	SCHE 3500	3500	2.85			1000	127x47x47	0.391

Compiled from [28 – 31].

The result of calculating the specific parameters is presented in the Table 4.

Table 4. Ultracapacitors products. Specific parameters.

No	Company	Product	Energy, W*h	Specific Energy, W*h/kg	Energy Density, W*h/L	Power, W	Specific Power, W/kg	Power Density, W/L
1	Maxwell	K2 2.7V Series	1.46	2.86	3.69	524.88	1029.18	1327.45
2	Maxwell	K2 2.85V	1.84	3.54	4.66	662.80	1274.61	1676.24
3	Maxwell	K2 3.0V	1.80	3.46	4.55	648.00	1246.15	1638.82
4	NESSCAP	3.0V	1.72	3.44	4.36	619.16	1238.33	1571.09
5	EATON	XL60	1.60	3.07	4.05	574.99	1105.75	1459.01
6	SKELCAP	SCHE 3500	1.43	3.65	5.09	514.19	1315.06	1832.83

Based on Table 3.
Stored energy in an ultracapacitor is defined as:

$$W_{cap} = \frac{C\left({U_1}^2 - {U_2}^2\right)}{2*3600} = \frac{C((0.8E)^2 - (0.4E)^2)}{2*3600} \quad (7)$$

Equations (8, 9) present the specific energy and energy density.

$$w_{m\_cap} = \frac{W_{cap}}{m_{cap}} \quad (8)$$

$$w_{v\_cap} = \frac{W_{cap}}{V_{cap}} \quad (9)$$

Released power in 10 sec is defined as.:

$$P_{cap} = \frac{W_{cap}*3600}{10} \quad (10)$$

Equations (11, 12) present the specific power and power density.

$$p_{m\_cap} = \frac{P_{cap}}{m_{cap}} \quad (11)$$

$$p_{v\_cap} = \frac{P_{cap}}{V_{cap}} \quad (12)$$

Where m_{cap} (kg) is weight, V_{cap} (L) is volume of ultracapacitor.

After determination of the specific parameters of energy storage devices, it is necessary to estimate energy and power parameters of vehicles. The Table 5 shows the main characteristics of cars with an internal combustion engine (ICE).

Table 5. Characteristics of cars with ICE

No	Car with ICE	Max. power	Fuel tank		ICE with gearbox		By 0-100 km/h time	Acceleration	Gross vehicle mass	Rolling resistance
			Volume	Weight with fuel	Weight [1]	Volume [1]				
		kW	L	kg	kg	L	s	m/s^2	kg	N
1	Mazda6	110	60	45	150	30	10.50	2.65	1980	291.06
2	BMW 3	100	60	45	150	30	8.90	3.12	1975	290.33
3	Renault LOGAN	75	50	37.5	150	30	11.70	2.37	1600	235.20
4	KIA RIO	73.3	50	37.5	150	30	12.20	2.28	1560	229.32
5	Volkswagen POLO	66	55	41.25	150	30	11.20	2.48	1700	249.90
6	LADA Vesta	78	55	41.25	150	30	11.20	2.48	1670	245.49
7	Toyota Camry	110	60	45	150	30	11.00	2.53	2100	308.70
8	Audi A3	110	50	37.5	150	30	8.20	3.39	1785	262.40

Based on [32].

[1]The weight ($m_{ICE+gearbox}$) and the volume ($V_{ICE+gearbox}$) of ICE with gearbox are assumed equal identical due to the lack of information.

The fuel tank weight with fuel is defined as:

$$m_{tank} = V_{tank} * \rho_{gas} \quad (13)$$

Where V_{tank} (L) is the volume of the tank, ρ_{gas} =0.75 kg/L is the density of petrol.

The acceleration can be written as:

$$a = \frac{v_{auto100}}{T_{100}} \quad (14)$$

Where v_{auto}=100 km/h is the vehicle speed, where T_{100} is the acceleration time from 0 to 100 km/h.

The rolling resistance of a car is defined as:

$$F_R = f * m_{auto} * g \quad (15)$$

Where f=0,015 is rolling resistance coefficient tires on the asphalt, m_{auto} is weight of car, g =9,8 m/s^2 is gravitational acceleration.

Calculation results of the energy and power, which required at the wheels to drive with constant speed of 60 km/h for 3 h, are presented in the Table 6.

Table 6. Energy and power parameters of cars with ICE.

№	Car with ICE	Moving at a constant speed of 60 km / h for 3 h			Acceleration to 60 km / h			
		Work / energy expended		Power	Work / energy expended		Time	Power
		kJ	kW*h	kW	kJ	kW*h	s	kW
1	Mazda6	52390.8	14.55	4.851	275.00	0.076	6.3	43.65
2	BMW 3	52258.5	14.52	4.839	274.31	0.076	5.3	51.37
3	Renault LOGAN	42336.0	11.76	3.920	222.22	0.062	7.0	31.66
4	KIA RIO	41277.6	11.47	3.822	216.67	0.060	7.3	29.60
5	Volkswagen POLO	44982.0	12.50	4.165	236.11	0.066	6.7	35.14
6	LADA Vesta	44188.2	12.27	4.092	231.94	0.064	6.7	34.52
7	Toyota Camry	55566.0	15.44	5.15	291.67	0.081	6.6	44.19
8	Audi A3	47231.1	13.12	4.37	247.92	0.069	4.9	50.39

Based on Table 5.

The work done for uniform motion is defined as:

$$A_{unif} = F_R * S = F_R * v_{auto} * T_{trip} \quad (16)$$

Where F_R (N) is the rolling resistance, S is the way, v_{auto} (km/h) is the constant speed of the car, and T_{trip} (h) is the duration of the trip.

The power for uniform motion can be written as:

$$P_{unif} = \frac{A_{unif}}{T_{trip}} \tag{17}$$

The work done for acceleration can be described using the following equation:

$$A_{acc} = \frac{m_{auto} * v_{auto}{}^2}{2} \tag{18}$$

The acceleration time from 0 km / h to constant speed is defined as:

$$T_{acc} = \frac{v_{auto}}{a} \tag{19}$$

The power for acceleration is defined as:

$$P_{acc} = \frac{A_{acc}}{T_{acc}} \tag{20}$$

Assuming the replacement of the fuel tank, ICE with the gearbox by the energy storage device, i.e. replacement by a similar mass and filling the volume occupied by these elements, the energy storage requirements are determined. The results of this approximate calculation are given in the Table 7.

Table 7. Requirements for energy storage device

№	Car with ICE	Energy	Specific Energy	Energy density	Power	Specific power	Power density
		kW*h	W*h/kg	W*h/L	kW	W/kg	W/L
1	Mazda6	28.30	145.14	314.48	43.65	223.85	485.01
2	BMW 3	28.23	144.78	313.68	51.37	263.43	570.76
3	Renault LOGAN	22.87	121.98	285.89	31.66	168.83	395.69
4	KIA RIO	22.30	118.93	278.74	29.60	157.86	369.99
5	Volkswagen POLO	24.30	127.06	285.89	35.14	183.72	413.36
6	LADA Vesta	23.87	124.82	280.84	34.52	180.47	406.07
7	Toyota Camry	30.02	153.94	333.54	44.19	226.63	491.02
8	Audi A3	25.52	136.08	318.94	50.39	268.74	629.87

Based on Tables 5 and 6.

The energy accumulated in the energy storage system is defined as:

$$W_{ESS} = A_{unif} + N * S * A_{acc} \tag{21}$$

Where N=1 (1/km) is the number of accelerations.

The power of energy storage system can be written as:

$$P_{ESS} = P_{acc} \tag{22}$$

Equations (23, 24) present the specific energy and specific power:

$$w_{m\_ESS} = \frac{W_{ESS}}{m_{tank} + m_{ICE+gearbox}} \tag{23}$$

$$p_{m\_ESS} = \frac{P_{ESS}}{m_{tank} + m_{ICE+gearbox}} \tag{24}$$

Equations (25, 26) present the energy density and power density:

$$w_{v\_ESS} = \frac{W_{ESS}}{V_{tank} + V_{ICE+gearbox}} \quad (25)$$

$$p_{v\_ESS} = \frac{P_{ESS}}{V_{tank} + V_{ICE+gearbox}} \quad (26)$$

3 Results and discussion

For the analysis of the obtained data, Figures 1 and 2 are presented. They show the distribution of the characteristics of storage devices and the calculated requirements for the energy storage devices. By 'requirements' it is meant providing the same energy and power parameters of car by energy storage device like in case of use gasoline as an energy source.

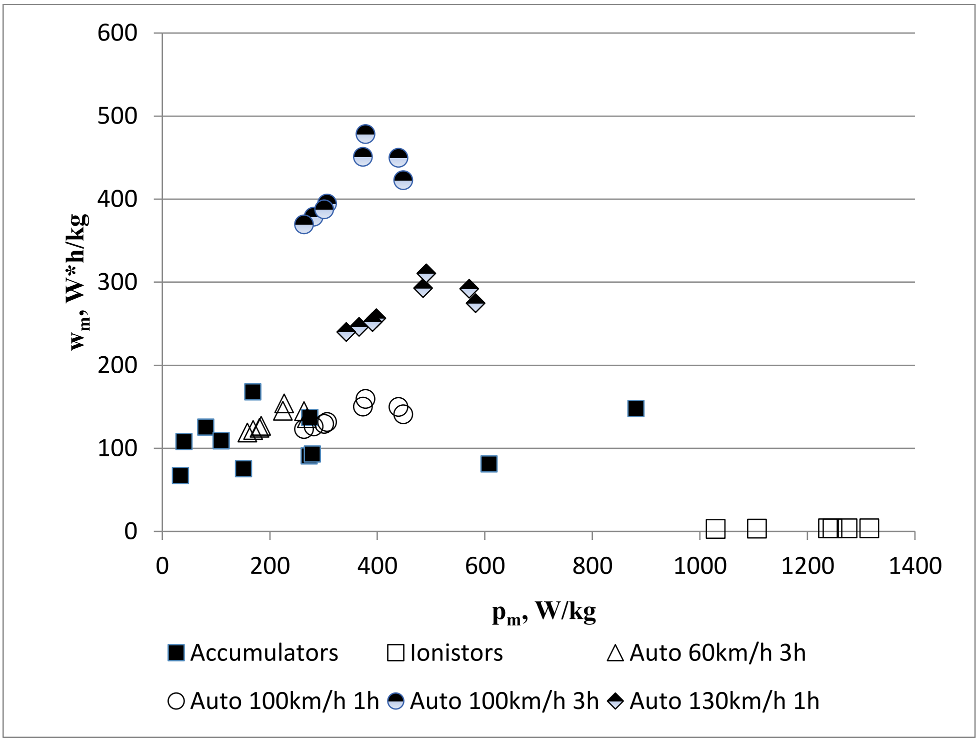

Fig. 1. Energy storage system and cars. Specific energy - specific power.

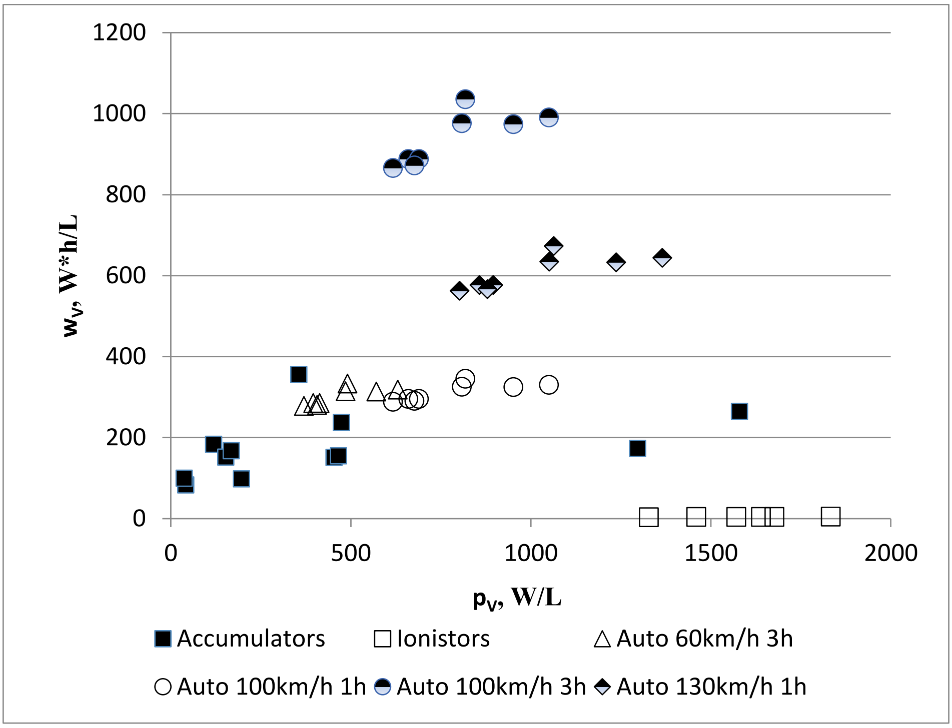

Fig. 2. Energy storage system and cars. Density of energy - power density.

Comparing the requirements for energy storage system for different driving style (Auto 60 km/h for 3h, Auto 100 km/h for 1h, etc.) with the specific parameters of the batteries and ultracapacitors, an assessment of the use of energy storage units in electric transport is made. So, according to the Figure 1, the considered installation of a battery of some companies will not increase the mass of the vehicle and will meet the energy and power needs when driving at a maximum speed of 60 km/h (Auto 60 km/h 3h) for most vehicles. The Figure 2 demonstrates that the battery will require an additional volume for this purpose. This volume can be obtained by creating an efficient design and structure of the entire battery pack, taking into account the design of the electric vehicle.

The demand for high power, arising during the process of motion, can be satisfied by an ultracapacitor. For this reason, its combined use with the battery has advantages.

Both figures show that, in comparison with the traditional ICE system, the electric storage system is inferior at long range of travel and at a higher speed.

4 Conclusion

Undoubtedly, electric transport is one of the most promising means of transportation and it can be considered as an alternative to traditional transport with an internal combustion engine. The study carried out in this paper demonstrated that modern energy storage units, installed in an electric vehicle, make it competitive for short trips. This kind of trips take place in urban conditions.

As conclusions it is necessary to allocate:

1. There is the possibility of application energy storage units for urban transport, both public and private.

2. It is possible to improve vehicles used in warehouses and industrial premises, as well as in agriculture, requiring a minimum amount of gas emissions.

The main reason that prevents the mass implementation of electric vehicles is their high cost. However, there is a downward trend in the cost of the energy storage device and upward trend in the specific energy [12].

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