CHANGES IN ELECTRIC CAR ENERGY CONSUMPTION DEPENDING ON MASS

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Abstract. The use of electric cars has developed rapidly in the last 10 years. The capacity of car batteries has increased. Initially, batteries with a capacity of 16-22 kWh were used, while today the batteries of modern electric cars have at least 3 times more capacity. The main disadvantage of any type of battery is the low specific energy density per kilogram of battery mass. Liquid fuel used in most vehicles today has one of the highest energy densities. This means that a liquid fuel tank with a relatively small mass can store and transport a much larger amount of energy than can be stored in the batteries of an electric car. The research designed and tested an analytical algorithm for calculating the energy consumed, depending on the change in the mass of electric cars. By choosing an electric car with a lighter battery, it is possible to achieve significant savings in reducing environmental pollution. Lower capacity and mass batteries consume less energy and raw material resources. Electric cars equipped with lower mass batteries can achieve more economical operation due to lower energy consumption per kilometre. However, the use of lower-capacity batteries in electric cars is not in line with the current trends in electric cars because car users want to get the same driving range per charge from electric cars as from internal combustion cars. The solution to the use of low-capacity batteries in electric cars can be found by introducing a new infrastructure, such as battery swap stations, inductive charging lanes on roads and other modern infrastructures. The analytical part of the research analysed various impacts of the mass of an electric car on the energy consumed. From the perspective of energy consumed, electric cars with lighter batteries, e.g. a *Citroen C-Zero* and a *Renault Zoe*, are more efficient than those examined.

Keywords: electric car, kerb weight, battery weight, energy consumption, calculation algorithm.

Introduction

The mass of a car is one of the most important factors that can affect various performance parameters of the car, especially those related to dynamics and braking. An analysis of mass change trends in a specific class of cars over the last 50 years revealed a tendency to reduce the mass of cars in the 1980s. Therefore, the safety of the car decreased, whereas the parameters of fuel consumption and dynamics improved. In the following decade, the safety performance of cars was improved with the mass production of ABS systems, airbags and other electronic systems. Environment-friendly exhausts and other systems, which were heavier than those of previous generations, also appeared as standard equipment. Overall, this again increased the mass of a car by an average of 10% compared with that of a car of the previous generation.

Changes in the mass of an electric car can be significantly affected by an increase in battery capacity. The first-generation lithium batteries that were in use until 2016 were overall heavier than the new-generation batteries of the same capacity. For this reason, it cannot be claimed that with progress in technology, the mass of a battery increases 2-fold if the capacity of the battery increases 2-fold. Such a trend could be identified by analysing the trend in various electric cars of the same brand.

A mass introduction of electric cars is associated with an increase in the consumption of additional resources such as lithium, copper etc. Increasing battery capacity also involves consuming more mineral resources as additional raw materials are needed. In the period until 2030, the consumption of lithium might increase up to 3.4-fold. The reserves of this ore are not inexhaustible and might run out within the next 100 years if other technologies are not developed [1].

Battery mass is also important for electric trucks. Increasing the mass of batteries to increase the driving range requires a reduction in payload capacity in order not to exceed the gross weight limits. For trucks, the mass of batteries can reach 3.3 t [2].

Various simulation tools, e.g. a MATLAB-Simulink model, are employed for researching the impacts of electric car mass on energy consumption. The research studies use various driving cycles: NEDC, WLTP and ALDC. The energy consumption identified under these driving cycles varied in the range of 0.55-0.97 $\text{kWh}\cdot(100\ \text{km}\cdot 100\ \text{kg})^{-1}$. The differences in energy consumption between the cycles were due to different maximum accelerations, which varied from 1.04 $\text{m}\cdot\text{s}^{-2}$ under NEDC to 3.25 $\text{m}\cdot\text{s}^{-2}$ under the ALDC cycle [3].

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To use electric cars with lower battery capacities, which do not exceed 25-30 kW·h or even less, it is necessary to improve or modify the charging infrastructure [4]. By creating an expensive but efficient charging infrastructure, e.g. battery swap stations with robots, it is possible to significantly reduce the time needed for energy replenishment, as well as the service life of the battery because the batteries can be charged in a slower charging mode. In this case, electric car manufacturers would be inconvenienced by the need to use batteries of the same size and design and have easy access to the battery from underneath the electric car. If, however, the manufacturer would like to use higher-capacity batteries in an electric car, it is possible to install two or more battery packs. When charging the batteries, the user of the electric car would also have certain advantages, as would not have to worry about a decrease in battery performance as the electric car gets older, as the defective batteries would be replaced with working ones at charging stations.

M. Grab et al. have researched the impact of acceleration on energy consumption by an internal combustion car in road tests. They road-tested the car that was accelerated in the range from 0.2 $m \cdot s^{-2}$ to 1.5 $m \cdot s^{-2}$. For internal combustion cars, it was found that by increasing the acceleration by 0.1 $m \cdot s^{-2}$, the average energy consumption increased by 0.15 $J \cdot (kg \cdot m)^{-1}$[5].

Energy consumption and the potential driving range for an electric car depend on the driving style. Carlos Armenta-Déu and Erwan Cattin divide driving styles into three categories: aggressive, normal and moderate. The average acceleration is different for each style: aggressive- 3.5 $m \cdot s^{-2}$, normal- 2.5 $m \cdot s^{-2}$ and moderate- 1.5 $m \cdot s^{-2}$. A simulation of an electric car with a mass of 1500 kg and a 50 kW·h battery revealed that the aggressive driving style resulted in 30% higher energy consumption, which reduced the driving range per charge by 24% [6].

Analytical simulations and examinations of middle-class electric cars with a mass in the range of 1400-1500 kg (*Renault Zoe and Nissan Leaf*) and batteries up to 50 kW·h assumed that the average life cycle is 150000 km. The simulations found that future electric cars produced by 2040 would have up to 20% less overall impact on the environment. The total CO_2 emissions from the production and operation of electric cars can reach 23- 52 $g \cdot km^{-1}$, depending on the type of electricity generation [7].

A calculation algorithm was developed to identify the impact of changes in the mass of an electric car on the driving range. The algorithm considers car movement parameters under real driving conditions in the city of Jelgava. The present research aims to design and test an algorithm for calculating the impact of changes in the mass of an electric car on energy consumption and the driving range. Real driving data from electric cars tested on a specific route were used to identify the accuracy of the algorithm.

Materials and methods

The calculation algorithm determines the energy consumed by the electric car, initially identifying the instantaneous power of the electric car. The instantaneous power could be calculated relatively accurately in smooth driving when the speed of the electric car does not change. The energy consumed during acceleration is also dynamic, depending on the change in acceleration. The process of energy recovery during regenerative braking should also be analysed separately. The calculation algorithm considered driving regimes in real traffic conditions in the city of Jelgava on a specific route. An electric car *Citroen C-Zero* was road-tested in D mode (no power limits) on the route to identify the driving regime. The electric car was equipped with a 48 kW alternating current electric motor, which delivered 180 N·m of torque, and a 16 kW·h battery pack. The electric car was accelerated to 100 $km \cdot h^{-1}$ in 15.9 s. The mass of the electric car was 1230 kg. The speed changes during the road tests on the route are shown in Figure 1.

The length of the route was 14.4 km. The road test was done during off-peak traffic hours from 10:00 to 15.00. A GPS logger Garmin Edge 230 was used to record car movement data. The road test was done in strict compliance with the road traffic rules and according to the traffic conditions. The road test route included sections with the main street and several traffic lights, as well as main streets intended for truck traffic to bypass the central part of the city. In total, the route included 30 traffic lights and two circular intersections.

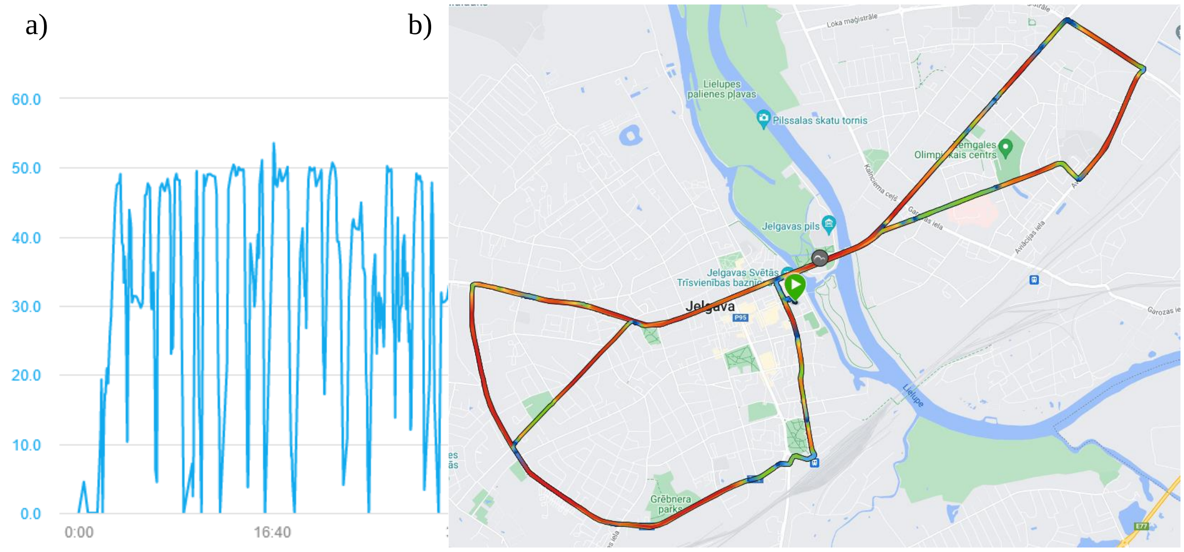

Fig. 1 **Characteristics of speed change during one road test; experimental route in Jelgava city**

The power required to overcome the road resistance of an electric car is calculated by an equation:

$$N_{\psi} = N_f + N_{\alpha} = fG_a v \cos\alpha + G_a v \sin\alpha\,, \tag{1}$$

where N_f – power to overcome rolling resistance, W;
N_{α} – power to overcome uphill, W;
f – rolling resistance coefficient;
G_a – mass of the electric car, N;
α – road slope angle, in degrees;
v – speed, m·s^{-1}.

If the electric car moves on a flat road with no ups and downs, $\alpha = 0$ un $N_{\alpha} = 0$. The power consumed to overcome air resistance for the electric car, W, is calculated by an equation:

$$N_W = \frac{1}{2}\rho c_x A v^3 \tag{2}$$

where ρ – air density, kg·m^{-3}, 1.225 for air at 15 ºC temperature;
c_x – drag coefficient for the particular electric car;
A – frontal area of the electric car, m^2.

The calculation used the air resistance parameter c_xA from the technical parameters of the particular electric car. The power, W, required to overcome the inertial force of the electric car was calculated by an equation:

$$N_a = m_a \delta a v\,, \tag{3}$$

where m_a – mass of the electric car, kg;
δ – rotating mass factor for the car (assumed 1.05-1.10);
a – acceleration, m·s^{-1}.

If the electric car moves at a constant speed, $N_a = 0$. The energy consumed by the electric car was calculated for one driving cycle in the city of Jelgava for a 14.4 km section and then recalculated for a distance of 100 km. The average speed of the car, based on the road tests done on a *Citroen C-Zero* on the route, was assumed to be 40 km·h^{-1} or 11.1 m·s^{-1}. The total power balance for the electric car on a flat road, W, was calculated as follows:

$$N_e = \frac{N_k}{\eta_t} = \frac{1}{\eta_t}\left(N_f + N_W + N_a\right), \tag{4}$$

where η_t – transmission efficiency for the electric car was assumed to be 0.97-0.98.

To calculate the energy consumed during acceleration, each 14.4 km driving cycle was analysed by counting the average number of times it was necessary to stop at intersections with traffic lights. The average frequency of stops at 30 traffic lights was 13 per cycle. The calculation used equation (3) considering acceleration up to 45 km·h^{-1}. The maximum speed during acceleration was usually not reached because of traffic conditions. The acceleration from 25- 50 km·h^{-1} on the route was also considered. The number of accelerations per cycle was on average 6.

The number of regenerative braking cases was also considered by the algorithm, which was equal to the number of stops at traffic lights, i.e. 13 on the route. It was assumed that 15% of the total energy consumed was recovered by regenerative braking [8]. The number of regenerative braking cases was assumed to be equal to the number of stops at red traffic lights, i.e. 16 per cycle.

To calculate the acceleration of the electric car, acceleration tests were done on the electric car. A Stalker ATS scientific radar was used in the tests. The average speed achieved at maximum acceleration during the tests is presented in Figure 2.

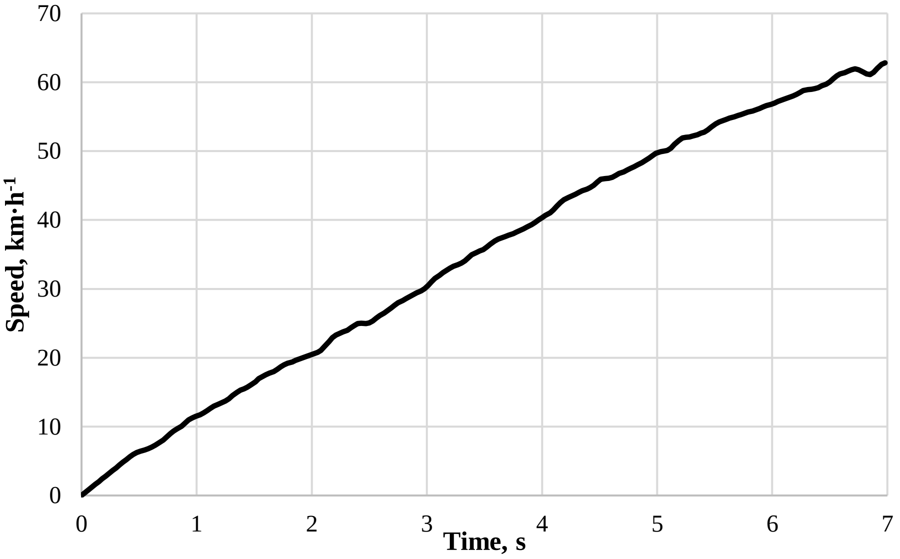

Fig. 2. **Characteristic curve for acceleration of the electric car *Citroen C-Zero***

The *Citroen C-Zero* represents a mass-produced low-power electric car. For other electric cars, the maximum acceleration is higher; however, the maximum acceleration is not usually achieved in urban driving. The tested electric car reached 50 km·h^{-1} in 5 seconds, achieving an average acceleration of 2.8 m·s^{-2}. The calculation of the energy consumed by the *Citroen C-Zero* during acceleration considered an average acceleration of 2.0 m·s^{-1}, which is often achieved in urban driving.

Results and discussion

The calculation algorithm was tested for electric cars that have one base model, yet the batteries are of different capacities. The input data were obtained from various information resources [9; 10], while the driving regime was chosen according to the regime analysed in the previous chapter.

One of the most important parameters of an electric car that can affect energy consumption is the mass of the battery, which also affects the curb weight and gross weight of the electric car. Lighter electric cars usually achieve lower energy consumption. Electric cars popular in Europe were selected for analysis: *Renault Zoe*, *Nissan Leaf* and *Tesla*. Data on the battery mass and car mass without the battery for the electric cars are presented in Figure 3. The battery capacity is also indicated in the trim name of an electric car, e.g. “ZE55” for *Renault Zoe* or “(40)” for *Nissan Leaf* and *Tesla*.

For the electric cars analysed, the battery capacity of which was not higher than 50 kWh, the battery mass did not exceed 326 kg and the kerb weight did not exceed 1600 kg (see Fig. 3). Electric cars with a battery capacity of 60 kWh and higher have a battery mass between 345 and 625 kg; however, newer high-capacity batteries tend to be lighter than those manufactured before 2015. The kerb weight of such electric cars sometimes exceeds 2000 kg and ranges from 1731 to 2215 kg.

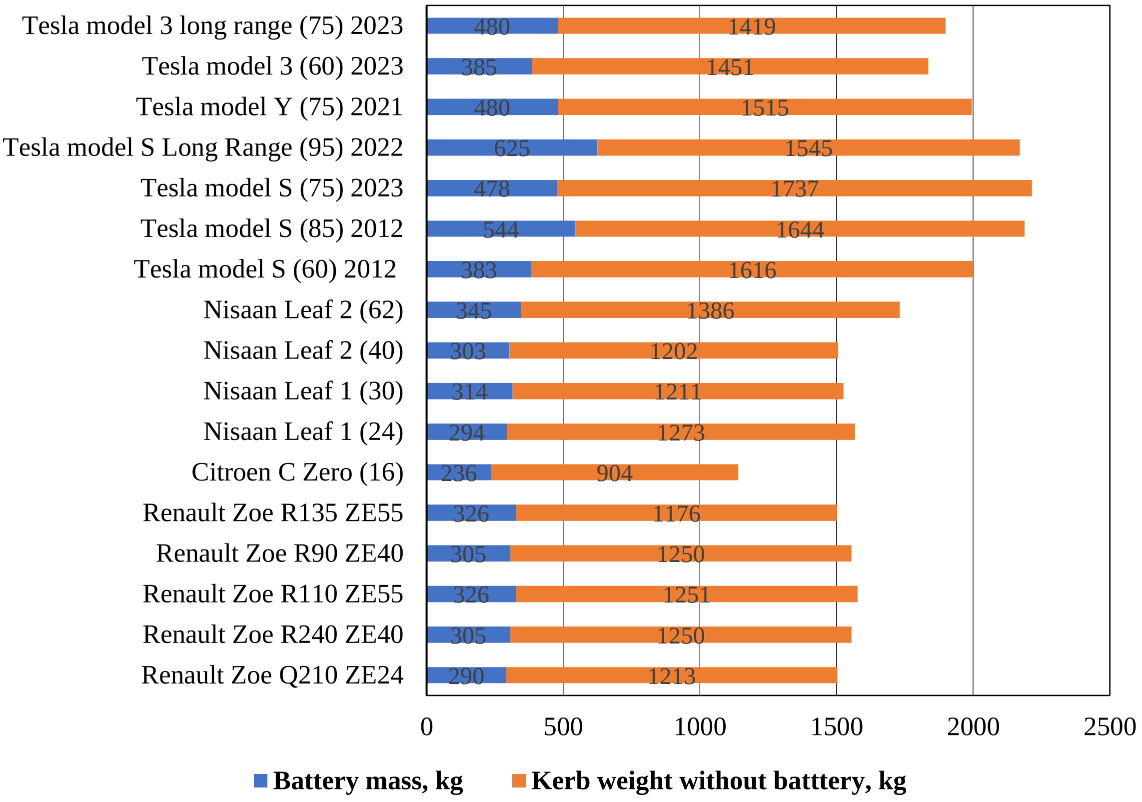

Fig. 3. **Mass of batteries and electric car mass without batteries**

The calculation results for the energy consumed by the electric cars for overcoming rolling resistance, air resistance and inertia on the route are presented in Figure 4.

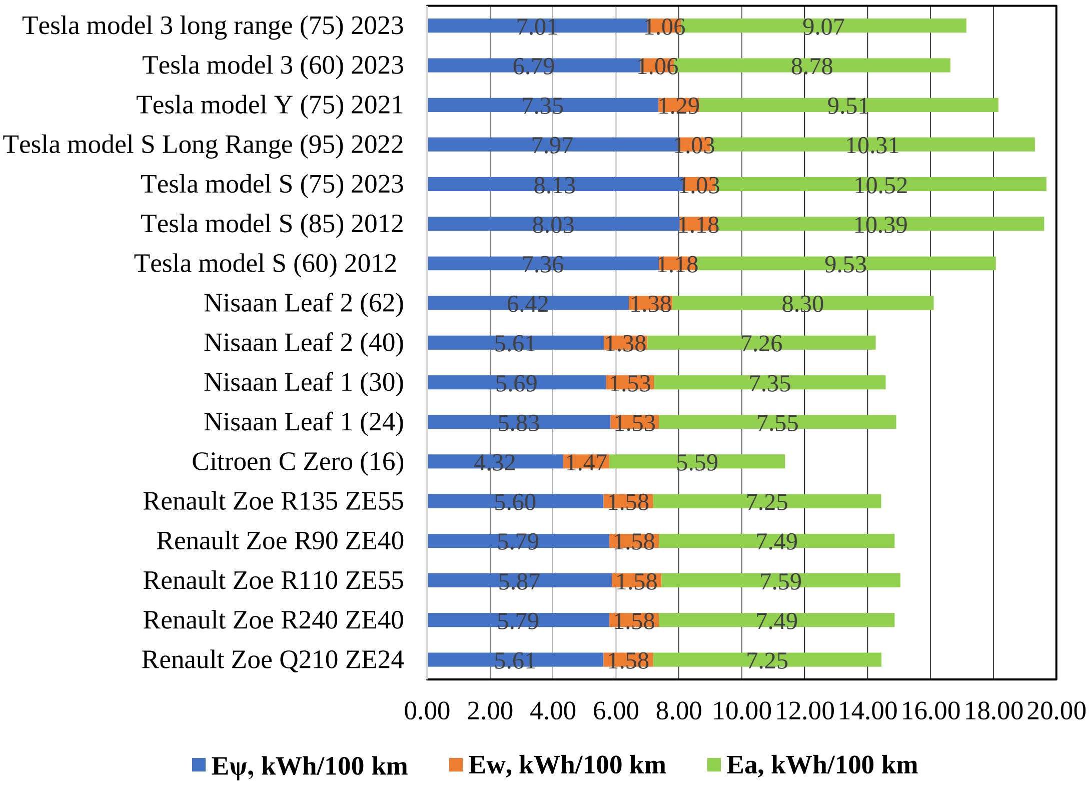

Fig. 4. **Energy consumed by electric cars for a distance of 100 km**

Lighter electric cars consume less energy for smooth movement. Since the *Citroen C-Zero* was the lightest car, it also demonstrated the best economy performance. Only 5.79 kWh of energy was consumed for overcoming air and road resistance, and 5.59 kWh·(100 km)$^{-1}$ for overcoming inertia. The electric cars with a battery capacity of up to 40 kWh also performed well, as the energy required to overcome road resistance was in the range of 5.61- 5.83 kWh·(100 km)$^{-1}$, while the energy required to overcome inertia was in the range of 7.27-7.55 kWh·(100 km)$^{-1}$. With the progress in battery technology, the curb weight of electric cars and the energy consumed for movement no longer increase significantly, as is the case with, for example, the electric car *Renault Zoe R*135 *ZE*55, which demonstrated energy consumption performance similar to that of the electric cars with smaller battery capacities.

Similar to internal combustion cars, the highest energy consumption per 100 km in the electric car segment is for *Tesla* luxury cars. For such electric cars, the energy required for overcoming road resistance was in the range of 6.79- 8. The proportion of energy required to overcome air resistance was small for any electric car because the power consumed at low speeds was low. At higher speeds, the proportion of energy needed to overcome air resistance increases. Then the winners are electric cars that demonstrate better air resistance, e.g. *Tesla* electric cars, whose air resistance coefficient c_x is in the range of 0.21- 0.24.

The energy consumed during the charging and movement of electric cars is presented in Figure 5. The calculation considered that the electric car recovers 10% of the total energy consumed during regenerative braking. In addition, the energy losses for charging an electric car is considered and assumed to be 8% if the electric car is charged at a slow charging point or at home. Losses of 12% are assumed for energy transfer from the batteries to the electric motor [11; 12].

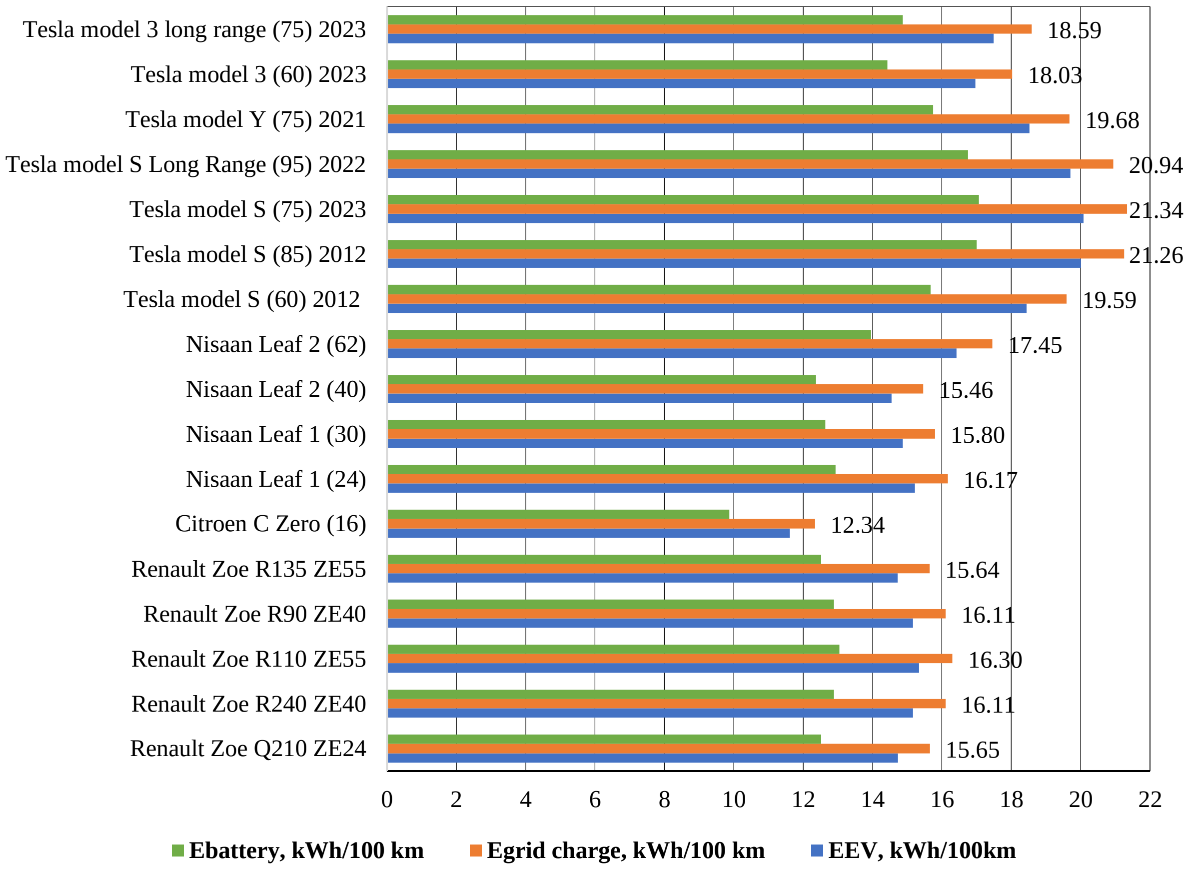

Fig. 5. **Energy consumed during charging and movement of the electric car**

When moving, the electric car consumes less energy from the battery ($E_{battery}$) than it is necessary for the movement because the energy recovered during regenerative braking is consumed as well. By adding up the energy recovered during regenerative braking and the energy from the battery ($E_{batterry}$), we can calculate the total energy consumed for movement (E_{EV}).

Just like the above analysis of the energy required for movement, the *Citroen C-Zero* consumed the least energy drawn from charging stations for 100 km, 12.34 kWh. For high-power *Tesla* electric cars, the energy consumed is in the range of 18.03- 21.34 kWh·(100 km)$^{-1}$. It is also necessary to consider the fact that electric cars of this class are charged at super-fast charging stations and energy losses during the charging might be twice as high and reach 16%. Electric cars with a battery capacity of up to 40 kWh need to consume 15.46 to 16.30 kWh from the grid to travel a distance of 100 km. In the case of using various comfort systems, e.g. interior heating, energy consumption increases, depending on the ambient temperature and the technology of the heating system.

Conclusions

1. The analytical algorithm for calculating the energy balance for an electric car has been tested and recognized as useful for identifying energy parameters for the electric car.
2. Comparing the data obtained in the developed calculation model with the data of the car databases, the difference in energy consumption in the city driving cycle differs by 6-8%.
3. To achieve more accurate results for the energy consumed, it is necessary to consider the efficiency factor for each electric car, as well as the efficiency factor for the particular charging equipment.
4. It could be observed in practice that the more the fast charging stations are used, the lower the efficiency factor for charging and the shorter the service life of the batteries.
5. By increasing the capacity of electric car batteries without changing the battery manufacturing technologies, the mass of the electric car increases in proportion to an increase in the battery capacity. Newer models of electric cars tend to be equipped with lighter batteries, yet the battery capacity tends to increase.
6. More energy is consumed to overcome inertia in urban driving than in smooth driving; therefore, to save energy, it is recommended to accelerate the car smoothly. Part of the energy consumed during acceleration can be recovered by regenerative braking.
7. The calculations revealed that in urban driving, the energy consumed by small-class electric cars was 35% lower than that by luxury electric cars with a heavy curb weight.

Author contributions

D. B.: Conceptualization, methodology, validation, experiment, visualization, writing. I. J.: formal analysis, literature analysis, schedule administration, writing – editing, references. J.M.: technical soundness, data analysis, writing – review. All authors have read and agreed to the published version of the manuscript.

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