Energy efficiency and equivalent CO_2 emissions of a light-duty electric vehicle depending on driving distance

M Noga[1] and Z Juda[1]

[1]Institute of Automobiles and Internal Combustion Engines, Cracow University of Technology, 37 Jana Pawla II Avenue, 31-864 Krakow, Poland

email: noga@pk.edu.pl

Abstract. The article presents the results of research regarding energy efficiency on the electric energy conversion chain: electric socket - charging device - electric vehicle machine depending on the amount of energy taken from the battery, which in a simple relation results from the distance travelled by the vehicle. The tests were conducted on a Melex-type light-duty vehicle. Measurements were made for five test routes with lengths from the range of 5.4 km – up to 43.4 km. The obtained results allowed to indicate the optimal distance between successive charging processes due to the obtained efficiency of energy conversion in the analysed chain. The specific energy consumption of the vehicle in terms of batteries-to-wheel (tank-to-wheel) and electric socket-to-wheel was estimated. Moreover, the results of estimation of the equivalent CO_2 emission resulting from the use of an electric vehicle which batteries are loaded from the power grid for several example European countries with a significant differentiation of electricity production methods are presented.

1. Introduction

Continuous development of automotive transportation with dwindling resources of traditional fossil fuels and problems resulting from environmental pollution by cars forces a gradual departure from the vehicle's drive using a classical internal combustion engine. Some experts estimate that in 2030 the share of vehicles with an internal combustion engine will still amount to 75% in the total number of new sold vehicles in the world [1], but to a large extent they will be optimized for cooperation with electric machines in hybrid propulsion systems. The latter appear as an effective and reasonable solution for the transition period to the prevalence of battery electric vehicles [2]. The internal combustion engine, understood as the only source of the vehicle's drive, is slowly becoming a thing of the past [3]. Various attempts are made to improve the efficiency of the internal combustion engine as a vehicle drive. It should be mentioned here the frequent use of innovative fuel supply systems [4], alternative fuels [5], [6], innovative exhaust gas cleaning systems [7], [8], as well as introducing unconventional engine designs [9]. These activities allow for the prolongation of the presence of internal combustion engines in motor vehicles[10], but it is practically certain that in the perspective of the next few decades, vehicles traveling on the roads, especially in Europe, North America or Japan, will be equipped with purely electric drive. So far, the main problems facing the development of electromobility are, first and foremost, the very limited capacity to accumulate energy by today available batteries and the high price of such batteries. A slightly less exposed issue is the limited possibilities of electricity production and distribution in some countries. In areas where electricity is produced mainly in coal-fired power plants, or for example oil shale, there is still the problem of relatively high CO_2 emissions associated with the use of electric vehicles. It often exceeds the results obtained by the latest constructions with a hybrid drive system.

On the other hand, electric vehicles have dominated the sector of small commercial vehicles used in in-plant transport of goods and people for several decades, as golf carts, or recently to transport tourists in the centres of historical cities. In above applications, the range of such a vehicle limited to tens kilometers is not a major problem, while the undisputable advantages of electric vehicle drive, such as zero exhaust emission at the place of use or low noise emission, come to the fore [11]. Among the vehicles belonging to this group, there are still a lot of construction based on lead-acid batteries and DC brush motors, however, solutions known from modern electric cars are also being implemented, i.e. advanced li-ion batteries as well as asynchronous or permanent magnet motors with electronic commutation [12].

2. Aim and scope of the work

The works constituting the subject of this study were a continuation of the research started in the Mechatronics Department in 2016 [13]. The main part of research activities was to determine the efficiency of energy conversion in a light utility vehicle with electric drive with lead-acid batteries charged from the 230V AC electric socket, depending on the distance covered by the vehicle. While maintaining the same driving style and the same test route, it translates into practically directly proportional to the amount of electric energy taken from the batteries.

3. Tested vehicle

As a research object a light commercial vehicle Melex 945DS of Polish production with seats for the driver and passenger and the possibility of carrying a load of 150 kg was used. A general view of the test vehicle is shown in Figure 1.

Figure 1. Tested vehicle Melex 945 DS.

The vehicle is powered by a separately excited DC motor with electronic control. The nominal voltage of the battery is 48V. They are deep-cycle acid-lead batteries with increased tolerance to deep discharge. The basic technical data of the tested vehicle is presented in Table 1 [14].

Table 1. Technical data of the tested vehicle

Parameter	Value	Parameter	Value
Length x width; wheelbase	2660 x 1230; 1660 mm	Motor symbol	DV3-4006AA
Gross vehicle weight (with driver)	about 700 kg	Rated armature current	100 A
Vehicle capacity	2 people + 150 kg load	Rated power	3.9 kW at 4300 rpm
Battery type	Trojan T-125 (6V)	Rated torque	8.2 Nm
Nominal voltage	48 V (8x6V)	Maximum motor efficiency	75%
Battery capacity (10h)	221 Ah	Total gear ratio	16
Stored energy	10.61 kWh	Tire size	145/80 B10
Battery weight	240 kg	Maximum speed	~30 kph
Motor type	DC, separately excited	Vehicle range	~60 km

To charge the batteries after finishing the ride, a charging device STC 48/30 powered from 230V single-phase AC grid was used.

4. Methods of research

The efficiency of the energy conversion chain from the AC electric socket, through the charging device, the battery of lead-acid accumulators and, finally, the motor of light commercial vehicle Melex was analysed. A test route was set up, mostly located in Krakow-Czyżyny at the Campus of Faculty of Mechanical Engineering of Cracow University of Technology. The research was conducted to assess the impact of the route length (the amount of energy taken from the batteries) on the efficiency of the battery and charging device. A total of five test drives with lengths between 5.4 and 43.5 km were completed. Subsequent test drives included multiple journeys of the same section of the road in the form of loops with a distance of approximately 2.7 km. The surface of the test route is made of asphalt for the most part. The terrain where the route is located is practically flat. In order to make the obtained results independent from the style of driving, the vehicle was always run by the same driver who kept the same average speed for each of the trips. A summary of the conditions of individual journeys is presented in Table 2.

Table 2. Conditions of the testing drives.

Numbers of loops	2	4	8	12	16
Driving distance [km]	5.41	10.81	21.55	32.60	43.51
Ambient temperature [°C]	22	18.5	20	21	21
Total time (with stops) [h:min:sec]	0:19:20	0:40:25	1:17:26	2:03:48	2:41:03
Average speed [km/h]	16.24	16.05	16.70	15.80	16.21
Average speed without stops [km/h]	16.79	16.85	16.85	16.90	16.76
Time of battery charging [h:min:sec]	1:53:04	2:54:37	4:16:40	6:19:57	8:02:33

Each trip was preceded by bringing the batteries to full charge on the previous day, while after finishing the ride the batteries were loaded to a fully charged state with registration of the parameters of this process. The schematic diagram of the measurement path used in the tests procedure is presented in Figure 2.

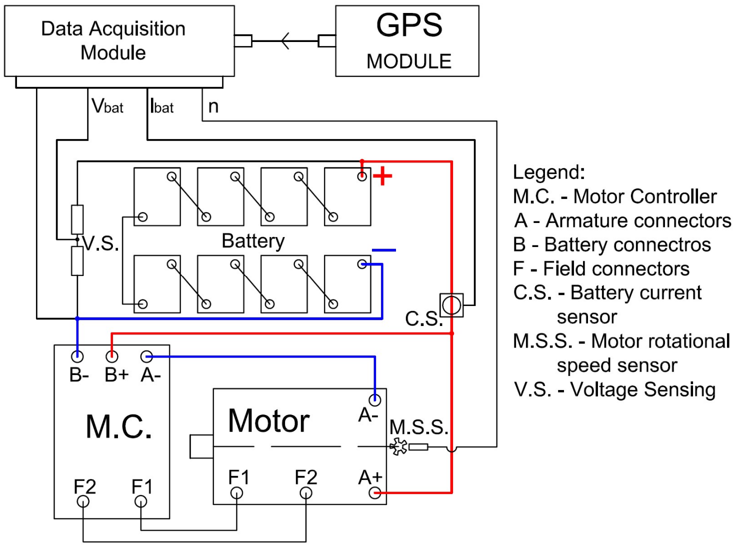

Figure 2. Scheme of data acquisition system.

The basic element of the measurement path was a Performance Box positioning device using a GPS signal with a frequency of 10 Hz. The device is additionally equipped with a data acquisition module with 4 analogue channels and one frequency signal. Signals from the GPS device (including vehicle speed and position) and from the data acquisition module were saved to files on the SD card. During the tests, the vehicle motor rotational speed signal was generated using the Hall sensor (5 impulses per turn). The data acquisition module has a measuring range of 0-14.5V, so the V_{bat} battery voltage was measured using a voltage divider of 5.9567 division ratio. The I_{bat} battery current measurement was carried out using a contactless Hall sensor LEM HAIS 150-P with an analogue voltage output with and sensitivity of 0.625V / 150A declared by the manufacturer. This sensor was used to test vehicle motion. A current sensor type WCS 1800 with a sensitivity of 65.5 mV/A determined during calibration was used to test the battery charging process. The amount of electric energy taken from the AC electric socket E_{chrg} by the charger was recorded using the Voltcraft Energy Logger 4000F electronic counter.

5. Research results and analysis

Figure 3 presents examples of speed courses and power P_{bat} taken from / delivered to batteries while driving the first test route (2x loop).

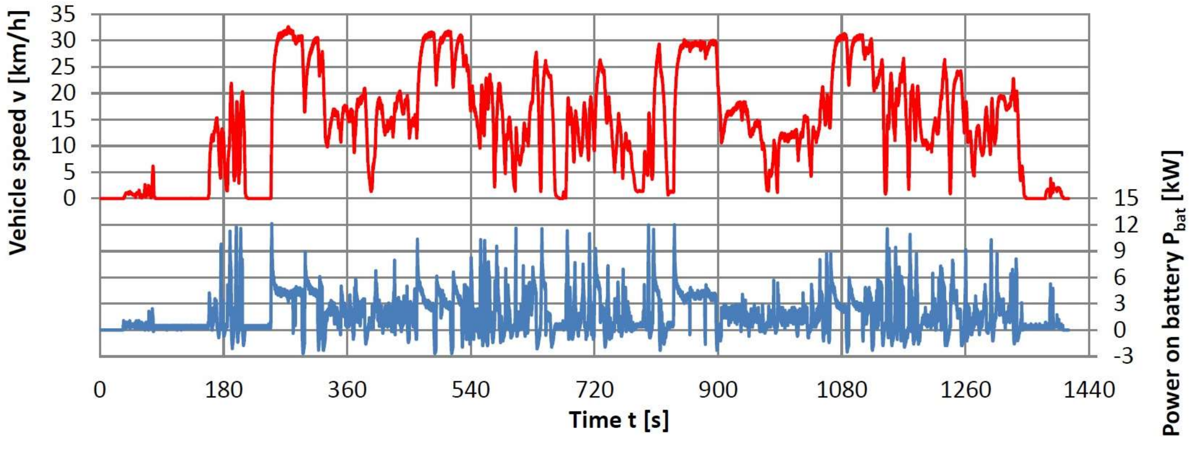

Figure 3. Vehicle speed and power of battery vs driving test duration.

The amount of energy taken from the battery for driving was calculated each time using the following formula (1):

$$E_{drv+} = \int_{t_0}^{t_1} V_{bat} \cdot I_{bat} dt, \text{ for } I_{bat} > 0, \quad (1)$$

where:
t – time, s
t_0 – time of the start of driving, s
t_1 – time of the end of driving, s

The amount of energy delivered to the battery while regenerative braking occurred was calculated by the use of formula (2):

$$E_{drv} \quad = \int_{t_0}^{t_1} V_{bat} \cdot I_{bat} dt, \text{ for } I_{bat} < 0, \quad (2)$$

The balance of energy used for driving was calculated from formula (3). It was assumed that, on average, 0.5 electricity generated during generator machine operation is stored in vehicle batteries[15].

$$E_{drv} = E_{drv} \quad + 0.5 \cdot E_{drv} \quad , \quad (3)$$

It should be noted here that the minimum possibility of regenerative braking intensity in the motor control unit of the vehicle has been set for testing purposes. However, it is not possible to completely deactivate the function of returning energy to the batteries in the controller. The weakening of regenerative braking was dictated by the desire to maximize the independence of results from the impact of the amount of energy returned to the battery when the vehicle slows down, because it is difficult to estimate the real energy of this process, which will be “captured” in the battery.

Figure 4 shows the current and battery voltage waveforms recorded during charging after the first test run.

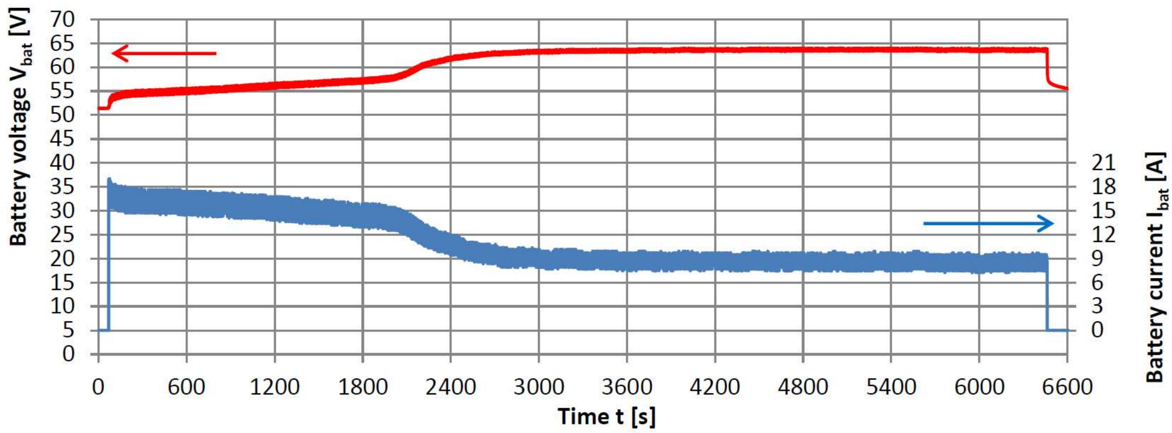

Figure 4. Electric parameters of the battery – voltage and current – vs charging process duration.

In order to calculate amount of the energy supplied to the battery from the charger following formula (4) was used:

$$E_{bat} = \int_{t_2}^{t_3} V_{bat} \cdot I_{bat} dt, \quad (4)$$

where:
t_2 - time of the start of charging, s
t_3 - time of the end of charging, s

Figure 5 shows the balance of energy consumed for driving E_{drv}, energy delivered to the battery from a charger E_{bat} and energy drawn from the power socket by the charger E_{chrg} as a function of the driving distance.

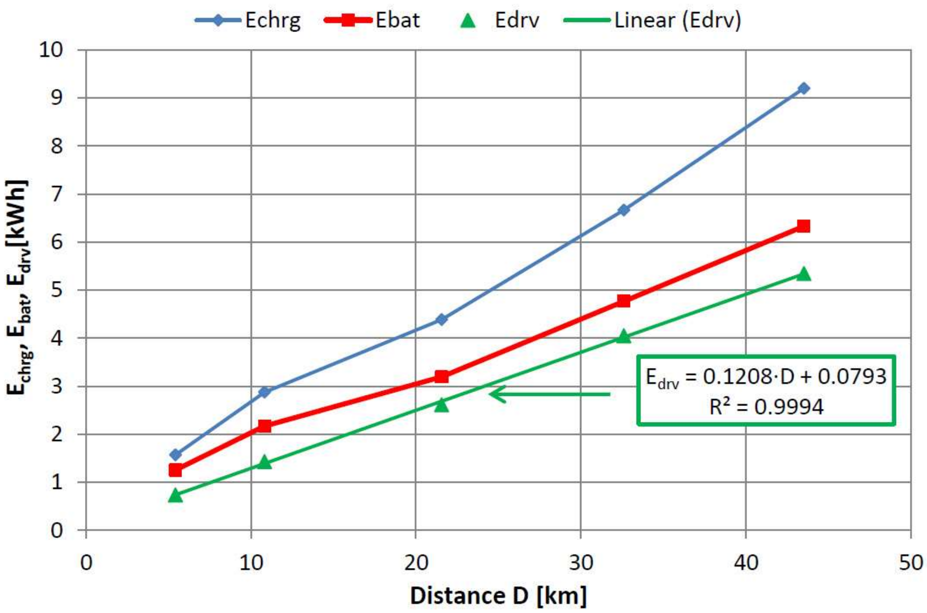

Figure 5. Balance of the energy consumed for driving E_{drv}, Energy delivered to the battery from a charger E_{bat} and energy drawn from the power socket by the charger E_{chrg} as a function of the driving distance.

It can be noted that the dependence of the energy balance on the distance is practically linear, which confirms that the driving conditions had to be very close test to test.

When the values of energy delivered to the battery from a charger E_{bat} and energy drawn from the power socket by the charger E_{chrg} are known an efficiency of the battery charger can be calculated using equation (5):

$$\eta_{chrg} = \frac{E_{bat}}{E_{chrg}}, \tag{5}$$

In the similar way, having known the values of balance of the energy consumed for driving E_{drv} and energy delivered to the battery from a charger E_{bat}, an energy efficiency of the battery η_{bat} can determined using expression (6):

$$\eta_{bat} = \frac{E_{drv}}{E_{bat}}, \tag{6}$$

And finally, efficiency $\eta_{ps\rightarrow m}$ in the entire analysed energy conversion chain, from power socket to charger to battery to electric machine, can be calculated using formula (7):

$$\eta_{bat} = \frac{E_{drv}}{E_{chrg}}, \tag{7}$$

In the Figure 6 efficiency calculated from power socket to vehicle motor $\eta_{ps\rightarrow m}$, battery efficiency η_{bat}, and charger efficiency η_{chrg} as a function balance of the energy consumed for driving E_{drv} are presented.

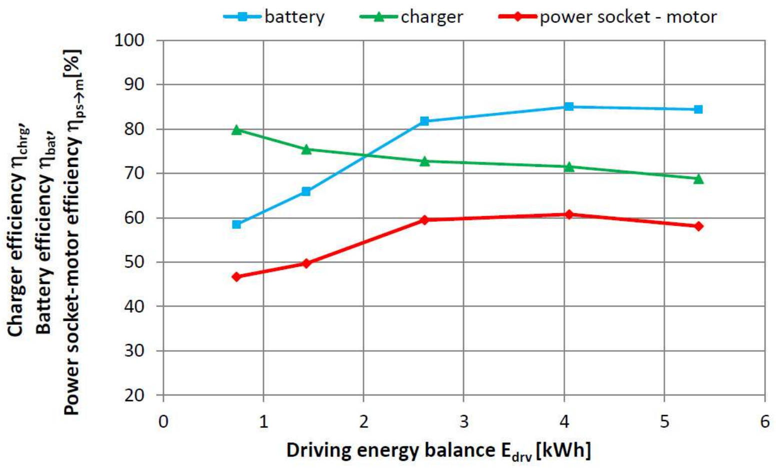

Figure 6. Efficiency calculated from power socket to vehicle motor $\eta_{ps \rightarrow m}$, battery efficiency η_{bat}, and charger efficiency η_{chrg} as a function balance of the energy consumed for driving E_{drv}.

The efficiency of the lead-acid batteries was getting higher with increasing the amount of energy taken from the battery reaching a maximum of about 85%. During the tests, there was also a certain decrease in the efficiency of the charging device along with increasing the charging time resulting from the greater amount of energy taken from the battery at a higher mileage of the vehicle on a given test day. Analysis of the obtained results indicated that the efficiency of energy conversion in a vehicle with electric drive in the chain "electric socket - charging device - batteries – electric machine" depends substantially on how the vehicle is operated before the next charging. The total energy efficiency $\eta_{ps \rightarrow m}$ calculated from the electric socket to the motor terminals in the vehicle has reached the maximum value of almost 61% for the 32.6 km route, what can be considered a good result.

In this situation, one can attempt to state that for the tested vehicle the distance to the next battery charge optimal for the efficiency of the entire energy conversion chain analysed is slightly over 30 km.

Figure 7 shows specific energy consumption calculated for the entire analysed energy conversion chain (from power socket to wheel) as well as calculated only in terms of the of the battery to wheel in a function of the amount of energy consumed for driving.

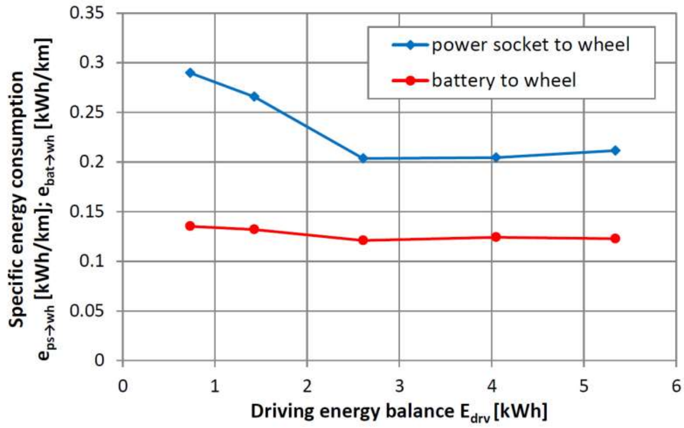

Figure 7. Specific energy consumption related to driving energy balance.

As it can be seen in the figure above variation of the specific energy consumption calculated in terms of the battery to wheel has almost flat course, what results from the same style of driving for each of the test routes. The obtained values can be considered as relatively high comparing to average results for passenger cars [16]. It is resulted by rather high losses in the tested-vehicle's driveline. The specific energy consumption calculated for the entire analysed energy conversion chain (from power socket to wheel) in significantly higher for lower values of energy consumed for driving to the next charging of the battery. This is caused by considerably lower efficiency of batteries in these cases. For the highest analysed value of energy consumed for driving, the specific energy consumption (calculated from power socket to wheel) increases slightly, what is result of decreased efficiency of the charger which has been working for a longer time and a practically constant value of the battery efficiency in this point in a comparison to the previous one point.

Having known the values of specific energy consumption calculated for the entire analysed energy conversion chain it was possible to determine the equivalent CO_2 emissions caused by using such a vehicle and then charging from a power grid for a few selected European countries.

Figure 8 shows comparison of the tested-vehicle equivalent CO_2 emissions in a function of the driving-energy for selected European countries.

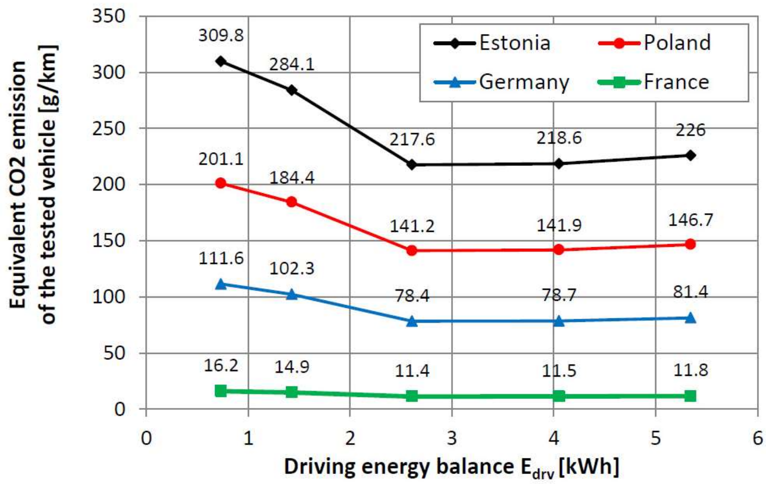

Figure 8. Tested vehicle equivalent CO_2 emission vs driving energy balance comparison for some European countries.

The measurements constituting the research base of this article were carried out in the 2017 summer season. Hence, the results of the equivalent CO_2 emissions in g/km shown in the Figure 8 were related to the specific CO_2 emission in grams per kWh of electric energy produced in example European countries. In addition to Poland, Germany was chosen as the nearest neighbour and two countries with extremely different CO_2 emissions: France with the low emissions and Estonia with the highest emissions. Statistics used at work are presented online and in the form of archived data on the website [17] The EU regulations state that the average CO_2 emission for the passenger vehicles fleet in 2015 is limited to 130 g/km, and in 2021 to 95 g/km. The results presented in Figure 8 mean that the tested vehicle, both in Poland and Estonia, does not meet the requirements of regulation. The reason for this is, of course, the way the electricity is produced in these countries, which puts into question the wider use of this type of drive for road vehicles. Obviously, the profit is zero-emissions at the point of use of such vehicles, especially if they are operated in confined spaces.

6. Summary and conclusions

In the case of light-duty vehicles with electric drive, lead-acid batteries due to low costs and operational requirements are still an attractive solution. Despite the relatively low efficiency of energy conversion, such benefits as the lack of local emission of both toxic exhaust components as well as CO_2 and noise support the continued use of such vehicles. CO_2 emissions may be lower if electricity production in a given country goes to low-carbon sources [18]. For countries in which currently most of electric energy is produced in coal-, lignite- or oil shale-fuelled power plants it will be not easy in a short-term. Additionally, in example of Poland availability of renewable energy sources is very limited, and a planned construction of nuclear power plant causes protests of some groups.

From the carried out tests, it can be concluded that subsequent charging cycles should be carried out with a relatively high state of battery discharge. This results in the highest energy conversion efficiency, and also reduces the final number of charging/discharging cycles, which should have a positive effect on the battery life.

In case of charging after low discharge a battery energy efficiency is low what is resulted by properties of electrochemical energy sources. The higher discharge the better battery efficiency occurs, but, on the other hand, longer charging process lowers the charger efficiency, so the maximum of efficiency calculated from power socket to wheel is not obtained at maximum range of the vehicle. In case of the described vehicle the highest value of overall energy efficiency was recorded for about 32 km route, while maximum range is about 60 km.

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