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*Brief Report*

# Analysis of the Use of Rational Electric Vehicle Battery Design as an Example of the Introduction of the Fit for 55 Package in the Real Estate Market

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**Abstract:** The European climate law contains a mandatory EU climate target of reducing emissions in the EU by at least 55% by 2030; to realistically implement it, a transformation of many economic sectors is required. The main solutions focus on energy production. However, an equally important aspect is its storage. It represents the biggest challenge to ensure the stability of energy use in the real estate market. Today, lithium-ion batteries are the most promising batteries. They have the advantages of high efficiency during the charge–discharge process, and high density of electrical energy. The potential range of electric vehicles on a single charge depends on the battery. Accumulator batteries, depending on their purpose, are assembled from a certain number of lithium-ion cells. At the same time, the battery connection scheme depends on what the goal is. This can be an increase in battery capacity, an increase in voltage, or a combination of both parametric characteristics of the device. This approach and research results can be implemented not only in the automotive field, but also in industry, the real estate market, etc.

**Keywords:** electric drive; electric vehicle; battery voltage; lithium-ion cell; efficiency; real estate; Fit for 55 Package



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## 1. Introduction

Climate change is driving the need to move away from conventional energy production solutions. Many industries are facing significant changes, but the biggest will be in the real estate market. According to the proposal for a directive of the European Parliament and of the Council on the energy performance of buildings (2021/0246 (COD)), to be classified as "zero-carbon", "a building (must) have very high energy performance in accordance with the first energy efficiency principle, and a very small amount of the required energy is fully covered by energy from renewable sources at the level of the building, district or community, where technically feasible". The EC's proposal for the automotive market is to tighten carbon dioxide emission standards for passenger cars: 55 percent by 2030 (compared to the status quo), and 100 percent from 2035. This means that in 14 years it will not be possible to register a car with an internal combustion engine in the EU. This applies to newly manufactured cars. The FIT for 55 package introduces significant changes in many sectors of the economy. While in the real estate market, zero-emission technologies are only the beginning of the changes in many countries, the automotive market has long spread these changes.

Lithium-ion batteries are widely used and had a promising future ahead due to their advantages over traditional battery technologies. The adoption of these batteries in electric vehicles has been growing steadily [1]. In the nearest perspective, we can expect even more widespread use of lithium-ion batteries in the automotive industry. Ongoing advancements in battery technology could lead to improved energy density, longer ranges, and faster charging times, making EVs more appealing to consumers [2]. This leads to the search for new deposits of this useful mineral and the improvement of mining technologies [3].

Lithium-ion batteries are being used for stationary energy storage systems, such as grid-scale storage and residential battery storage [4]. These systems help integrate renewable energy sources like solar and wind into the grid by storing excess energy and providing it during peak demand times. In the nearest perspective, further reductions in battery costs and improvements in efficiency may lead to an increased deployment of such systems [5].

The usage of lithium-ion batteries has long been the primary choice for portable electronic devices like smartphones, laptops, tablets, and wearables [6]. In the nearest perspective, we can expect ongoing improvements in battery technology to enhance the performance, lifespan, and safety of these devices, enabling longer usage times and faster charging [7,8].

Despite the wide distribution of lithium batteries for various industries, their main use remains the main one for automobile transport [9]. This fits into the general concept of modern industrial development [10,11]. For this purpose, the use of research methods is an effective mechanism for increasing the efficiency of their use [12].

The power and efficiency of the electric drive power source are the main factors for electric vehicles. The larger the battery capacity, the better—because the electric vehicle in this case has a higher mileage [13]. However, at the same time, the large capacity of the battery requires a long charging time, which makes it necessary to solve the problem of fast charging [14]. Additionally, the problem of increasing the capacity of the power supply arises. This problem can be solved by creating an integrated power source based on combining different sources of electrical energy [15]. However, such a complex source can create certain problems for the electric drive [16].

Lithium-ion batteries are most often used in modern production of electric vehicles. There are three main types of lithium-ion batteries: cylindrical, prismatic, and packet batteries. The well-known company Tesla uses standard cylindrical elements marked, which means its dimensions are 18 × 65 mm [17]. Prismatic elements are large and heavy. They are comparable to vehicle batteries, but they are slightly lighter because they do not contain lead. Packet elements are cathode and anode sheets with a partition in the middle with a thin wrap around. Most batteries of this type are 21 by 27 cm in size and wrapped in a metal shell [18].

In the automotive industry, lithium-ion cells connected in an assembly of parallel–series modules are used as power sources for the electric motor of an electric vehicle when building the main battery [19]. Battery voltage is determined by the number of series connections. A parallel connection is used to increase the capacity of the battery [20]. The required voltage and capacity of the battery is achieved through various configurations of lithium-ion cells or modules. Different configurations lead to different battery performances [21]. For example, as shown in Figure 1, Audi in the E-tron 55/E-tron 60S electric vehicle uses a battery of 95 kW/h and a nominal voltage of 396 V. The battery consists of 36 modules of 12 cells each, giving a total of 432 elements. The lithium-ion cells in each module are connected in a 4p3s configuration. This means that four elements and four more are grouped in parallel and then connected in series.

Since each cell has a capacity of 60 A/h, each parallel group gives a capacity of 240 A/h. (4 × 60 years). When connecting 36 such modules in series, the nominal voltage is 396 V. (396 V * 240 A/h = 95,040 W/h or 95 kW/h.). Each module operates at 11 V and has a power of 240 × 11 = 2640 W/h or 2.64 kW/h [22].

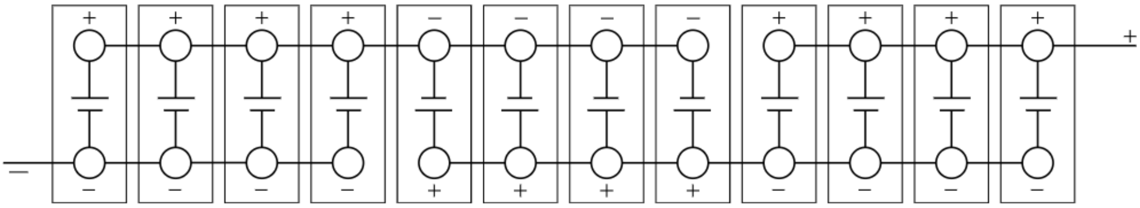

**Figure 1.** Connection diagram of a 95 kWh battery with a 4p3s configuration.

In Tesla batteries, the 18,650 cylindrical elements are folded vertically. The battery is quite flat and can hide imperceptibly from the bottom of most cars [23]. The Tesla electric vehicle uses several blocks of modules in parallel, i.e., if one of the elements fails, the whole battery will continue to work [24].

As an example, in comparison to the popular electric vehicles Chevrolet Volt and Nissan Leaf, the battery modules are connected in series. The Chevrolet Volt uses 192 cells, divided into two blocks of 96 pieces each. Because the battery can generate 18.4 kWh of electricity, the approximate battery voltage can be calculated. Lithium elements emit approximately 3.8 V, so the total battery will have 365 V. The batteries of the Nissan Leaf are equipped with units with a voltage of about 400 V. This value of electric voltage is chosen to ensure that the voltage was sufficient for low-power motors. Lithium elements have a voltage of 3.8 V to 4.2 V, therefore, an in-series connection of 100 elements will receive approximately 400 V [25]. In this type of battery cell connection, if one link fails, the whole battery will stop working. Furthermore, it is difficult to detect a broken element.

## 2. Materials and Methods

Any high-voltage electric vehicle battery consists of a parallel–series connection of elementary cells. In this case, a certain part of these cells is formed in the form of a separate structural module. The connection of such modules creates the design of the battery of the electric vehicle. For example, the Nissan Leaf battery: 24 kWh, 400 V, 60 A, has the design shown in Figure 2. The figure shows that the battery has 48 modules connected in series. Each module consists of four elements connected in parallel and in series (Figure 3). Each module has a terminal for voltage control on parallel pairs of elements for the battery management system (BMS). Each element of the module emits a voltage of 3.8 V. . . 4.2 V and a power of 125 W per hour (30 Ah).

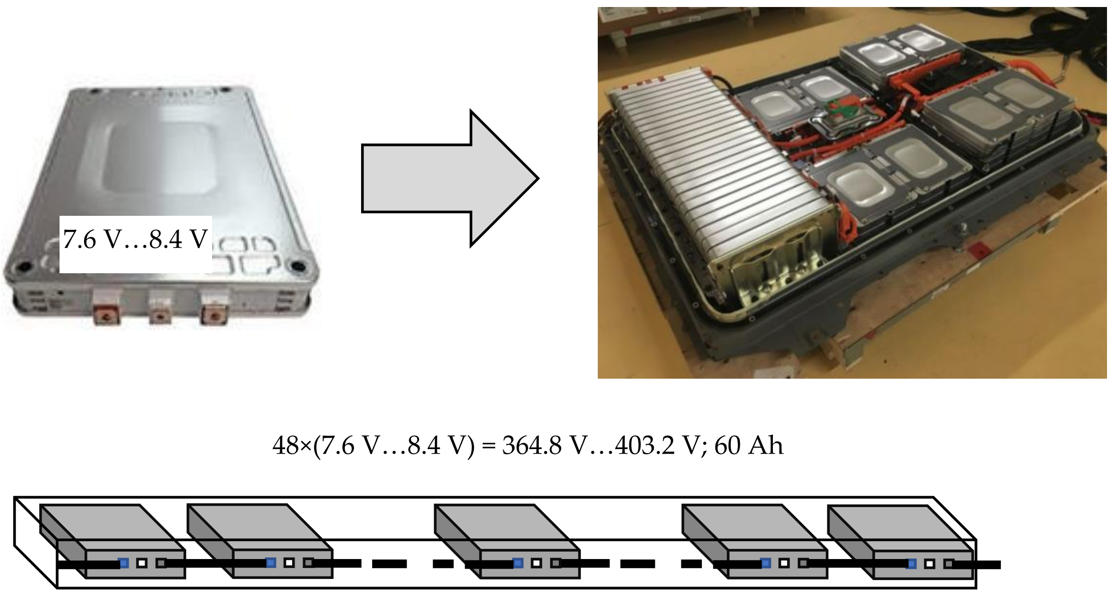


**Figure 2.** Nissan Leaf battery design.

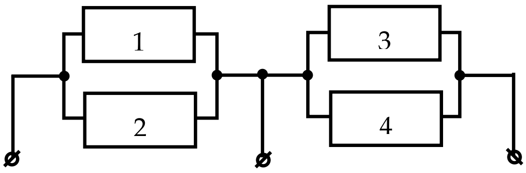


**Figure 3.** Nissan Leaf 2S2P electric vehicle battery module.

Thus, the output voltage of the module is 7.6 V. . . 8.4 V, and its power is 0.5 kW per hour. This is a nominal charge of the module of about 60 amps per hour.

In contrast to the considered battery design, the battery design of the Tesla electric vehicle with parameters of 85 kWh, 400 V, 212.5 A looks slightly differently (Figure 4).

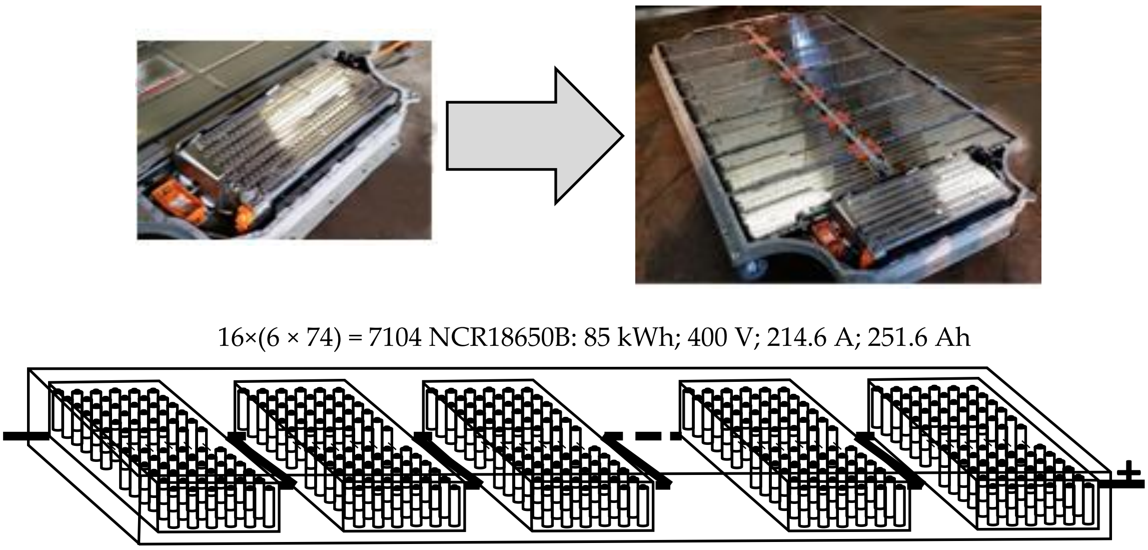


**Figure 4.** Tesla electric vehicle battery design.

Figure 4 shows that the battery consists of 16 series-connected modules with 25 V parameters; 214.6 A. Each module is 6 circuits of 74 elements connected in parallel, each with the parameters of 4.2 V; 2.9 A (Figure 5). Thus, each circuit is designed for a current of 214.6 A. BMS controls the mode of operation of the modules.

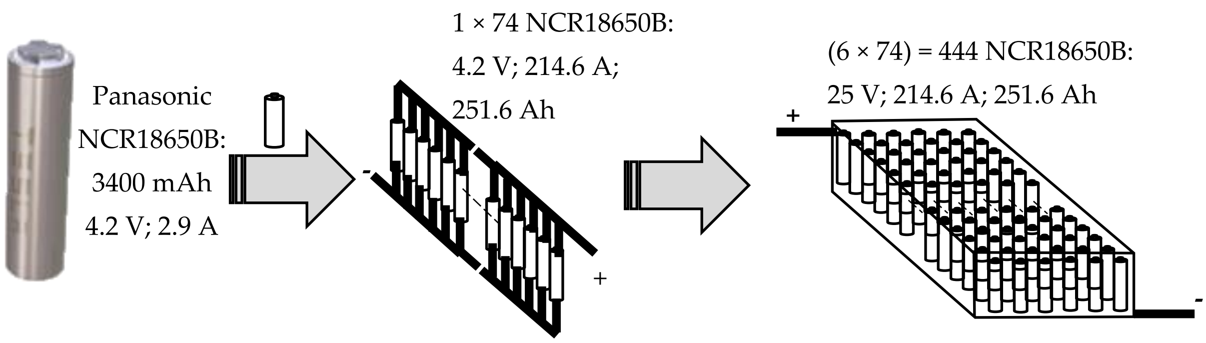


**Figure 5.** Tesla electric vehicle battery module.

Consider how the capacity of the battery varies depending on the degree of degradation of the unit cells and the design features of the battery.

*C*—capacity of the unit cell, which consists of a structural module of the battery; $n_1$—the number of elementary cells connected in parallel in one circuit of the module; $m_1$—number of circuits in the module; m—the number of modules connected in series in the battery.

Based on these definitions, we can obtain the following indicators of battery capacity: capacity of the $i$-th circuit of parallel cells:

$$C_i = \sum_{i=1}^{n_1} C = n_1 C \tag{1}$$

in units relative to $C$:

$$c_i = (n_1 C)/C = n_1 \tag{2}$$

- capacity of the module

$$C_{m1} = \prod_{i=1}^{m_1} C_i / \sum_{i=1}^{m_1} C_i = C_i / m_1 \tag{3}$$

in units relative to $C$:

$$c_{m1} = n_1 / m_1 \tag{4}$$

- battery capacity

$$C_b = \prod_{j=1}^{m} C_{m,j} / \sum_{j=1}^{m} C_{m,j} = C_{m1} / m \tag{5}$$

in units relative to $C$:

$$c_b = n_1 / (m_1 m) \tag{6}$$

Formulas (1)–(6) can be used to determine the capacity of the structural elements of a non-degraded battery. However, when the degradation of the battery begins, it is necessary to take into account the uneven degradation of individual elements of its structure.

We assume that $\Delta c_i$ is the degradation value of the $i$-th circuit of parallel cells of the battery module. Then, the capacitance of the module $c'_{m1}$ after the degradation of its one parallel circuit is defined as:

$$c'_{m1} = 1/\sum_{i=1}^{m_1} \left( \frac{1}{n_1 - \Delta c_i} \right) \tag{7}$$

and the battery capacity after the degradation of its one parallel circuit is defined as

$$c'_b = 1/\sum_{j=1}^{m} \sum_{i=1}^{m_1} \left( \frac{1}{n_1 - \Delta c_{j,i}} \right) \tag{8}$$

where $\Delta c_{j,i}$ is the amount of degradation of the $i$-th circuit of parallel cells of the $j$-th battery module in relative units.

If we assume that the battery degrades symmetrically, equally on all parallel circuits of all modules and $\Delta c_{j,i} = \Delta c$, then from Formula (8) it follows that:

$$c'_b = \frac{n_1 - \Delta c}{m_1 m} \tag{9}$$

Regarding the capacity of a non-degraded battery, $c_b = n_1/(m_1 m)$, we obtain:

$$\frac{c'_b}{c_b} = 1 - \frac{\Delta c}{n_1} \tag{10}$$

That is, the capacity of the degraded battery in symmetrical degradation does not depend on the number of series-connected elements but depends on the degree of degradation of parallel links and their number.

## 3. Results and Discussion

Consider the effect of these factors on the residual capacity of the battery. The dependence $c'_b/c_b$ in the function on $n_1$, where $n_1$ is the number of elementary cells connected in parallel in one circuit of the module for different $\Delta c$ is shown in Figure 6.

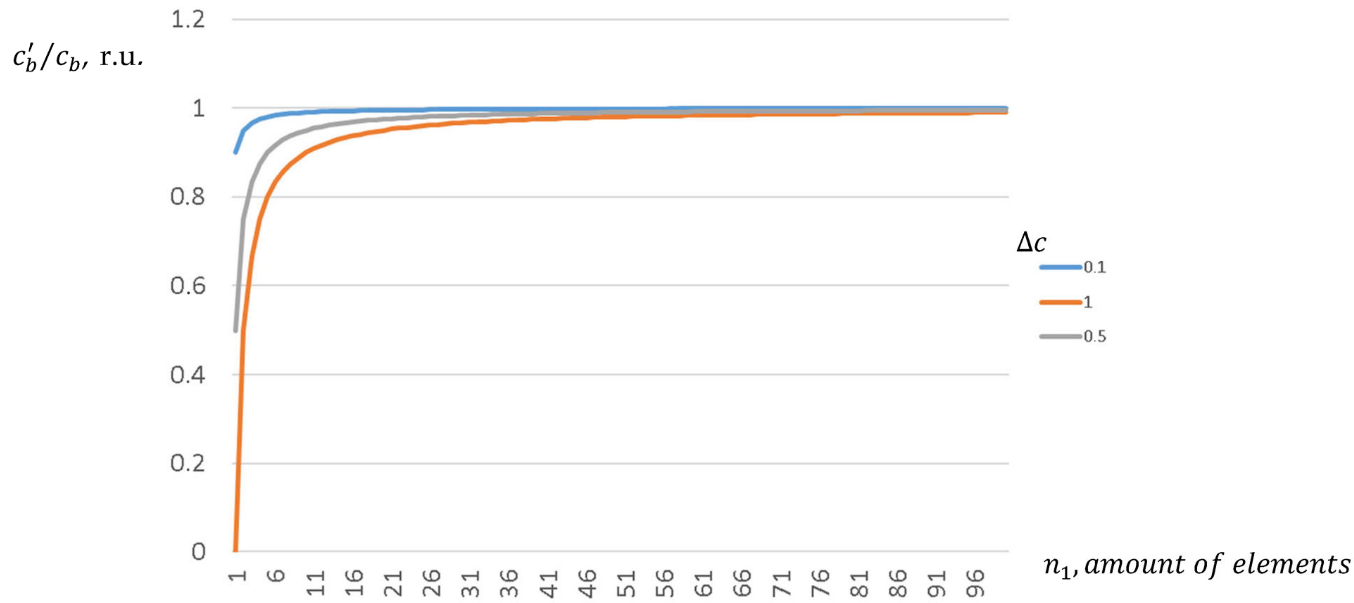


**Figure 6.** Dependence $c'_b/c_b$ as a function of $n_1$ for different $\Delta c$.

The figure shows that in the range $\Delta c = c'_b/c_b = 0.1 \ldots 1$, an increase in the number of parallel cells leads to an increase in the residual capacity of the battery. However, this dependence is significantly nonlinear and, starting from $n_1 \geq 20$, the efficiency of increasing the number of parallel links is significantly leveled.

This can be seen in the example of batteries for electric vehicles Leaf and Tesla.

Leaf. The battery is characterized by the following design parameters: $n_1 = 2$; $m_1 = 2$; $m = 48$. Using Formula (10), we obtain for $\Delta c = 0.1$ (10%) $c'_b/c_b = 0.95$ (95%). That is, when the degradation of two of the four cells in the module by 10% (Figure 3), there is a degradation of battery capacity by 5%.

If one of the four cells in the module fails, i.e., $\Delta c = 1$ (100%), the module will have a capacity according to Formula (7):

$$c'_{m1} = (2/2)/[1/(2-1) + 1/(2-0)] = 0.75$$

that is, it will lose 25% of its nominal capacity, and the battery will have a capacity according to Formula (8):

$$c'_b = 48(2/2)/\{1[1/(2-1) + 1/(2-0)] + 47[1/(2-0) + 1/(2-0)]\} = 0.99$$

that is, it will lose 1% of its nominal capacity.

Tesla: For a battery with 18,650 cells, the parameters are $n_1 = 74$; $m_1 = 6$; $m = 16$. We obtain for $\Delta c = 0.1$ (10%) $c'_b = 0.999$ (99.9%). That is, when the degradation of the parallel circuit of one module is 10%, the degradation of the battery capacity is only 0.1%.

If one of the six circuits in the module fails, i.e., $\Delta c = 1$ (100%), the module will have a capacity according to Formula (7):

$$c'_{m1} = (6/74)/[1/(74-1) + 5/(74-0)] = 0.9977$$

that is, it will lose 0.23% of the nominal capacity, and the battery will have a capacity according to Formula (8):

$$c'_b = 16(6/74)/\{1[1/(74-1) + 5/(74-0)] + 15[6/(74-0)]\} = 0.99984$$

that is, it will lose 0.016% of its nominal capacity.

From these calculations, it follows that increasing the number of parallel circuits of elementary cells in the battery module leads to a significant reduction in battery degradation in the event of failure of one of the circuits. This is a significant advantage of Tesla batteries. However, it should be noted that the number of parallel elements $n_1 = 74$ in the module circuit is exaggerated. Using a reduced number of parallel elements in the circuit of the module $n_1 = 20$ and maintaining the parameters of the battery 400 V and 214.6 Ah, i.e., given that the element has a voltage of 4.2 V ($m_1 = 6$), and the battery module 25 V ($m = 16$), we have:

$$c'_{m1} = (6/20)/[1/(20-1) + 5/(20-0)] = 0.9913,$$
$$c'_b = 16(6/20)/\{1[1/(20-1) + 5/(20-0)] + 15[6/(20-0)]\} = 0.99946,$$

That is, $c'_b \approx 99.95\%$. The results show that the deterioration of the residual capacity is only about 0.3%.

Thus, it is advisable to use the number of parallel links not more than 20, using elements with parameters of 4.2 V; 2.9 A.

Given the above conclusions, it is possible to design the battery of an electric vehicle, choosing a rational number of parallel–serial connections between the elements of the battery module, based on their voltage and current parameters.

Since $m_1 \times m$ determines the voltage of the battery, and the number $n_1$—its current, it is possible to form the modules and the battery itself, taking into account the requirements of the electric part of the electric vehicle, on the one hand, and the parameters of the elements of the module on the other hand.

For example, leaving the supply voltage of the electric drive 400 V, i.e., $m_1 \times m \times V_e = 400$ V, where $V_e$ is the voltage of the lithium-ion element of the battery, then varying the ratio between $m_1$ and $m$ we obtain the battery module voltage taking into account the proposals discussed in this article. The ratio between the current of the inverter and the current of the lithium-ion cell $I_e$ will determine the number of parallel connections in the battery module.

Consider the evolution of Tesla batteries.

As previously discussed, the design of the battery using 18,650 cells with parameters of 3.6 V... 4.2 V; 2.9 Ah is 16 modules in which 6 circuits of 74 parallel elements 18,650 are connected in series. Thus, the parameters of the modules are as follows: $n_1 = 74$; $m_1 = 6$; $m = 16$; 25 V; 214.6 Ah.

Switching to cells 2170 with parameters 3.6 V... 4.2 V and 4.9 Ah, to ensure the total battery voltage of 400 V, it is necessary to have $m_1 \cdot m = 6 \cdot 16 = 96$ series-connected circuits with parallel elements 2170, while maintaining the total battery capacity of 212.5 Ah. Thus, it is necessary to have $n_1 = 214.6$ Ah/4.9 Ah » 42...43.

In the future it is planned to switch to cells 4680 with parameters 3.6 V... 4.2 V; 23... 25 Ah. Therefore, with 96 series circuits with parallel elements 4680 connected in series, it is necessary to have $n_1 \approx 9 \ldots 10$ to obtain 214.6 Ah.

Comparison of Tesla batteries with the presented parameters of unit cells, as well as Leaf batteries during their degradation is shown in Figure 7.

The figure shows that while maintaining the Tesla battery charge at the set level of 214.6 Ah, ensuring the same battery size and increasing the capacity of the unit cells, it is possible to implement the battery when it consists of 4 modules, each of which will have 24 series links with 10 parallel elements 4680, i.e., $n_1 = 10$; $m_1 = 24$; $m = 4$; 100 V; 214.6 Ah, where $n_1$ is the number of elementary cells connected in parallel in one circuit of the module; $m_1$ is the number of circuits in the module; and m is the number of modules connected in series in the battery. This design will not significantly reduce the capacity of the battery when degrading individual cells in parallel circuits of modules compared to the design of the Leaf battery.

The degree of degradation of the Tesla battery is much less than that of the Leaf battery due to the larger number of cells and parallel circuits. Moreover, for Tesla batteries with 18650 cells, the number of parallel circuits is excessive, so the transition to new cells with a higher capacity does not actually reduce the degree of battery degradation in the event of a failure of one of them.

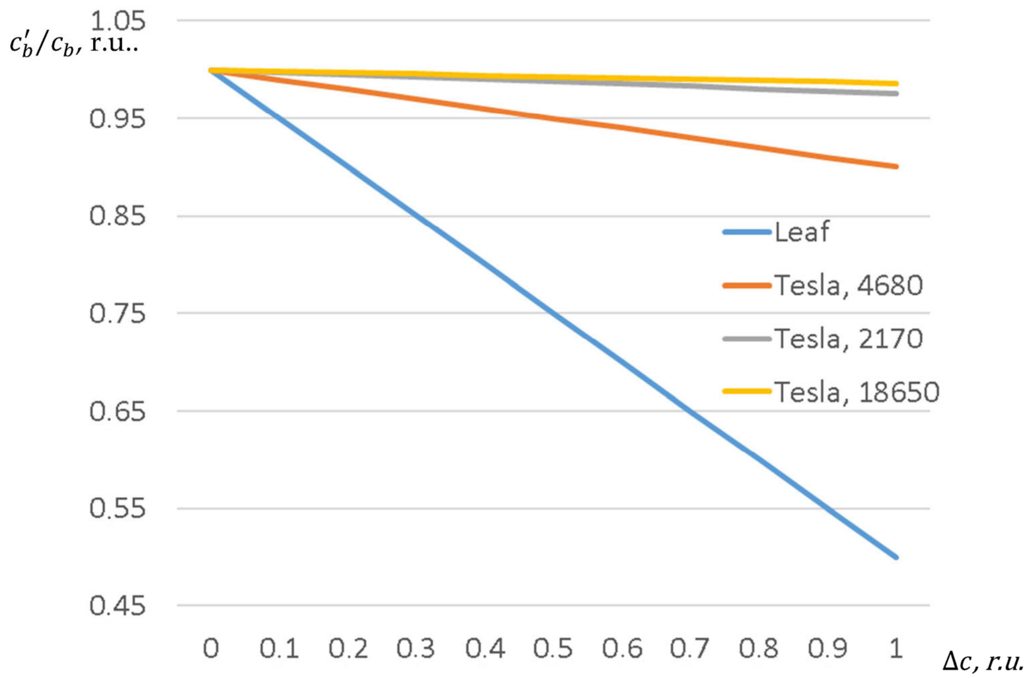


**Figure 7.** Dependence $c'_b/c_b$ as a function of $\Delta c$ for different cell types of Tesla and Nissan Leaf batteries.

## 4. Conclusions

Energy storage solutions are the biggest denomination of the real estate market today, for which the energy transition is just beginning. The best practices of zero-emission technologies should be the benchmark for rapid change in the real estate market. The transformation of the automotive market is a good example that this can be achieved in other markets. It is important that, with these types of solutions, we consider not only economic viability but also environmental and social viability [26].

The rational construction of an electric vehicle (EV) battery involves carefully designing and engineering the battery to meet specific performance, safety, and cost requirements. The construction of such batteries involves collaboration among materials scientists, chemical engineers, electrical engineers, and other experts in battery technology. The development of new materials and the refinement of existing ones play a crucial role in continually improving EV battery performance and safety.

The field of battery technology is constantly evolving, and new breakthroughs and discoveries may shape the perspective on lithium-ion batteries and other battery technologies in the future. In this study, a method of choosing a rational number of parallel–serial connections of lithium-ion cells to preserve residual capacity during battery degradation is proposed.

Analysis of the design of different types of batteries with a small and significant number of parallel connections of lithium-ion elements of the battery of the electric vehicle showed that increasing the number of parallel connections leads to a more reliable operation of the battery in case of failure or degradation [27].

During the study, it was found that a significant increase in parallel cells in the battery module circuit does not significantly preserve the residual capacity during battery degradation. With a simultaneous and uniform degradation of battery cells, the number of parallel cells in the module circuit should not exceed 20 units.

It has been established that depending on the change in the power of the electric vehicle, the voltage, and current parameters of the lithium-ion cells, it is possible to design batteries by selecting the rational number of parallel–series connections between the battery module elements and the modules themselves.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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