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Formula Student class electric vehicle energy storage – study and design assumptions

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The goal of this article is to present the design assumptions of an energy storage for a Formula Student electric car equipped with one electric motor. The correct selection of the parameters of the energy storage is dictated by the regulations applicable to all cars competing in this class, especially the maximum battery power. The growing interest in electric cars visible on the passenger car market is also reflected in motorsport, where are created new competitions or classes specifically for BEV. In addition, the work contains a definition of BEVs, types of cells used in electric vehicle batteries, and a brief description of Formula Student. The study presents a description of the requirements contained in the competition regulations regarding the energy storage in the Formula Student vehicle, an overview of the cells that can be used in the battery, and the selection of the most optimal among several solutions. Based on specific requirements, the arrangement of cells inside the battery was designed, divided into smaller segments and their connection, and placed in a safe housing in the form of a container.

Key words: *energy storage, BEV, Formula Student*

1. Introduction

Formula student is a competition category intended for university students from around the world. Each team taking part in the competitions has to build its own vehicle in accordance with the competition regulations [8, 14, 15]. The number of teams starting to build vehicles powered by electric engines increases every year [4, 22]. This is due to the prevailing trend of promoting electromobility. Electric motors are also more efficient than combustion engines. The tank to wheel efficiency for electric cars is 65–82%, and for cars equipped with combustion engines – 19–25% [12]. Electric cars do not emit exhaust gases, so they are considered ecological vehicles [1, 9–11, 23]. Analysing data on vehicle sales, one can notice an annual increase in the number of registered new BEV cars [16, 17, 19, 20].

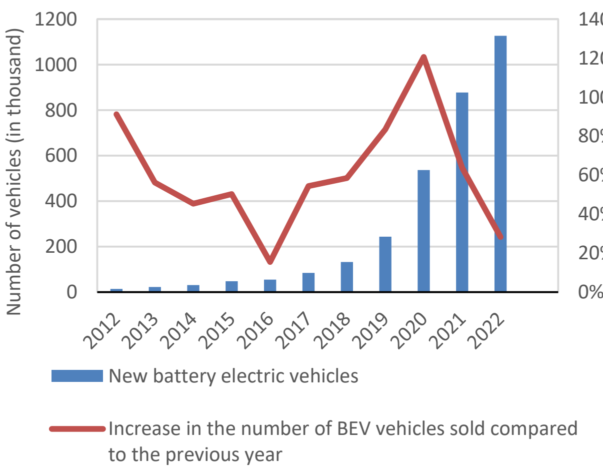

Fig. 1. New electric vehicles sold in Europe in 2012-2022 [21]

Figure 1 shows this situation in Europe. Many global car manufacturers are declaring a significant increase in the sales of BEV cars and phasing out combustion vehicles from their offer in the coming years [6,20]. According to forecasts, in 2035 more than half of new passenger cars sold worldwide will be BEVs, and in 2040 the share of these vehicles in total sales should be almost 2/3 [2]. Due to the growing interest in electric vehicles, special racing classes for these vehicles are also being created. The most famous are eTouring Car World Cup (ETCR) and Formula E. Considering the current and forecasted future of motor vehicles presented above, both on the market and in sport, it is highly probable that in the future, people with significant knowledge and experience in the field of building electric vehicles will be in high demand on the labour market. One of the goals of the Student Formula is also to develop knowledge in the field of motor vehicle construction. Being aware of this goal and the situation regarding the future of motor vehicles presented above, the increase in the number of teams building electric cars is fully understandable [8].

The main assumption when designing an electric car is to achieve the lowest possible weight of the vehicle while ensuring a range sufficient to complete the Endurance event, which involves driving twice on a closed track for approximately 11 km with one stop during which the driver is changed. The Endurance course must not have straights longer than 80 meters, continuous turns with a diameter of more than 50 meters, or sharp turns with an external diameter of less than 9 meters. In addition, the route may include slaloms with gaps between posts of 9 to 15 meters, chicanes or turns with variable radius, and the minimum track width cannot be less than 3 meters [3, 14]. This means that Formula Student vehicles perform many short accelerations, which place a significant load on the drive system and high energy demand. For this reason, it is common to equip vehicles with a braking energy recovery system. This increases the vehicle's range by charging during braking without increasing the size of the battery [7]. According to the Formula Student regulations, each car must ensure maximum safety, so when designing electric vehicles, in addition to passive safety, which is to protect the driver during a collision, the risk of fire in electrical components and electric shock to the driver or people around the vehicle should be minimized. Each vehicle must undergo a mandatory technical inspection before being allowed to participate in dynamic events. The technical inspection includes a thorough inspection of the entire electrical installation of the vehicle. It involves a thorough comparison of the elements of the vehicle's electrical installation with the requirements of the regulations by visual inspection and, in case of doubt, conducting an interview with team members regarding the materials used and their certification. Another important part of the inspection is a rain test, which aims to check the insulation of the electrical installation from water. It involves simulating rain falling on the vehicle for 2 minutes and then assessing the operation of the installation [3, 4].

2. Methodology

2.1. Regulatory requirements for an electric vehicle

The Formula Student regulations require that the power of the tractive system does not exceed 80 kW and the maximum voltage in the system does not exceed 600 V (excluding control signals of engine controllers and inverter/power processing unit). It is permitted to install engines both inside the vehicle (with half-axles transmitting torque to the wheels) and in the wheels (transmitting torque to the wheels directly or via a single-stage gearbox).

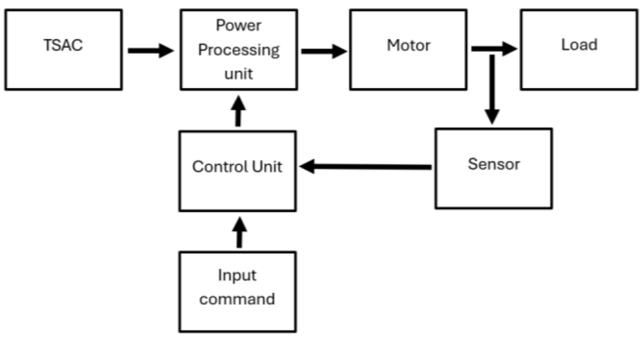

Fig. 2. Block diagram of a tractive system

In the case of traction system energy storage (TSES), the maximum voltage of a single segment must not exceed 120 V DC, 6 MJ of energy, and 12 kg of mass.

The bottom of the housing can be made of steel with a minimum thickness of 1.25 mm or aluminum with a minimum thickness of 3.2 mm, while the thickness of the external and internal walls is 0.9 mm for steel and 2.3 mm for aluminum, respectively. The height of internal walls cannot be less than 75% of the height of external walls. Walls cannot divide single energy storage segments, and all connections must be welded, glued or screwed [3, 4].

2.2. Selection and optimization of energy storage parameters

When designing an energy storage, the energy demand should be taken into account to ensure that there is no shortage of energy during competitions and at the same time to minimize the size and weight of the energy storage. It was assumed that the engine should not have a higher rated power than that permitted in the regulations, i.e. 80 kW. The EMRAX 228 engine in the Low Voltage specification was selected for the project, requiring a power supply of 160 V and 450 A [13]. Its technical parameter are presented in Table 1. Figure 3 shows the external characteristics of the motor, and its efficiency map is shown in Fig. 4.

Table 1. Selected parameters of the EMRAX 228 Low Voltage engine [13]

Parameter	Unit	Value
Weight	kg	12
Diameter/width	mm	228/86
Maximal battery voltage	Vdc	160
Peak motor power at max load rpm	kW	109
Continuous motor power	kW	50
Maximal rotation speed	rpm	5500
Peak motor current	A	900
Continuous motor current	A	450
Maximal motor torque	Nm	230
Continuous motor torque	Nm	96
Torque/motor current	Nm/1Aph rms	0.27
Motor efficiency	%	86–96

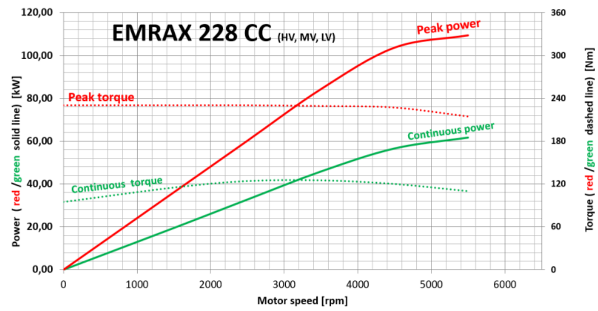

Fig. 3. External characteristics of the EMRAX 228 motor [13]

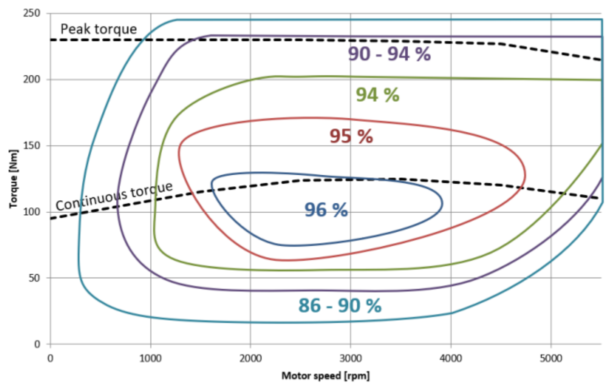

Fig. 4. Efficiency map of the EMRAX 228 motor [13]

After selecting the engine, a review of cells available on the market was carried out, from which 13 models were selected and compared. They has been shown in Table 2.

Table 2. Selected cells and their parameters [4]

Type	Cell	Nominal voltage	Capacity	Continuous discharge	Weight	Dimensions
		V	mAh	A	g	mm
Li-ion	ANR26650M1b	3.30	2500.00	50.00	76.00	ϕ26.00 × 68.00
	UR18650NSX	3.60	2600.00	20.00	45.80	ϕ18.30 × 64.85
	INR18650-25R	3.60	2500.00	20.00	45.00	ϕ18.40 × 65.00
	INR21700-30T	3.60	3000.00	35.00	69.00	ϕ21.22 × 70.30
	INR18650-33G	3.60	3150.00	6.50	48.00	ϕ18.40 × 65.20
	INR21700-50E	3.63	5000.00	9.80	69.50	ϕ21.10 × 70.15
	VTC5A	3.60	2600.00	35.00	44.00	ϕ18.35 × 65.20
	VTC6	3.60	3130.00	30.00	46.50	ϕ18.50 × 65.20
	MB18650	3.70	2600.00	3.90	45.00	ϕ18.50 × 65.50
LiPo	LP7843128	3.70	5000.00	5.00	98.50	43.00 × 7.80 × 127.50
	SLPB9395183	3.70	22000.00	110.00	358.00	94.00 × 9.00 × 182.50
$LiFePO_4$	LFP8167100	3.20	4100.00	82.00	100.00	67.00 × 7.70 × 100.00
	MB-IFR26650	3.20	3800.00	11.40	92.00	ϕ26.20 × 65.20

3. Results discussion

3.1. Selection of cells for the considered energy storage

The most important parameters of cells are their energy and power mass densities, which determine the amount of energy and power per unit of mass. Higher density values allow more energy and power to be stored in the battery at the lowest possible weight. As the weight increases, the performance and range deteriorate, which is crucial in the case of BEVs, which is why these parameters are so important. Equally important parameters include power and energy volume densities, i.e. the amount of power and energy per unit of volume. Formula Student vehicles have a very limited space to use, and any attempts to adapt the structure to accommodate a larger energy storage unit may significantly increase the weight. Also, a battery with the required capacity but too low volumetric density may increase the size of the vehicle beyond the permitted limits specified in the regulations.

To determine the power and energy density values, the power and energy values of each cell must be calculated. Power (P_d) is the product of the nominal voltage (U_N) and the maximum current (I_{dmax}) of the cell [18]:

$$P_d = U_N \cdot I_{dmax} \quad (1)$$

The cell energy (E) is the product of the nominal voltage (U_N) and the cell capacity (C_d) [18]:

$$E = U_N \cdot C_d \quad (2)$$

Table 3. Power and energy values of selected cells

Type	Cell	Cell power	Cell energy
		W	Wh
Li-ion	ANR26650M1b	165.00	8.25
	UR18650NSX	72.00	9.36
	INR18650-25R	72.00	9.00
	INR21700-30T	126.00	10.80
	INR18650-33G	23.40	11.34
	INR21700-50E	35.57	18.15
	VTC5A	126.00	9.36
	VTC6	108.00	11.27
	MB18650	14.43	9.62
LiPo	LP7843128	18.50	18.50
	SLPB9395183	407.00	81.40
$LiFePO_4$	LFP8167100	262.40	13.12
	MB-IFR26650	36.48	12.16

The determined power and energy values of each cell are presented in Table 3.

Referring to the PN-EN IEC 62660-1:2019. standard, and having the calculated power and energy values, it is possible to calculate the volume and mass densities of energy and power. the ratio of a cell's power (P_d) expressed in watts to its mass (m) in kilograms is called power mass density (ρ_{pd}) [18]:

$$\rho_{pd} = \frac{P_d}{m} \quad (3)$$

Energy mass density (ρ_{ed}) is the ratio of the cell's energy (E) expressed in watt-hours to its mass (m) in kilograms [18]:

$$\rho_{ed} = \frac{E}{m} \quad (4)$$

The ratio of a cell's power (P_d) to its volume (V) is called power volume density (ρ_{pvlm}) [18]:

$$\rho_{pvlm} = \frac{P_d}{V} \quad (5)$$

The value of bulk energy density (ρ_{evlmd}) is calculated by dividing the energy of the cell (E) by its volume (V) [18]:

$$\rho_{evlmd} = \frac{E}{V} \quad (6)$$

The values of mass and volume power and energy densities for each cell are presented in Fig. 5–8.

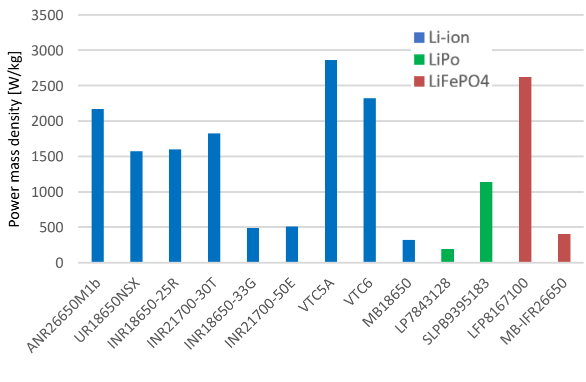

Fig. 5. Power mass density of selected cells

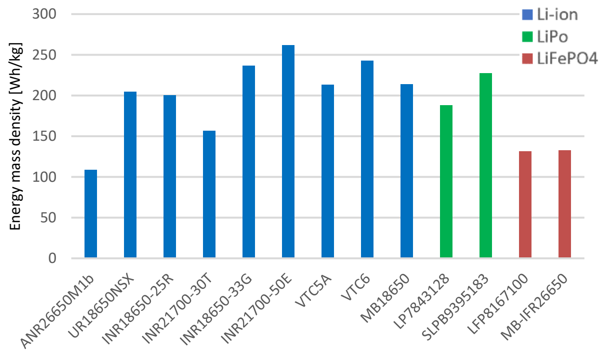

Fig. 6. Energy mass density of selected cells

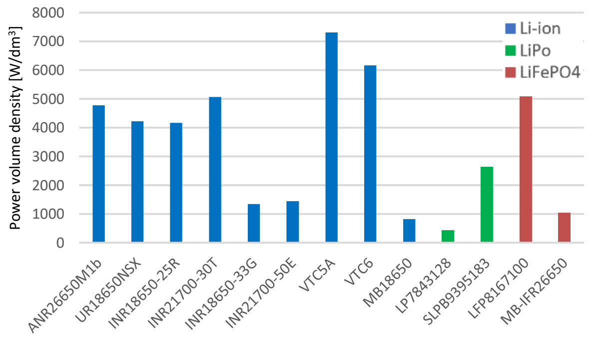

Fig. 7. Power volume density of selected cells

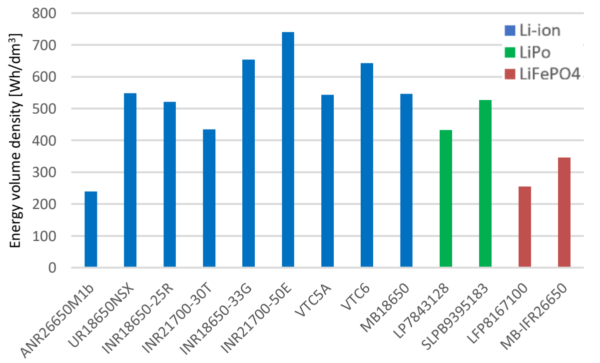

Fig. 8. Energy volume density of selected cells

There are huge differences in the considered densities. The biggest differences is in power volume density (Fig. 7): the best cell, VTC5A, has nearly 17 times more power volume density than LP7843128. Energy densities does not have such a big discrepancy, but even in energy volume density (Fig. 8) the difference between the best cell (INR21700-50E) and the worse one (ANR26650M1b) is 3 times. As it was said before, the best cells for power a vehicle should have the highest values of power and energy density, both volume and mass. To choose the best ones their power and energy densities were included in one graph for mass and one for volume. It shows the cells with the highest total density values, thanks to which it is possible to select the most efficient cells from among the tested (Fig. 9, 10).

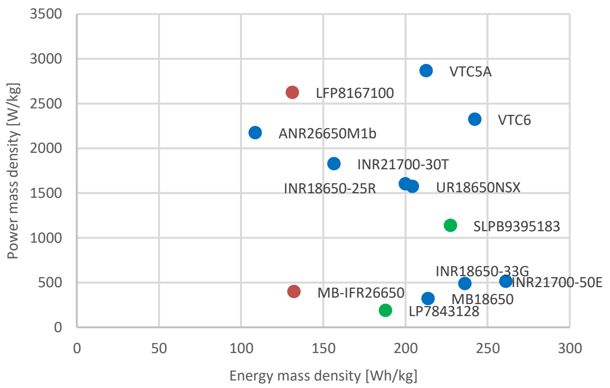

Fig. 9. Power mass densities of selected cells depend on energy mass density

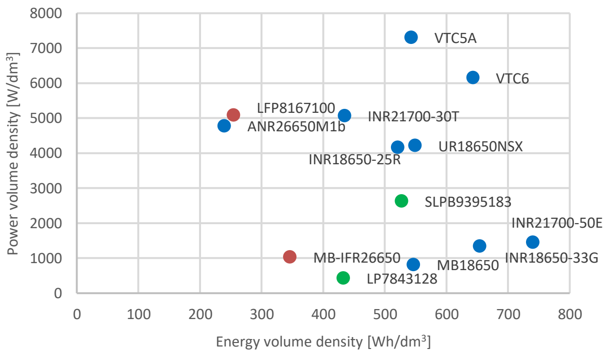

Fig. 10. Power volume densities of selected cells depend on energy volume density

After analyzing the obtained data, it can be seen that the overall best parameters among those considered are achieved by VTC5A and VTC6 cells. Moreover, some cells have very low energy density values. In order to illustrate the differences between cells in their use in the construction of energy storage to power the considered engine, the amount necessary to obtain voltage and current was calculated for each type and their masses were calculated (Table 4).

Table 4. Minimum quantities of selected cells, their total minimum capacities and masses to obtain appropriate parameters for operation with the EMRAX 228 engine in the Low Voltage version

Type	Cell	Minimum amount of cells	Minimum cells capacity	Minimum cell weight
			Ah	kg
Li-ion	ANR26650M1b	436	1090.91	33.16
	UR18650NSX	1000	2600.00	45.80
	INR18650-25R	1000	2500.00	45.00
	INR21700-30T	571	1714.29	39.43
	INR18650-33G	3077	9692.31	147.69
	INR21700-50E	2024	10119.75	140.66
	VTC5A	571	1485.71	25.14
	VTC6	667	2086.67	31.00
	MB18650	4990	12972.97	224.53
LiPo	LP7843128	3892	19459.46	383.35
	SLPB9395183	177	3891.89	63.33
$LiFePO_4$	LFP8167100	274	1125.00	27.44
	MB-IFR26650	1974	7500.00	181.58

Based on the study presented in Table 4, VTC6 cells were selected. Despite the 23% greater weight of the battery consisting of these cells for both variants of the engine in question compared to the lightest set consisting of VTC5A cells, the energy storage has a 40% larger capacity. In order to obtain the same capacity from VTC5A cells as we can obtain with the minimum demand for VTC6 cells, the weight of VTC5A cells would be 14% greater. An example of VTC6 cell is shown in Fig. 11.

Fig. 11. VTC6 cell used

To build the energy storage needed for the vehicle in question, 667 cells would be enough. Nevertheless, it was assumed that approximately 1000 cells would be used to increase the durability and capacity of the entire battery by limiting the maximum current drawn from a single cell, and therefore the cell load. As a result, the phenomenon of cells heating during operation will be reduced. For this reason, the cooling system will not have to achieve high efficiency, which will make it simpler. In addition, a larger number of cells increases the capacity of the energy storage, resulting in a greater range of the vehicle.

The energy storage must consist of smaller sections (so-called packages), with a weight not exceeding 12 kg, a voltage of 120 V and an energy of 6 MJ (point EV 5.3.2 of the regulations). The minimum number of sections used for 1000 VTC6 cells is 9. It was assumed that all packages, both in terms of construction (arrangement of cells inside) and connection, are to be the same. After careful analysis, it was decided to use 990 cells in the 45S22P (45 in series, 22 in parallel) configuration. Each package has an internal 5S22P (5 in series, 22 in parallel) configuration, and all sections are connected in series (Fig. 12). As a result, 162 V and less than 450 A were obtained while limiting the maximum current consumption from a single cell to 20 A. This connection system ensures the appropriate parameters to power the EMRAX 228 engine in the Low Voltage version, while ensuring the maximum battery power below the statutory 80 kW.

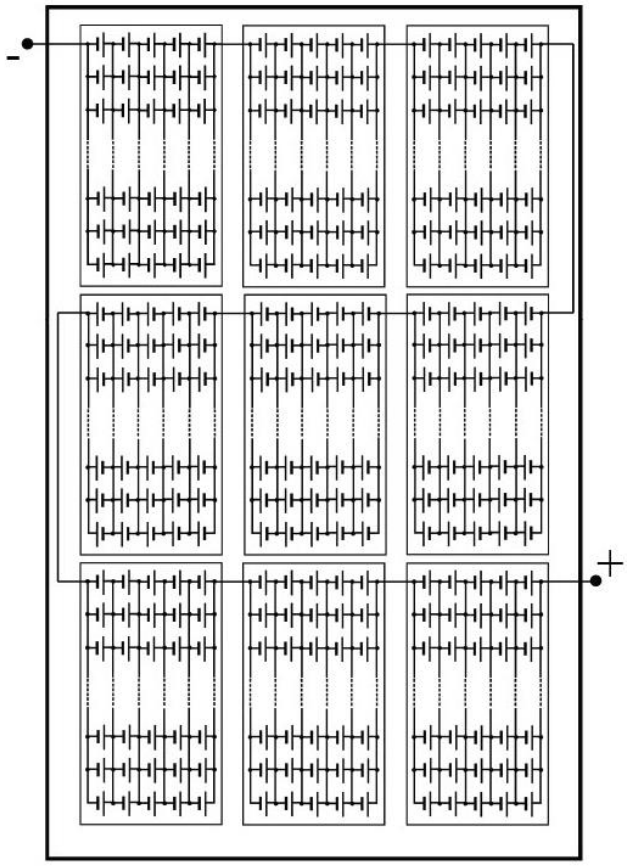

Fig. 12. Diagram of the cell system in an energy storage

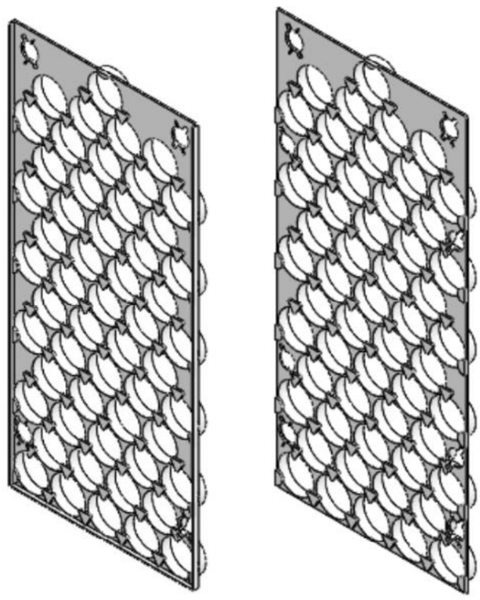

Fig. 13. Cell holder models

Knowing the configuration of individual sections and the entire energy storage, the exact arrangement of cells was determined in such a way as to make the best use of the space inside the vehicle frame and to reduce the vehicle's center of gravity as much as possible. For this purpose, the energy storage should occupy the largest possible area and at the same time, the lowest possible height. It was calculated that it would be most convenient to arrange 3 packages in width and 3 in length. Each section consists of two identical parts, each of which has 55 links arranged longitudinally to the direction of travel, creating a pattern similar to a honeycomb. These elements are shown in Fig. 13. The cells were mounted in holders designed specifically for the energy storage in question and made using 3D printing technology. It was decided to make two types of handles: external and internal, intended to connect two parts of the package. The difference is the use of additional holes in the internal handles, enabling them to be connected both to each other and to external handles.

To ensure connections between the handles, special connectors were designed, which were also made using 3D printing (Fig. 14).

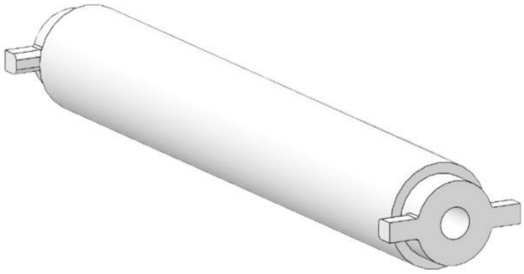

Fig. 14. Cell holder connectors models

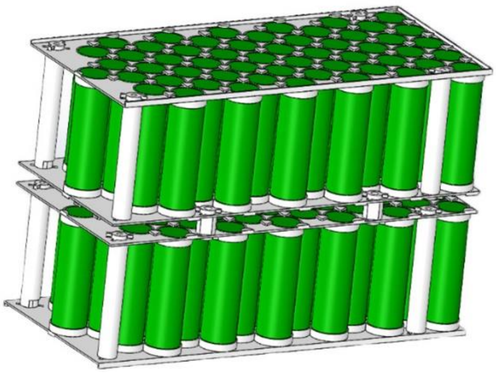

Fig. 15. One pack of energy storage model

3.2. Energy storage casing model

According to the regulations, the energy storage casing should provide protection against both mechanical damage and weather conditions. Materials that can be made include composite materials, steel or aluminum. When creating a metal casing, minimum sheet thicknesses should be considered, and adequate electrical insulation should be ensured. Additionally, walls should be made of the same material as the housing, and an insulating layer should be used between the packages.

Due to the prices of materials, their availability and the possibilities of their processing, it was decided to make the housing from steel. According to the regulations, the thickness of the steel sheet from which the floor is to be made cannot be thinner than 1.25 mm, and the side walls and interior partition walls – 0.9 mm. In order to achieve the lowest possible weight of the energy storage unit, it was decided to make the casing from the thinnest allowed sheet metal, as a box with a put-on cover. To ensure electrical insulation between the packs and the housing, it was decided to separate each of them from the housing with a 1 mm thick layer of fiberglass. The casing may contain only the necessary openings, which include holes for cable outlets, intended for mounting the energy storage device to the vehicle, and holes for ventilation. In the case of the latter, the regulations require that the driver should not be able to see them, even after dismantling the fire shield. Taking into account the small width of the energy store and its location directly behind the driver's back, the ventilation holes can only be located on the rear wall of the housing. A possible solution would be to design additional channels to supply air inside the energy storage, e.g. from the side sections. Due to the very small amount of space, this would result in significant complexity of the structure and the likelihood of shifting the energy storage towards the rear axle, increasing the already high load on this axle, which could worsen the traction properties of the vehicle. Figures 16 and 17 presents the storage casing.

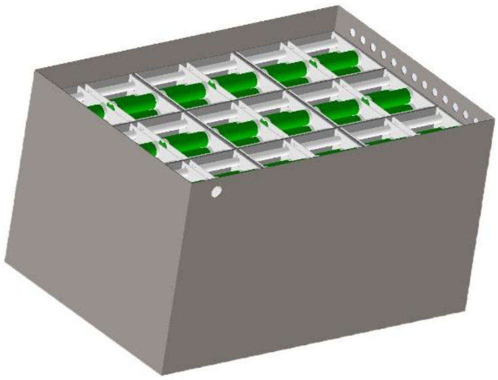

Fig. 16. Open storage casing

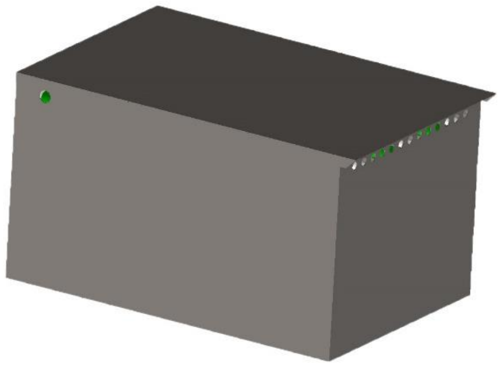

Fig. 17. Storage case with cover

3.3. Verification of TSAC

The battery test is scheduled after the vehicle is completed. The test involves uniformly loading the battery by accelerating the vehicle on a chassis dynamometer to a specified speed and maintaining a constant speed for a specified period of time. During the test, the cell voltage, resistance and temperature will be constantly monitored. At the end of the test, the results obtained will be compared with the results of calculations performed before the test. This will allow you to assess the actual condition and parameters of the battery in relation to theoretical values. Figure 18 shows the study flowchart.

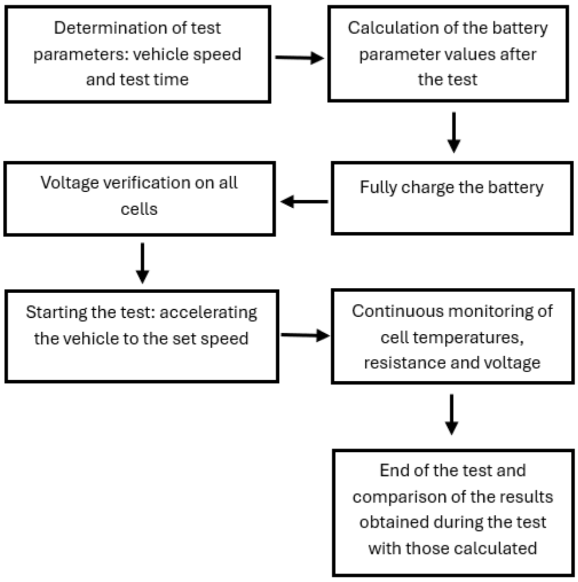

Fig. 18. Battery test flowchart

4.Conclusions

VTC6 cells were selected for the construction of the energy storage facility, which are characterized by high energy and power densities, which translates into high parameters with minimal weight and volume, and a very low cell mass necessary to ensure appropriate power parameters for the selected engine. In order to increase the capacity and reduce the load on the cells, 990 cells were used, which were divided into 9 sections (packs). The cells inside each pack were connected in a 5S22P (5 in series, 22 in parallel) configuration, and all packs were connected in series to each other. This resulted in a 45S22P (45 in series, 22 in parallel) energy storage configuration, a voltage of 162 V and a current close to 450 A while limiting the maximum current from a single cell to 20 A. The cells inside the packs are arranged in a honeycomb structure, thanks to which the volume of each package and the entire energy storage is as small as possible. The energy storage casing is made of steel with a floor thickness of 1.25 mm and walls and cover with a thickness of 0.9 mm. The ventilation holes are located on the back wall of the housing, just below the edge of the cover. Each package was insulated from the floor and walls of the energy warehouse with 1 mm thick glass fiber.

Nomenclature

BEV	battery electric vehicle
C_d	cell capacity
E	cell energy
ETCR	etouring car world cup
I_{dmax}	maximal current
m	cell weight
P_d	cell power
TSES	traction system energy storage
U_N	nominal cell voltage
V	cell volume
ρ_{ed}	energy mass density
ρ_{pd}	power mass density
ρ_{pvlm}	power volume density
ρ_{evlmd}	energy volume density

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