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A comparative study of different battery geometries used in electric vehicles

Diego Nieto Hummes[1], Julian David Hunt[1,2,*], Bruno Barcellos Hervé[1], Paulo Smith Schneider[1], Pedro Marin Montanari[1]

[1] Federal University of Rio Grande do Sul, Brazil
[2] International Institute for Applied Systems Analysis (IIASA), Austria
* Corresponding author, E-mail: hunt@iiasa.ac.at

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Abstract: This paper contributes with a review of current and future electric vehicle battery geometries, as there are few comparisons regarding performance criteria in the literature. With these considerations, this paper seeks to fill this gap by comparing commercial batteries with different geometries. First, the specifications of each battery (found on manufacturers' websites or in specialized media) are presented. Then, the battery evaluation criteria are defined considering two distinct applications: economy and performance cars, using the Multi-Attribute Utility Theory (MAUT) method. From that analysis, the blade battery presented the best overall performance with a good rating for both applications. The cylindrical geometry followed with a rating suited better for performance vehicles, and the pouch geometry followed showing promise for use in economy-driven vehicles mostly. Lastly, a case study is carried out by evaluating the application of each of the batteries in a commercial vehicle. It was found that when compared to new technologies, the potential for improvement on any of the studied criteria is enormous. In particular, the Licerion pouch battery (Sion) showed the best performance regarding range and capacity-to-weight ratio, while the 4680 cylindrical battery (Panasonic) and blade battery (BYD) were superior in capacity-to-volume and capacity-to-cost ratios, respectively.
Keywords: Multi-Attribute Utility Theory, Battery geometry, Electric vehicle, Case study, Performance criteria

1 Introduction

Due to the need to reduce CO2 emissions (Coelho, Meneguelo and Chaves, 2022; Viana and Asencios, 2022), there is a growing interest from automobile manufacturers in alternative technologies to internal combustion engines, such as hybrid power systems (Croce et al., 2020) or the use of bio and alternative fuels (Simões, Romeiro and Kurita, 2021; De Araujo et al., 2022). The highest investment, though, seems to be in electric vehicles (Kester et al., 2020; Skjølsvold and Ryghaug, 2020). Areas benefiting from these investments are, for example, the use of batteries as a structural component (Dionisi, Harnden and Zenkert, 2017; Carlstedt and Asp, 2020) and the development of new materials (Yang et al., 2020; Mahmud et al., 2022). The focus, however, remains on improving the current technology of lithium batteries, which have good performance and great commercial potential (Liu et al., 2017; Hamed et al., 2022). The more traditional cylindrical and prismatic cells share space with some recently developed geometries available in the current market (such as pouch cells and blade batteries) and others still in an experimental phase (such as structural batteries). Despite the growing number of available battery configurations, no standard or legislation currently influences the geometry to be used (Sankaran and Venkatesan, 2021).

Determining the ideal battery geometry for a given application is pivotal for project optimization. The reasons for a manufacturer choosing between one type of geometry or the other are closely associated with the advantages and disadvantages related to the system in question, evaluating parameters such as costs and performance. However, their motivations are often locked behind commercial confidentiality. That is advantageous from a business standpoint, but it fragments battery geometry knowledge found in the literature. Studies in the field seek to investigate the performance of each geometry concerning mechanical and thermal aspects, for example Avdeev and Gilaki (2014) and Dionisi, Harnden and Zenkert (2017).

However, it is noticeable the absence of studies that aim to compare different battery geometries concerning financial and operational impacts (vehicle weight, range, available volume, among others) that each choice may entail. Also, it is rare to find papers that evaluate case studies with vehicles and batteries available in the market, which hinders a practical analysis of results for commercial decision-making in the choice of battery geometry. For this reason, the research conducted in the present study becomes of great interest, comparing commercial batteries among themselves to fill these aforementioned gaps for electric vehicle projects. In addition, the relevance of this paper is strengthened by the fact that the most common and promising battery geometries are studied - cylindrical, prismatic, pouch, blade, and structural. A case study was conducted to evaluate how each battery would perform in the Tesla Model Y Long Range Dual Motor car - which was chosen as the benchmark due to being, in 2022, the best-selling electric vehicle in the world (Q3 2022 Kelley Blue Book - Electrified Vehicle Sales Report, 2022). It is also important to note that due to the high level of innovation of the technologies mentioned, there is a need to cite technical reports and technology reviews outside the scope of academic literature.

Finally, as this paper focuses on comparing different battery geometries, it is not in the scope to consider battery performance with respect to current cathode and anode materials, as such studies have already been carried out in the literature (Fotouhi et al., 2016; Li, Khajepour and Song, 2019). Consequently, future trends for battery material development remain to be studied in further work. Studies involving this topic are also already available in the literature (Simon, Ziemann and Weil, 2015; Burd et al., 2021) but, as shown by Mauler et al. (2021), the current state of development is so fast that accurate predictions about EV battery materials are hard to make.

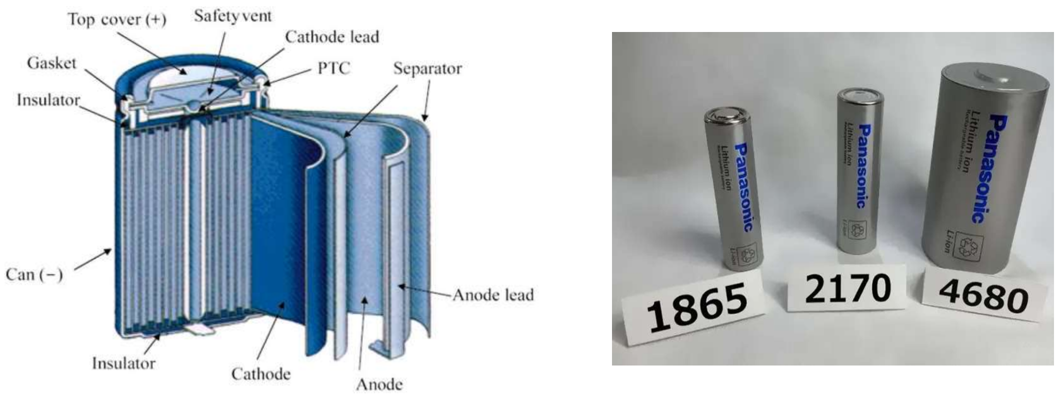
This paper is divided into five sections. Section 1 presents the motivation and an introduction to the battery geometries studied in this work. Section 2 presents the analysis methodology used for battery comparison. Section 3 develops the decision analysis process by defining objectives to be achieved, criteria to be considered, and presenting performance results of each battery shape. Section 4 concludes by evaluating the results obtained and summarizing the performance of each battery shape. Section 5 presents the references used. Throughout this paper the following physical units are used: Watt-hour [Wh], Liter [L], kilogram [kg], kilometer [km], Ampere-hour [Ah], kilowatt [kW] and kilowatt-hour [kWh]. The monetary cost unit is the dollar [$].

1.1 Technology description

As pointed out by Warner (2014; 2015), the most common battery type for any application overall is cylindrical, although prismatic and pouch are estimated to ramp up their participation in the market. Considering EVs over the last decade - there seemed to be a prevalence of pouch battery cells. The Nissan Leaf EV, the Ford Focus EV, and the Chevrolet Volt used pouch cells, while the Mitsubishi i-MIEV used prismatic cells, for example. The main characteristics of current and upcoming battery cell shapes are described in the following subsections.

1.1.1 Cylindrical cell

Cylindrical cells are analogous to household batteries and composed of layers of cathodes and anodes rolled into a cylindrical shape, as can be seen in Figures 1 (a) and (b).



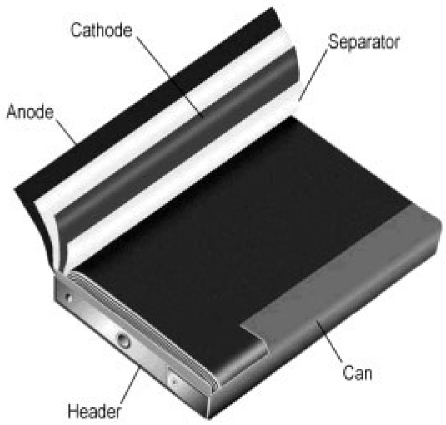
(a) (b)

Figure 1. (a) Structure of a cylindrical cell (Bankole, Gong and Lei, 2013), (b) examples of cylindrical cells produced by Panasonic and used in electric vehicles (Borrás, 2021).

Cylindrical cells are relatively easy and inexpensive to manufacture (Liu et al., 2017). In addition, as shown by Sahraei, Hill and Wierzbicki (2012), they have good structural integrity, which is higher and consistent in all directions when compared to the prismatic and pouch cell geometries, which have high strength towards the direction of compression in thickness but low strength in others. Regarding thermal integrity, as noted by Park et al. (2020), this battery shape has more variation in properties when compared to the pouch cell, with temperature gradients having a greater impact on charging and discharging power. Furthermore, their thermal gradients should be taken into account when designing the battery pack and thermal management system (Jeon and Baek, 2011; Saw, Ye and Tay, 2013). As indicated by Das et al. (2018), cylindrical cells have good thermal management capabilities due to their small size. As indicated by Warner (2015), compared to prismatic or pouch cells, they tend to have a higher rate of heat generation, and it makes more sense to use air cooling, which is not the most efficient cooling method. Still, this is a minor disadvantage because, as these cells are small, the heat generation tends to be easily manageable. In addition, as shown by Cai (2016), differently from prismatic and pouch cells, the manufacturing of cylindrical cells permits the use of safety features such as positive temperature coefficients (PTC) and current interrupt devices (CID) to be integrated. That makes cylindrical batteries more secure in the event of overheating, for example. A company that uses this battery geometry in its vehicles is Tesla.

1.1.2 Prismatic cell

Prismatic cells, represented by Figures 2 (a) and (b), are composed of electrolytes arranged in foils covered usually with aluminum or steel.



(a)

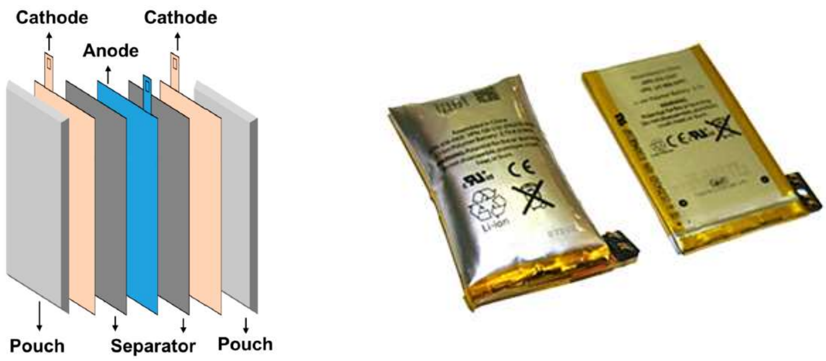
(b)

Figure 2. (a) Schematics of a prismatic cell (Battery University, 2010), (b) a commercial prismatic cell (Samsung SDI, 2022).

Regarding the mechanical integrity aspect, as observed by Xing et al. (2021), it is highly direction-dependent (different from cylindrical cells, for example) - which is undesirable from the structural point of view. They tend to present higher energy density but less charge and discharge power when compared to cylindrical batteries. Prismatic cells are usually bigger than cylindrical ones, which means that, in comparison, fewer cells are needed to achieve the same energy content, and fewer electrical connections are necessary, potentially enabling a cheaper battery assembly process. In addition, these batteries continue to show potential for future use as they are considered an excellent format for the lithium-iron-phosphate (LFP) chemistry, a mix of materials currently being heavily researched as it does not employ rare and expensive materials like nickel and cobalt (Laserax, 2022). Examples of companies that use this battery shape in their cars today are Fiat and BMW (Lima, 2021a; Samsung SDI, 2022; Nast, 2020).

1.1.3 Pouch cell

One of the differences between pouch cells and the technologies previously presented is that their casing is not rigid - they are composed of flexible electrolyte pockets wrapped in films that are usually composed of plastic with aluminum. For this reason, this configuration allows the construction of lighter batteries than cylindrical and prismatic. Figure 3 (a) shows an example configuration for pouch cells.



(a) (b)

Figure 3. (a) Structure of a pouch cell (Yoo et al., 2019), (b) swollen pouch cell (left) due to gas generation during battery operation (Epectec, 2021).

Concerning mechanical integrity, because it does not have a rigid casing, the pouch cell does not have high mechanical strength. As demonstrated by Jiang et al. (2021), the effect of cell overlap must be taken into account, as the pressure generated by contact between the cells can lead to both variation in mechanical properties and even events such as shocks that can puncture the pocket and cause accidents.

Concerning thermal integrity, as commented in Section 1.1.1, these battery properties, such as charging and discharging power, are less sensitive to temperature gradients than cylindrical cells, for example. However, their temperature control system is usually more complex, as pouch cells can present swelling caused by gas generation during operation (Epectec, 2021), which is shown in Figure 3 (b). That can be dangerous as the pressure build-up on the inside can crack the battery cover and even other components nearby. Puncturing is also an issue in this case as the escaping gasses may ignite.

1.1.4 Structural battery

The structural battery aims to develop a component that accumulates two functions - structural and energy storage - allowing weight relief and increased system efficiency. Figure 4 shows a representation of this battery shape.

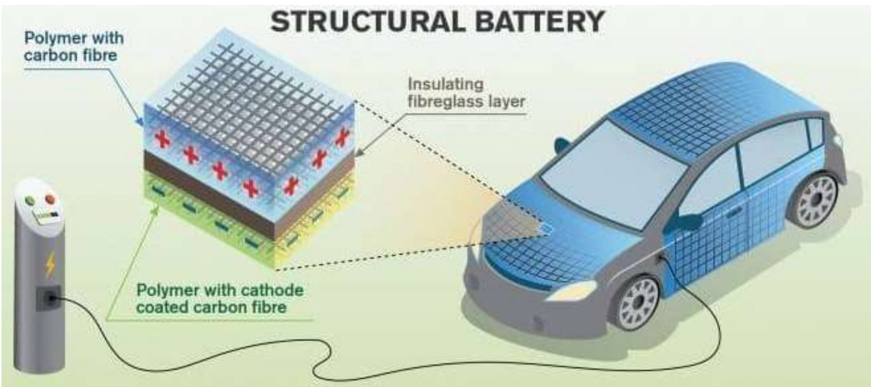


Figure 4. Example of a PFSB (Power Fiber Structural Battery) type structural battery (Nathan, 2018).

The most common structural battery components are composite materials such as Carbon Fiber Reinforced Plastics (CFRP) because of the easy adaptation of mechanical properties. There are three CFRP-based structural battery designs: PSB (Packing Structural Battery), PFSB (Power Fiber Structural Battery), and LSB (Laminate Structural Battery) (Yu et al., 2017).

In the case of PSBs, energy storage is accomplished by positioning lithium-ion batteries next to the CFRP. However, the mass reduction proposed by this method is not as advantageous as the others. In the case of PFSBs, the energy storage comes directly from the fibers, which comprehend both the electrolyte and cathodes. This method tends to have a high cost associated, complex manufacturing, and not much reliability. LSBs, on the other hand, are classic composites, with each component designed with satisfactory structural and electrochemical properties. They can be manufactured like ordinary composites, therefore offering flexibility in terms of geometries and materials. However, recurring problems such as electrical insulation, changing properties due to manufacturing, and incompatibility between materials diminish the performance of this type of design (Dionisi, Harnden and Zenkert, 2017; Carlstedt and Asp, 2020).

1.1.5 Blade battery

The blade battery, as shown in Figure 5, is a recent technology improved on the design of prismatic batteries (FutureCar, 2022, InsideEVs, 2022), having substantial differences such as the lack of modules (Natarajan, 2021, p.202).

Figure 5. Blade battery assembled in CTP (cell-to-pack) format (Natarajan, 2021, p.202).

The estimated cost of the blade battery is very advantageous (around €55/kWh, compared to approximately €85/kWh for a conventional battery today). It is safe - when subjected to benchmark tests, this battery showed no signs of fire or smoke, with surface temperatures reaching 30 to 60°C (Lima, 2021b). In addition, tests conducted in an oven at 300°C and 260% overload also showed no response to fire or smoke. The battery is compact and, due to its arrangement, tends to occupy less volume. Unlike conventional prismatic batteries, which need to be arranged in modules before being fitted to the vehicle, blade batteries dispense modules and are directly assembled to the chassis (cell-to-pack format). That guarantees a better heat exchange capability due to the greater distance between the cells and their greater surface area, as well as eliminating the need for separate thermal management systems for each module (FutureCar, 2022). Regarding longevity, the battery promises 1.2 million km or 3,000 charge/discharge cycles, with a range of 505 km and recharging from 30 to 80% in 30 minutes at 110 kW (Lima, 2021b; Natarajan, 2021). The battery is assembled so that the arrangement of the blades is structural.

2 Methodology

Four main steps were employed in the review of current and future battery geometries, as presented in Figure 6.

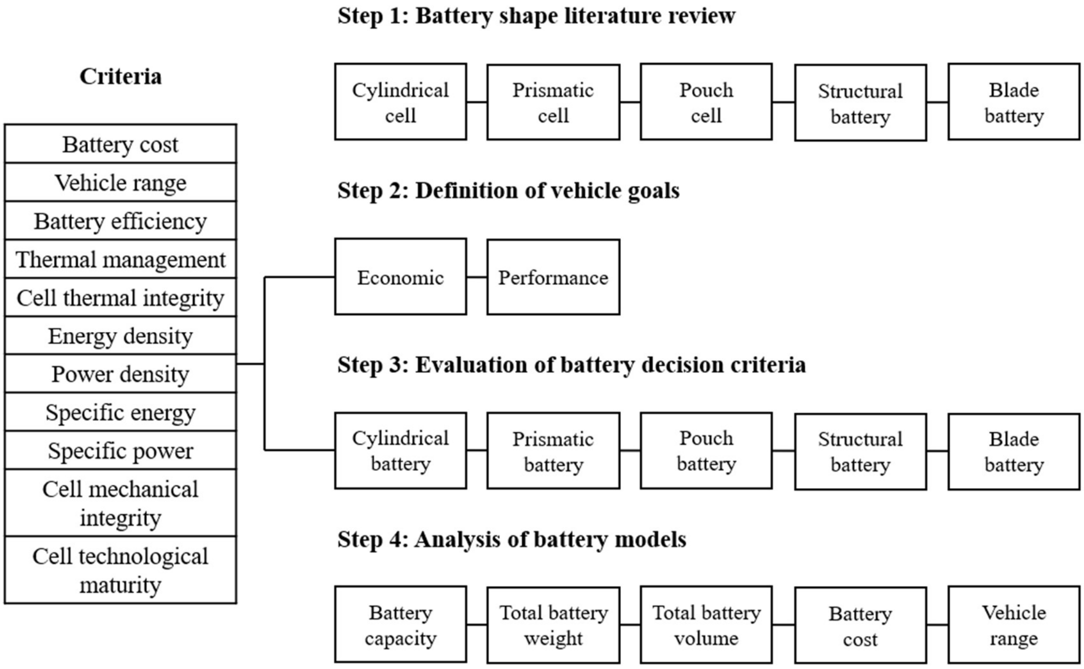


Figure 6. Steps employed in the review process of different battery shapes.

First, the literature was reviewed to understand qualitative and quantitative aspects (such as the operational characteristics) of cylindrical, prismatic, and pouch cells, along with other non-conventional geometries (blade and structural batteries). Subsequently, from the criteria presented in Figure 6, their application in batteries was evaluated for electric vehicles aimed at different applications (economy or performance) using the Multi-Attribute Utility Theory (MAUT). That was the chosen method as this paper looks to provide a more transparent and intuitive decision-making process for the reader, being more direct and straightforward than others such as ELECTRE III and the Analytic Hierarchy Process (AHP), the latter of which has already been used in the context of material research for electric vehicle batteries (Ben Ammar, Hafsa and Hammami, 2013).

Then, based on the characteristics associated with these batteries, a case study was carried out using commercial batteries intended for electric vehicles. For this, data on capacity, weight, and volume of the battery used in Tesla's Model Y Long Range Dual Motor car were compared with the following battery models: the Ultium (GM) and Licerion (Sion) pouch batteries, the 120 Ah prismatic battery (Samsung SDI) and the 4680 cylindrical battery (Panasonic). The data for these four batteries was calculated based on the current Tesla Model Y Long Range Dual Motor car battery specifications to provide a better performance comparison. Regarding costs, the blade battery (BYD) was added to the evaluation, as information regarding this criterion is already available in the literature. The structural battery considered was of solid-state coaxial type previously studied in the literature (Danzi, Camanho and Braga, 2021).

Since the assembly of the blade and structural batteries differs from the other batteries investigated in this paper, which are assembled in modules, they were not included in the analyses regarding capacity, weight, and volume. Furthermore, it is also important to note that structural batteries, the Licerion pouch cell (Sion), and the 4680 cylindrical cell (Panasonic) are under development and not currently being used in electric vehicles.

Finally, this paper concentrates on a global performance evaluation of the commercial batteries presented. As such, their specifications, which are shown in Tables 1 and 2, were obtained from current or future electric vehicle applications. The investigation of specific details related to battery performance, such as cell arrangement, number of layers, module assembly, and overall pack structure, remains to be carried out in future studies.

Table 1. Cell specifications of each battery investigated in this paper.

Battery	2170	120 Ah cell	Ultium	4680	Licerion	Blade	Structural
Battery cell manufacturer	Panasonic	Samsung SDI	GM	Panasonic	Sion	BYD	University of Porto
Battery cell shape	Cylindrical	Prismatic	Pouch	Cylindrical	Pouch	Blade	Structural
Cathode material	NCA Nickel-Cobalt-Aluminum	NCM Nickel-Cobalt-Manganese	NCMA Nickel-Cobalt-Manganese-Aluminum	NCA Nickel-Cobalt-Aluminum	Nickel-rich*	LFP Lithium Iron Phosphate	Copper foil
Anode material	Graphitic carbon electrode	Graphitic carbon electrode	Solid Lithium-metal	Silicium-based	Ultra-thin Lithium-metal	Graphitic carbon electrode	Aluminum rod
Cell energy density [Wh/L]	732	445	614	902	780	448	56.2
Cell specific energy [Wh/kg]	261	196	272	380	400	166	38.0

The energy density for the 2170 and 4680 cylindrical cells (Panasonic) and the Ultium pouch cell (GM) was calculated based on specifications from Williams (2022) for the first two and Morris (2021) for the latter, according to Eq. (1):

* This battery is compatible with most cathode materials and allows cells to be engineered for needs of specific applications (Sion Power, 2022).

$$u_d = \frac{V_{nominal} \cdot C_{nominal}}{v}. \qquad (1)$$

Where u_d: cell energy density [Wh/L]; $V_{nominal}$: nominal cell voltage [V]; $C_{nominal}$: nominal cell capacity [Ah]; v: cell volume [L].

Table 2. Battery specifications of each model investigated in this paper.

Battery	2170	120 Ah cell	Ultium	4680	Licerion	Blade
Vehicle model	Model Y Long Range	500e	GMC Hummer	-	-	Han
Vehicle manufacturer	Tesla	Fiat	GM	-	-	BYD
Battery energy density [Wh/L]	205	179†	210	252†	267†	279
Battery specific energy [Wh/kg]	155	143	161	225†	236†	150
Battery cost [$/kWh]	170	127	100	75	105	66
Battery capacity (gross) [kWh]	82	42	213	82	-	85.4
Battery capacity (usable) [kWh]	75	37.3	200	75.9	-	76.9
Battery efficiency [%]	91.5	88.8	93.9	92.6	-	90.0
Vehicle power [kW]	378	87	745	-	-	380
Vehicle range [km]	449	320	529	-	-	710
Battery weight [kg]	530	294.3	1326	364†	347†	592
Battery volume [L]	400	235†	1012	325†	307†	306
Gravimetric cell-to-pack ratio (GCTP) [%]	59.2	72.8	59.0	59.2†	59.0†	86.9
Volumetric cell-to-pack (VCTP) ratio [%]	28.0	40.2†	34.3	28.0†	34.3†	62.3
Battery specific power [kW/kg]	0.71	0.30	0.56	-	-	0.64
Battery power density [kW/L]	0.95	0.37†	0.74	-	-	1.24

As data was not found in the literature for every battery type, the battery energy density and specific power were calculated based on the values of the cells and the Gravimetric and Volumetric Cell-To-Pack ratios. These indicators represent how much of the battery weight and volume are related to the cells - the

† Estimated by the authors.

remaining being occupied by other battery hardware such as housings, connectors, etc. That allows the consideration of battery specific details for calculations. Since the Licerion and the 4680 are still not currently used in any vehicle, battery weight and volume data are not available. It was assumed that the pairs of batteries with the same geometries would have the same GCTP and VCTP. These are the pouch batteries (Licerion and Ultium) and the cylindrical batteries (2170 and 4680). That can be thought of as a worst-case scenario since these batteries are likely to improve performance compared to current-generation technology. The battery capacity was assumed as the one on the Tesla Model Y Long Range currently available. For the Samsung SDI battery, as data for the battery volume was not found in the literature (as well as for the energy density directly), the battery volume for the Fiat 500e for the 2019 model year was used, and the battery volume for the 2020 model year was calculated by correcting this battery volume with the ratio of battery masses of both vehicles. Although the 4680 is still not used in any commercial vehicle, some performance estimates regarding the Model Y can already be found on the specialized media (Battery Design, 2022).

It is important to note that there can be discrepancies between the battery efficiency and power density data calculated and shown in Table 2 related to the data reported by vehicle manufacturers. That is possible for the battery efficiency as it was calculated by the ratio between the total battery capacity and the usable capacity, according to Eq. (2):

$$\eta_b = \frac{E_{usable}}{E_{nominal}} \times 100\%. \qquad (2)$$

Where η_b: battery efficiency [%]; E_{usable}: usable battery capacity [kWh]; $E_{nominal}$: nominal battery capacity [kWh].

The specific power and power density of batteries were calculated by dividing the vehicle engine power by the total weight and total volume of the battery packs, respectively, according to Eqs. (3) and (4):

$$p_s = \frac{P_e}{w_t}, \qquad (3)$$

$$p_d = \frac{P_e}{v_t}. \qquad (4)$$

Where p_s: battery specific power [kW/kg]; p_d: battery power density [kW/L]; P_e: vehicle engine power [kW]; w_t: total weight of the battery pack [kg]; v_t: total volume of the battery pack [L].

As the volume for the 120 Ah battery (Samsung SDI) was estimated based on the 2019 Fiat 500e battery pack, this implies that all volume-related battery parameters calculated are estimations, such as the battery energy density and power density. The same happens for weight and volume-related attributes for the 4680 cylindrical battery (Panasonic) and the Licerion pouch battery (Sion), which had all their battery parameters calculated based on GCTP and VCTP values from related battery models. All references used for obtaining the data can be found in Table 4, presented in Section 3.

Finally, to compare the different battery geometries in Sections 3.2.3 and 3.2.4, the estimated cost and vehicle range associated with each battery model applied to the Tesla Model Y Long Range Dual Motor car were calculated using the Eqs. (5) and (6):

$$c = 75 \cdot c_{kWh}, \qquad (5)$$

$$R = \frac{E}{e_c}. \qquad (6)$$

Where c: battery cost for a capacity of 75 kWh [\$]; c_{kWh}: battery cost per kWh [\$/kWh]; R: vehicle range [km]; E: battery capacity for a total battery weight of 530 kg [Wh]; e_c: energy consumption [Wh/km].

3 Discussion

3.1 Decision analysis

3.1.1 Vehicle goals

The batteries were compared on eleven fronts (battery cost, vehicle range, battery efficiency, cell thermal management, cell thermal integrity, energy density, power density, specific energy, specific power, cell mechanical integrity, and cell technological maturity) which were given scores related to each battery shape. These were assigned according to qualitative and quantitative criteria and are shown in Table 3.

Table 3. Vehicle goals normalized with the data of the battery shapes.

Criterion	1 (Very weak)	2 (Weak)	3 (Intermediate)	4 (Good)	5 (Very good)
Battery cost [$/kWh]	> 149	129 – 149	108 – 128	87 – 107	< 87
Vehicle range [km]	< 300	300 – 450	451 – 550	551 – 700	> 700
Battery efficiency [%]	< 88.0	88.0 – 90.3	90.4 – 92.6	92.7 – 95.0	> 95.0
Thermal management	Complex	Medium-complex	Medium	Simple-medium	Simple
Cell thermal integrity	Very high risk	High risk	Medium risk	Low risk	Very low risk
Energy density [Wh/L]	< 199	199 – 219	220 – 240	241 – 261	> 261
Power density [kW/L]	< 0.54	0.54 – 0.73	0.74 – 0.93	0.94 – 1.13	> 1.13
Specific energy [Wh/kg]	< 161	161 – 180	181 – 200	201 – 220	> 220
Specific power [kW/kg]	< 0.38	0.38 – 0.47	0.48 – 0.57	0.58 – 0.67	> 0.67
Cell mechanical integrity	Very weak mechanical load bearing capability	Weak mechanical load bearing capability	Average mechanical load bearing capability	Good mechanical load bearing capability	Excellent mechanical load bearing capability
Cell technological maturity	Development	Introduction	Growth	Maturity	Extension

For the quantitative criteria, the data were normalized based on the highest and lowest values presented in Table 2. The highest value was labeled 5 (Very good). The lowest was labeled 1 (Very weak). Linear interpolation was used to obtain the scores from 2 to 4. The exceptions to this rule were the “vehicle range”, “specific energy”, “energy density” and “battery efficiency” criteria, where the intervals were adapted by the authors from the result of the linear interpolation.

It is relevant to clarify the meaning of thermal management and cell thermal integrity. The thermal management criterion addresses how complex the thermal management system is considering a given battery geometry. For example, as discussed in Section 1.1.3, pouch cells tend to have a relatively complex thermal management system because of their mechanical fragility, even if their electrical properties do not heavily suffer from the impact of thermal gradients. This criterion is related to the battery because it involves components other than the cells themselves. Cell thermal integrity, on the other hand, addresses the risk associated with two aspects: the change of electrical, thermal, and mechanical properties with thermal gradients and the thermal response of the cell to mechanical/electrical loads (such as the risk of thermal runaway).

The eleven criteria presented in Table 3 were then evaluated for each type of application (economy or performance), as seen in Table 4.

Table 4. Battery criteria weight for each type of vehicle (economic and performance).

Criterion	Economic	Performance
Battery cost	5	1
Vehicle range	5	1
Battery efficiency	5	3
Thermal management	4	5
Cell thermal integrity	3	3
Energy density	5	3
Power density	1	5
Specific energy	5	3
Specific power	1	5
Mechanical integrity	3	5
Cell technological maturity	5	3

For economy-oriented vehicles, the most important characteristics were considered as the cost, the range, the energy density, the specific energy, and the cell technological maturity. For this type of vehicle, the energy content is more significant than the available power because they prioritize vehicle range over performance.

For cars with a focus on performance, there is a change in priorities. Because of the relatively higher load on the cells that performance-focused vehicles tend to develop compared to economy-focused ones, thermal management also becomes an even more important key factor. Cell technological maturity is not as crucial as these vehicles tend to be state-of-the-art. Specific power and power density are prioritized over specific energy and energy density.

3.1.2 Battery decision criteria

As described in the Methodology Section, the different battery geometries were scored and evaluated for the criteria presented in Section 3.1.1 according to the Multi-Attribute Utility Theory (MAUT) method. That can be seen in Table 5.

It is important to note that since there are two cylindrical batteries (the Panasonic 2170 and 4680) and two pouch batteries (the GM Ultium and the Sion Licerion), the quantitative criteria scored in Table 5 were considered the mean of each battery criterion. For example, for the battery cost criterion, the Panasonic 2170 has an estimated cost of 170 \$/kWh, while the Panasonic 4680 has an estimated cost of 75 \$/kWh. That led to a mean battery cost of the cylindrical battery of 123 \$/kWh, which relates to a score of 3. In the case of the structural battery (University of Porto), because of a lack of data, the energy density and specific energy were considered the same as the cell. That would be equivalent to GCTP and VCTP values of 100%, which is a best-case scenario. Since structural batteries do not present modules (as is the case with the Blade Battery), it is reasonable to infer that their GCTP and VCTP tend to be high, which is confirmed by the fact that these cells can easily be assembled in series (Danzi, Camanho and Braga, 2021).

Table 5. Criteria scored for each battery shape.

Battery Shape	Cylindrical	Prismatic	Pouch	Blade	Structural
Battery cost	3	3	4	5	-
Vehicle range	3	3	3	5	-
Battery efficiency	3	2	4	2	-
Thermal management	4	3	2	5	-
Cell thermal integrity	4	3	2	5	-
Energy density	3	1	3	5	1
Power density	4	1	3	5	-
Specific energy	3	1	3	1	1
Specific power	5	1	3	4	-
Cell mechanical integrity	4	3	1	5	4
Cell technological maturity	5	5	3	3	1
Economic	**3.55**	**2.55**	**2.93**	**4.43**	**1.50**
Performance	**3.92**	**2.22**	**2.62**	**4.50**	**2.07**

The total score for each battery geometry was calculated by combining the criteria weights in Table 4 and scores for each criterion in Table 5 according to Eq. (7).

$$S = \frac{\sum_{i=1}^{n} w_i s_i}{w_i}. \quad (7)$$

Where S: final score of the battery geometry [-]; w_i: weight of criterion i [-]; s_i: score of criterion i [-]; n: number of criteria [-].

It is important to note that only the evaluated criteria were used in the calculations. Therefore, in case of a battery not having scores assigned to some criteria, these were disregarded. The battery efficiency criterion was not included in the evaluation of the structural battery, for example. The final scores for each battery geometry analyzed in Table 5 are presented in Figure 7.

Regarding battery cost, the blade battery (BYD) promises a revolution over current models, with an estimated cost of $66/kWh. The 4680 cylindrical cell (Panasonic) follows relatively closely, and both current-generation and next-generation pouch cells, the Ultium (GM) and Licerion (Sion) are not that far behind, while the 120 Ah prismatic cell (Samsung SDI) and the current-generation cylindrical cell (2170) present significantly higher costs. It is important to note that the new 4680 cylindrical cell (Panasonic) is estimated to be cheaper than or at least equivalent in terms of cost compared to the blade battery (BYD) at $75/kWh. However, it is relevant to note that this battery is still under development, with the costs being only estimated - based on the technology already available on the market, the blade battery (BYD) is still the better option. The structural battery (University of Porto) was not considered for this criterion for lack of data.

Regarding vehicle range, it is noticeable that the BYD Han EV with the blade battery has a significant advantage related to the others, while the Fiat 500 with its 120 Ah prismatic cell (Samsung SDI) has the shortest range. That is a curious fact, as cars presenting the lowest and second highest battery costs have the highest and lowest range, respectively. This achievement underlines how the blade battery (BYD) can become a trend for economy-focused models, being an evolution compared to current-generation conventional prismatic cells like the 120 Ah cell from Samsung SDI. The 4680 cylindrical cell (Panasonic), Licerion pouch cell (Sion), and the structural battery (University of Porto) were not considered for this criterion as they are not currently applied in any vehicle.

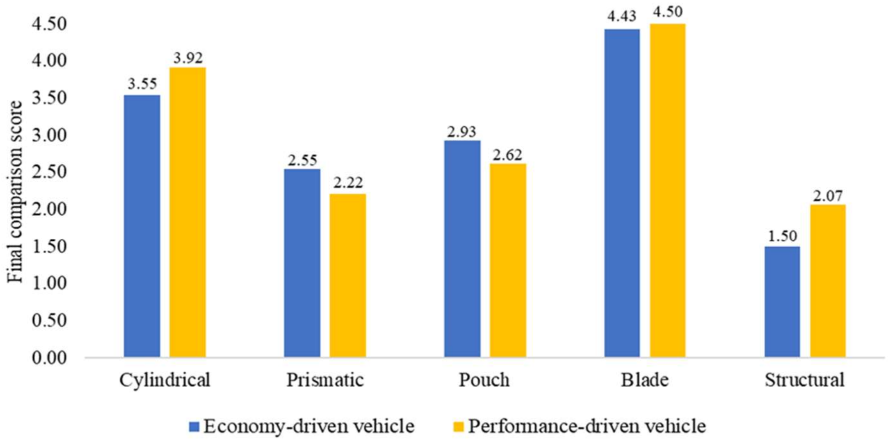


Figure 7. Scores for each battery geometry investigated in Table 5.

Regarding battery efficiency, the Ultium pouch cell (GM) presented the best performance, with the 4680 following relatively close. Interestingly, the estimated performance of the 4680 cylindrical cell (Panasonic) in this regard is not substantially better than the 2170. All batteries followed relatively closely in this criterion, with the difference between the highest and lowest efficiency being only 5.09%, which could be considered negligible for practical aspects. It is important to notice that this criterion is based mainly on estimates made by the specialized media as official data for usable and total capacity are hardly found. The structural battery was not considered for this criterion for lack of data.

Regarding power density, the blade battery (BYD) presents by far the best performance. The fact that the 120 Ah prismatic battery (Samsung SDI) presents the lowest power density further enhances the argument that the blade technology is a notable evolution of the prismatic form factor. Considering the specific power criterion, the current-generation 2170 cylindrical battery (Panasonic) has the edge, but the blade follows relatively close. One should be mindful that, for performance-focused vehicles, the power density and specific power are crucial attributes to consider, as providing maximum performance over their volume and reducing weight is the principal concern in this case. The 4680 cylindrical cell (Panasonic), Licerion pouch cell (Sion), and structural battery (University of Porto) were not considered for these criteria for lack of data.

Regarding thermal management, the structural battery was not considered for lack of data. The highest score was attributed to the blade battery (BYD): its characteristics, as pointed out in Section 1.1.5, make them safer and their thermal management easier than conventional, module-assembled batteries. Respectively following it are the cylindrical batteries (which have better thermal management capabilities than the prismatic batteries (Das et al., 2018)), the prismatic, and, with the lowest score, the pouch batteries, due to their mechanical fragility that can lead to additional precautions for the thermal control.

Regarding thermal integrity, the best current battery is the blade (BYD) for its safety. The cylindrical cell was ranked as the second-best and the prismatic as the third as, in comparison to the cylindrical, it can present more vulnerability to swelling and a shorter life cycle, for example Laserax (2022). The pouch cell was the lowest ranked. Even though its properties, compared to the cylindrical, do not change as much with temperature, its sensitivity to swelling was considered a more aggravating factor.

Regarding specific energy, the Ultium pouch battery (GM) has the highest value among the currently used batteries. The 2170 cylindrical battery (Panasonic) outperforms both prismatic form factor batteries, the blade battery (BYD), and the 120 Ah battery (Samsung SDI). These two presented the lowest specific energies of all batteries evaluated, which indicates that this might be the handicap of the prismatic form factor. The energy issue is more critical for cars focused on the economy rather than performance. No current battery, however, can compete with the developing batteries Licerion (Sion) and 4680 (Panasonic), which promise significant advances in this regard and could be interesting, especially for performance cars. One remark is that the structural battery (University of Porto) has a low value for the specific energy because the weight of the battery is the weight of the structure itself. An observation, in this case, is that as the body of a vehicle using structural batteries is effectively the battery, there is no extra weight due to a battery pack - in contrast, on a conventional electric vehicle, the total weight is the summed weight of its body plus the battery pack. For this reason, one could infer that the structural battery would be lighter. However, due to the difficulty of similarly assessing both structural batteries and traditional battery packs, the criterion was based on available data from the manufacturer (University of Porto).

For energy density, the blade battery (BYD), due to its cell-to-pack format, outperforms every other battery, even the next-generation 4680 cylindrical battery (Panasonic) or the Licerion pouch battery (Sion). Nonetheless, these provide significant improvements over the current-generation cylindrical and pouch batteries. As for the specific energy criterion, no current battery can also compete with the next-generation Licerion pouch battery (Sion) and the new 4680 cylindrical battery (Panasonic), with energy density gains that greatly favor bundling - which could be interesting for use in small vehicles such as LEVs (Light Electric Vehicles) or motorbikes (Chien, Hsieh and Chang, 2023). Once more, it is not straightforward to compare structural batteries and other geometries because as the whole body is the battery, its volume is large. Consequently, the energy density tends to be low, similar to specific energy. Therefore, for the structural battery, the energy density was obtained from the available data of the manufacturer (University of Porto).

Regarding mechanical integrity, the best battery - as in the case of thermal management and thermal integrity - is the blade (BYD), which has passed crash tests without any issues. Pouch battery cells, having low rigidity (even if assembled in rigid modules), tend to be the weakest and, therefore, the least safe among the tested. It should also be noted that the structural battery (University of Porto) promises significant evolution in terms of current technologies - the vehicle architecture has considerable room for flexibility and optimization since the energy storage would be distributed throughout the body of the vehicle and not only on the chassis, in the form of battery packs, as with most battery technologies today.

Concerning maturity, the most traditional geometries are cylindrical and prismatic, already in the mature phase. Pouch battery cells, although not so recent, are gaining more interest. New battery geometries such as the structural and blade are emerging (the blade is an adaptation of the prismatic cell but different enough to be considered a new battery geometry). That reveals there is still room for research and improvement as these batteries are currently in development.

Some conclusions can be made based on the strengths and weaknesses observed for each battery geometry. From Table 5, the blade battery is considered the best option for both applications (economy and performance) because of its high scores across most criteria (apart from specific energy), making it an efficient choice overall for any situation. However, the cylindrical geometry showed consistent performance across all criteria, while the pouch cell has significant advantages in specific attributes but at least one notable disadvantage in others. The pouch cell excels in battery cost and battery efficiency, showing potential for economic applications such as small or entry-level vehicles intended for city use. Even though it performs poorly considering mechanical integrity, its application in these categories makes sense as the use case of these is inner-city driving, for example. The blade battery presents sublime performance among practically all criteria, being adapted to practically any use case. The prismatic geometry seems to be the least compelling option for both applications according to the chosen criteria, presenting an average or weak performance among most criteria. However, as stated in Section 1.1.2, this battery shape should still be relevant in the future in EV applications due to the ongoing studies of the LFP chemistry and clear potential for cost reductions in the manufacturing process. At present, it would fit better in entry-level or family cars, as it has a very mature development status (which drives down maintenance costs, for example) and could present modest performance all around. Regarding the structural battery, its poor performance may relate to the difficulty in evaluating this battery shape in the same way as more traditional geometries, which might not reflect its true capabilities. In addition, this battery shape is still under development, not used in any commercial electric vehicle today.

3.2 Analysis

3.2.1 Capacity and weight analysis of battery models

The first comparison between the Tesla's Model Y Long Range Dual Motor original battery, the 2170 cylindrical battery (Panasonic), and the other four modular battery models - Ultium pouch battery (GM), Licerion pouch battery (Sion), 120 Ah prismatic battery (Samsung SDI) and the 4680 cylindrical battery (Panasonic) - involved the capacity that each battery would have with a battery weight of 530 kg, based on the specific energy of each battery. That is the total weight of the Tesla Model Y Long Range Dual Motor car battery pack. In addition, it was evaluated how much each battery would weigh with an energy content of 82 kWh, which is the capacity of the Tesla vehicle. Figure 8 shows the results obtained.

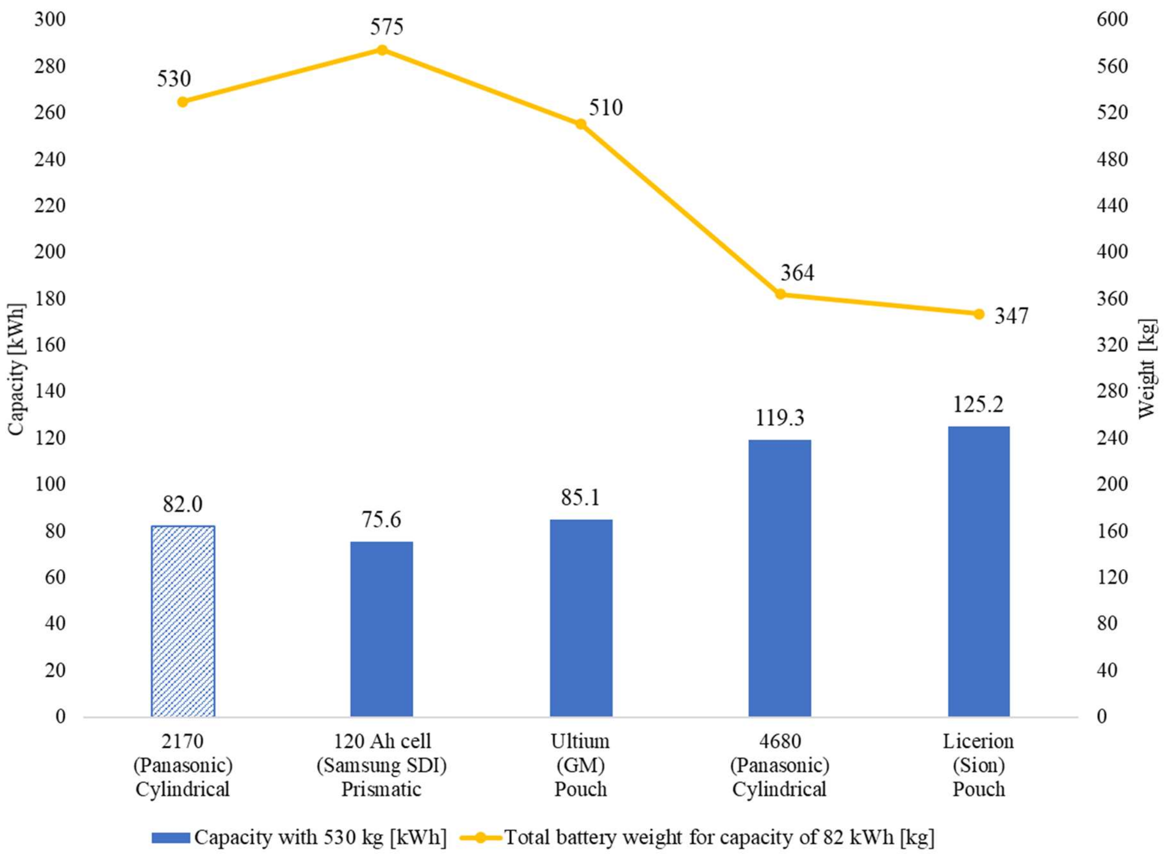


Figure 8. Capacity and total battery weight for the five battery models.

Regarding current technologies, the 120 Ah prismatic battery (Samsung SDI) would weigh more for the same capacity (or have a lower capacity with the same weight). That can explain one of the reasons why it is used on smaller cars such as the Fiat 500 and BMW i3. The Ultium pouch battery (GM) already improves the performance slightly compared to the 2170 cylindrical battery (Panasonic), but the real leap comes from both future technologies - the 4680 cylindrical battery (Panasonic) and the Licerion pouch battery (Sion). In conclusion, as seen in Figure 8, it should not make too much of a difference in weight to change the battery shape and structure between current generation models. However, that changes for next-generation cylindrical and pouch batteries: the Licerion pouch battery (Sion) presents a 52.7% greater capacity for the same 530 kg weight or a reduction of 34.5% for the same 82 kWh capacity when compared to the 2170 cylindrical battery (Panasonic), which could lead to a significant increase in vehicle range.

3.2.2 Packing analysis of battery models

Next, the total volume each battery would occupy was evaluated. That was carried out based on the battery energy density, calculating the capacity with a 400 L volume. That is the total battery volume for Tesla's Model Y Long Range car, according to the United States Environmental Protection Agency (EPA) (2022). After that, the battery volume needed to obtain the 82 kWh capacity was determined (for each other battery evaluated). These results are shown in Figure 9.

Based on the values presented, it can be observed that the 120 Ah prismatic battery (Samsung SDI) occupies more volume for the same capacity, showing a disadvantage to the 2170 cylindrical battery (Panasonic). In addition, from a volume standpoint of current generation batteries, cylindrical-based batteries seem to perform similarly to pouch batteries, presenting only a slightly lower capacity for the same volume for the models compared. Regarding future technologies, the 4680 cylindrical battery (Panasonic) and the Licerion pouch battery (Sion) provide a greater capacity for the same volume when compared with the current generation batteries. The pouch battery pack remained with a better overall performance concerning volume occupation. That highlights the significant potential the Licerion battery has for future electric vehicle applications, outperforming the other compared batteries in both specific energy and energy density parameters.

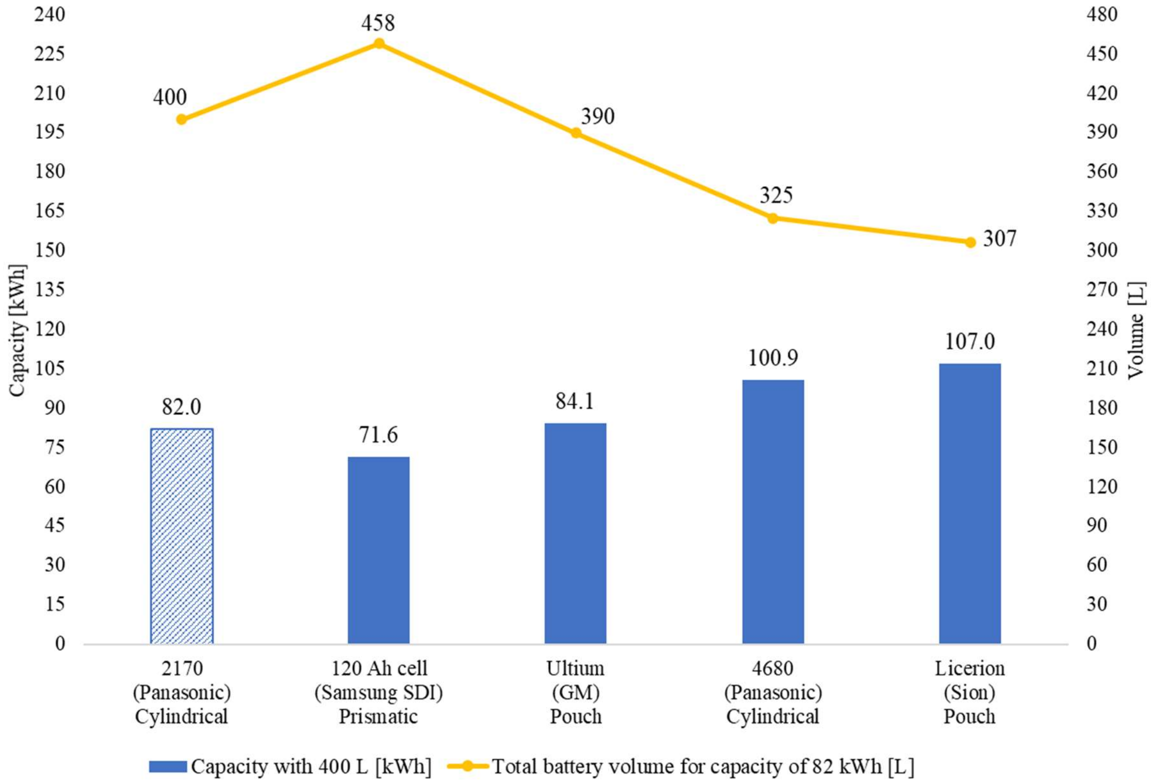


Figure 9. Capacity and total battery volume for the five battery models.

3.2.3 Cost analysis of battery models

Another considerable aspect is the cost impact for each battery model, shown in Figure 10.

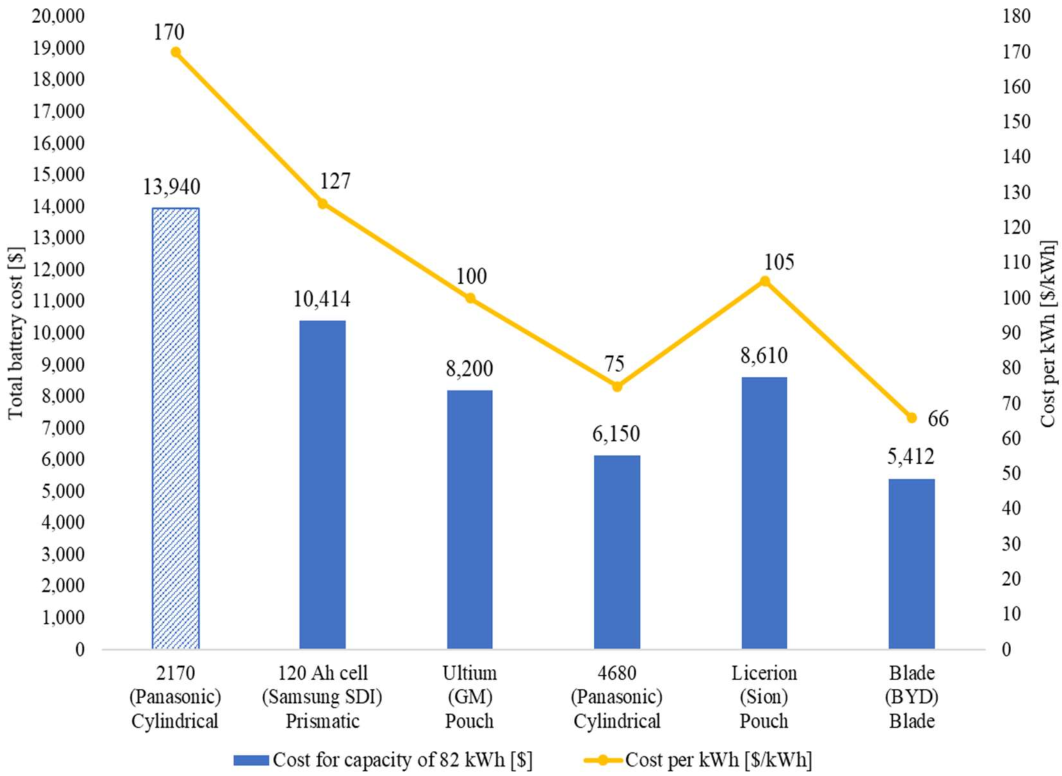


Figure 10. Cost for six of the battery models in this paper.

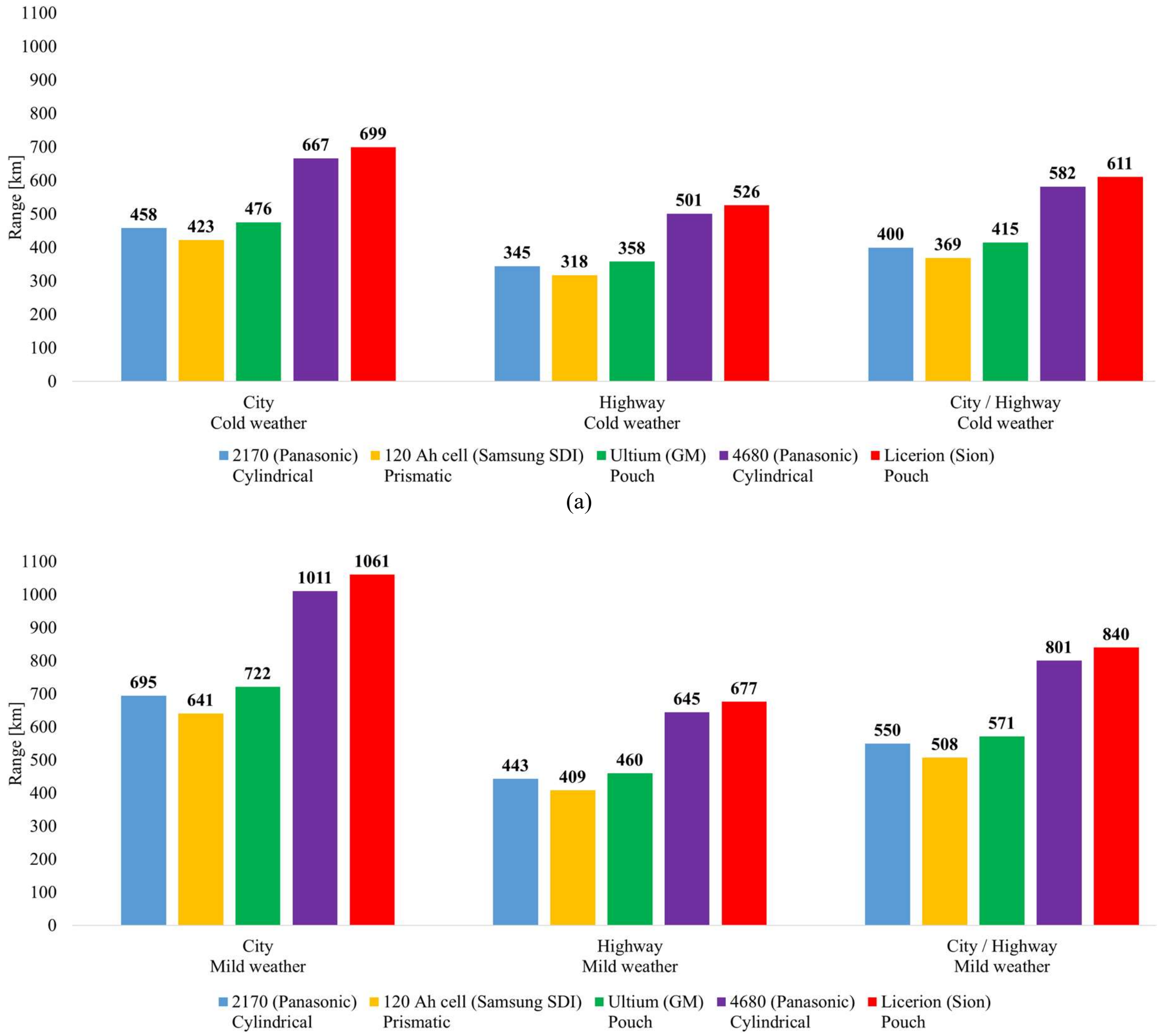
Based on the costs per kWh shown in Figure 10, there is an estimated cost of $13,940 for the 82 kWh battery used in the Tesla Model Y Long Range Dual Motor car today. The Ultium (GM) and Licerion (Sion) pouch cell batteries have an estimated cost of $8,200 and $8,610, respectively. That leads to a difference of approximately 40% compared to the 2170 cylindrical cell battery (Panasonic). In addition, the 4680 cylindrical cell battery (Panasonic) and the blade battery (BYD) have a significant cost reduction compared to the others, with values of $6,150 and $5,412, respectively. The 120 Ah prismatic cell battery (Samsung SDI) is the second most expensive, with an estimated cost of $10,414 for the 82 kWh capacity. One remark is that the most traditional battery geometries (prismatic and cylindrical) currently in use are the most expensive among all tested. That explains in part the shift towards the development of other battery geometries.

3.2.4 Vehicle range

For each evaluated battery, the estimated range was calculated from the known Tesla Model Y Long Range Dual Motor car energy consumption data for different weather and driving conditions (EV Database, 2022). The following assumptions were made:

1). All batteries have the same total battery weight found in the Tesla Model Y Long Range Dual Motor car;
2). The energy consumption of the vehicle remains the same for a different battery with the same total battery weight;
3). There is the possibility of accommodating a larger volume for the battery in the vehicle if needed.

Figure 11 presents the results obtained.



(b)

Figure 11. Battery autonomy at different driving cycles for total battery weight of 530 kg (a) during cold weather and (b) during mild weather.

In Figure 11, it can be seen that with the current technologies, the prismatic battery (Samsung SDI) ends up providing the lowest range for all driving conditions. That is to be expected, as this battery is used mainly in smaller cars such as the Fiat 500 EV and the BMW i3, whose functionality is not necessarily long-distance traveling. Furthermore, there is a slight addition in the range provided by the Ultium pouch battery (GM) compared to the 2170 cylindrical battery (Panasonic) - approximately 4%. Even so, future technologies raise the bar significantly. The Licerion pouch battery (Sion) has an advantage over the 4680 cylindrical battery (Panasonic) - both providing approximately 53% and 45% better range than the 2170 cylindrical battery (Panasonic), respectively. That is an impressive amount that could make the difference between a vehicle being more city-focused or prone for traveling purposes, for example.

4 Conclusions

This paper presented qualitative and quantitative comparisons of different geometries of commercial batteries using the Multi-Attribute Utility Theory (MAUT) method and a case study considering a commercial vehicle available in the market, the Tesla Model Y Long Range Dual Motor car. The steps applied in this work were: first, a literature review for electric vehicle battery geometries (cylindrical, prismatic, pouch, blade, and structural). Then, battery models for each geometry were investigated - the 2170 cylindrical cell (Panasonic), 120 Ah prismatic cell (Samsung SDI), Ultium pouch cell (GM), blade battery (BYD), and structural battery (University of Porto). Performance criteria were defined and subsequently scored considering two applications: economic and performance vehicles. The score of each geometry was calculated based on these criteria and the performance of the selected cell models. That allowed the creation of a ranking considering each application. Finally, a case study was carried out to evaluate the application of each cell in the Tesla Model Y Long Range Dual Motor commercial vehicle regarding the aspects of range, weight, and the expected cost.

Regarding the ranking of the batteries given by the Multi-Attribute Utility Theory (MAUT), it can be seen that for both applications (economic or performance vehicles), the battery geometry with the highest score overall was blade. That is since it presented the highest scores for most criteria, with two handicap criteria – the battery efficiency and the specific energy. The cylindrical cell presented consistent performance overall, with no notable handicaps. The other battery shapes – prismatic, pouch, and structural – showed average performance overall, with at least one score with very low performance. It is also noticeable that, when compared to upcoming battery cells, the leap in performance is immense. That demonstrates the clear improvement potential of current technology batteries.

It is important to note that it was not possible to include blade and structural batteries in some of the evaluations of the decision criteria and the case study. That is due to them being installed differently than other batteries in electric vehicles (which would invalidate a direct comparison) and because certain specifications required for performance quantification are not yet available. Therefore, it is recommended that future work develop ways to include these geometries in the comparison to allow a more assertive analysis.

Finally, it is emphasized that, while this study provides valuable insights into the performance of different cell geometries with respect to each other, future work following a similar comparison methodology would be interesting. For instance, a database containing more battery models, for example, could potentially lead to more extensive comparisons.

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