UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola Politècnica Superior d'Enginyeria
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Bachelor Thesis

# Affordable Battery Electric Vehicle Design Concept

Automotive Engineering Degree

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# Abstract

Battery electric vehicles are considered by many the future of the automobile in the transition from fossil fuels to less polluting energy sources. It has become clear that, although they still have a noticeable carbon footprint and have their own environmental issues, battery electric vehicles are overall less polluting than internal combustion cars, and they are the next step forward to reduce pollution, and consequently global warming. Sales for electric cars have been steadily increasing over the past years, and the public is more inclined than ever to purchase an electric vehicle instead of a combustion engine car.

Nevertheless, there currently exists a very limited amount of different battery electric models in the European market which are in the low price range, and the existing ones are still noticeably more expensive than the most affordable internal combustion engine cars. This is one of the causes for the current low number of battery electric vehicles sold worldwide when compared to combustion engine cars, and the focus of this project’s objectives.

The aim of this project is to assess what design specifications are needed in order to manufacture the most affordable BEV for the European market, with a number of desired specifications as starting points; and to calculate its approximate price to see if price parity with the most affordable A-segment combustion engine cars can be achieved, without sacrificing the utility of the vehicle.

Even with all the cost-cutting measures applied on this design, the desired price parity is not quite achieved, although the proposed BEV does decrease in price substantially when compared to the most affordable European BEVs. A vehicle like the one proposed still holds potential to help with the transition to BEV mobility for people who do not have the budget to currently afford an electric car, by filling this yet unaddressed gap in the market.

# Resum

Els vehicles elèctrics de bateries es consideren el futur de l’automòbil en la transició dels combustibles fòssils a fonts d’energia menys contaminants. Ha quedat clar que, encara que tenen una petjada de carboni notable, i tenen els seus propis problemes ambientals, els vehicles elèctrics de bateria són generalment menys contaminants que els cotxes de combustió interna, i són el següent pas endavant per a reduir la contaminació, i en conseqüència, l'escalfament global. Les vendes de vehicles elèctrics han anat augmentant de manera constant en els últims anys, i el públic està més predisposat que mai a comprar un vehicle elèctric en lloc d'un cotxe amb un motor de combustió interna.

No obstant això, actualment existeix una quantitat molt limitada de diferents models elèctrics de bateria en el mercat europeu que es troben en la gamma baixa de preus, i els existents segueixen sent notablement més cars que els vehicles amb motor de combustió interna més assequibles del mercat. Aquesta és una de les causes del baix nombre actual de vehicles elèctrics de bateria que es venen arreu del món, en comparació amb els vehicles de motor de combustió, i és el principal problema a resoldre d'aquest projecte.

L'objectiu d'aquest projecte és avaluar quines especificacions de disseny són necessàries per a fabricar un cotxe elèctric assequible per al mercat europeu, amb una sèrie d'especificacions desitjades com a punt de partida; i calcular el seu preu aproximat per a veure si es pot aconseguir la paritat de preu amb els vehicles de motor de combustió més assequibles des segment A, sense sacrificar la utilitat del vehicle.

Fins i tot amb les mesures extenses de reducció de costos aplicades en aquest disseny, la paritat de preu desitjada no s'aconsegueix del tot, encara que el vehicle proposat disminueix substancialment de preu en comparació amb els vehicles elèctrics més assequibles de la UE. Un vehicle com el proposat encara té el potencial d'ajudar en la transició cap a la mobilitat elèctrica de les persones que no tenen el pressupost per a permetre's en l'actualitat un cotxe elèctric, i per tant ompliria un sector del mercat que actualment està poc representat.

# Abbreviations

| | |
|---|---|
| **EU** | European Union |
| **USA** | United States of America |
| **EV** | Electric Vehicle |
| **BEV** | Battery Electric Vehicle |
| **HEV** | Hybrid Electric Vehicle |
| **PHEV** | Plug-in Hybrid Electric Vehicle |
| **FCEV** | Fuel-Cell Electric Vehicle |
| **PC** | Passenger Car |
| **ICE** | Internal Combustion Engine |
| **ICEV** | Internal Combustion Engine Vehicle |
| **LCV** | Light Commercial Vehicle |
| **MPV** | Mid-size Passenger Van |
| **SUV** | Sport Utility Vehicle |
| **MSRP** | Manufacturer Sales Retail Price |
| **ICM** | Indirect Cost Multiplier |
| **PMSM** | Permanent Magnet Synchronous Motor |
| **IM** | Induction Motor |
| **WLTP** | Worldwide harmonised Light vehicle Test Procedure |
| **NEDC** | New European Driving Cycle |
| **RWD** | Rear Wheel Drive |
| **FWD** | Front Wheel Drive |
| **AWD** | All Wheel Drive |

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# 1. Introduction

## 1.1. Objectives and purpose

This project was motivated by the fact that, while BEVs are widely thought to be the replacement for ICEVs in passenger cars, hardly any affordable BEV models are available in the European market, as of May 2021. This is a large set-back in the road to electrifying our commutes, as it means that a large percentage of the population is not able to afford the purchase of a BEV, even if the people in question are favourable towards a BEV purchase.

The main goal for this project is to conceptualize a vehicle with specific characteristics in order to achieve price parity with the most affordable ICEVs. All cost reduction methods will be considered throughout the various vehicle systems, all while maintaining an acceptable level of usability, meaning most importantly, having 5 doors and an acceptable battery range.

This will be achieved by carrying out the next objectives in the presented order:

- Analysis of BEV sales in comparison to ICEV sales.
- Technical analysis of BEVs.
- Current BEV models benchmarking.
- Specification of the characteristics of the proposed vehicle.
- Selection of cost reducing methods.
- Cost calculation for the proposed vehicle.
- Designation of the product target.
- Analysis of the proposed vehicle, and comparison with existing BEVs and ICEVs.

A 3D design is also shown, nevertheless its objective is to be a visualisation tool to help understand how all the specifications of the proposed vehicle would come together as a whole.

In the final analysis, it will be concluded whether the desired price parity is achieved, and whether a vehicle like the one theorized would be successful in the European market.

The reasons for which the vehicle is designed with the European market in mind are discussed in detail in the paper, but fundamentally it is due to the fact that the vehicle is intended to be manufactured in the EU, even though manufacturing in China would dramatically decrease price. Furthermore, China already has various affordable BEV models, and the USA market does not have high sales of sub-compact cars.

## 1.2. Scope of the project

There are numerous ways to reduce a car’s price, which can be related to the design of the product, the location of the manufacturing plant, the management of the company, logistics, plant layout and design, just to name a few.

It is a wide array of subjects, so for this paper, the scope of the project will be limited to determining technical and design specifications which directly lower manufacturing costs, and in some cases, which also have an indirect effect on indirect costs.

# 2. Background

## 2.1. Information and cited sources

For *Section 2.2. Automotive sector analysis,* numerical data has been collected and filtered from various online sources, most importantly (EVdatabase, 2020), (CSB, 2020), (GCBC, 2020) and (Chinamobil, 2020). The technical information explained regarding vehicle characteristics stems from numerous sources as well, all of which are cited in their respective sections.

For the BEV's cost calculation, the most crucial papers have been (Fries, et al., 2017), (Wolfram, et al., 2016), and (Cuenca, et al., 1999), although other sources have been necessary to complete the gaps in the cost calculation.

Deloitte and McKinsley reports [ (Dr. Hamilton, et al., 2020), (Dr. Wu, et al., 2019), (McKinsley, 2021)] are the main bases for information about the trends and State of the EV market.

Finally, non-specific information from the author's experience in the automotive sector is cited. The information has been left intentionally vague in order to not disclose the project under an NDA agreement, but the information is useful nonetheless to understand certain concepts.

## 2.2. Automotive sector analysis

In order to understand why a vehicle with the characteristics detailed in *Section 3. Design Concept* has been theorized in this project, an analysis of the current state of the BEV in regards to the global PC sector has to be presented, so one is able to appreciate why a vehicle similar to the one introduced in this paper might be a possible solution to make BEVs more abundant.

This analysis is separated into three main sections. The first is an analysis of the relevant data regarding PC and BEV sales (*2.2.1. Global and EV sales*) and is presented in such a way that first the international PC sales are analysed, and afterwards a more in-depth analysis of the key markets and BEV sales is conducted. As is explained in further detail in said section, BEV sales still only account for a very small percentage of the global PC market, the reasons for which are laid out in *Section 2.2.2. Current BEVs benchmarking*, and discussed in detail in *Section 2.2.3. The cost gap between ICEs and BEVs.*

*Section 2.2.2. Current BEVs benchmarking* conducts a price and technology benchmarking of the existing BEV models, and also a brief overview of the best-selling BEVs and of the relevant BEV models, meaning affordable BEVs, is carried out, in order to be able to compare the final proposal of this project to existing models.

### 2.2.1. Global and EV sales

During 2019 approximately 88 million PC vehicles were sold globally, while this number decreased to 73 million in 2020. Sales had been declining since 2018 by around 5% yearly (IEA, 2020), but the 17% decrease in 2020 was mainly due to the pandemic. It is expected for global sales to increase 9 % in 2021, and another 5% in 2022 (Statista, 2020)

During 2020, 63% of these global sales come from the combination of the European, Chinese and North-American market (*Figure 1*), with 11.9, 19.8 and 14.5 million sales respectively.

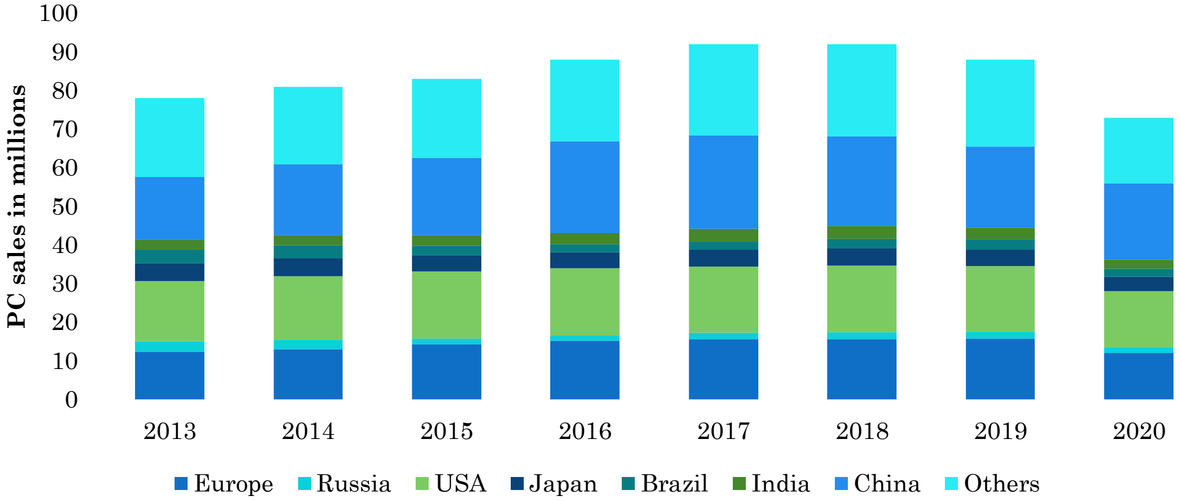


*Figure 1. Worldwide PC sales, by country, 2013 – 2020 Source: (Bekker, 2021); (IEA, 2020); own calculations. Data in Appendix Table A-1*

It has not been possible to obtain data from 2020 regarding the distribution of worldwide PC sales in function of the vehicle's body type (or segment). Nevertheless, we can safely assume that they have been similar to the international distribution from Q1 2019 (*Figure 2*), as changes in automotive market segment trends take various years to vary noticeably.

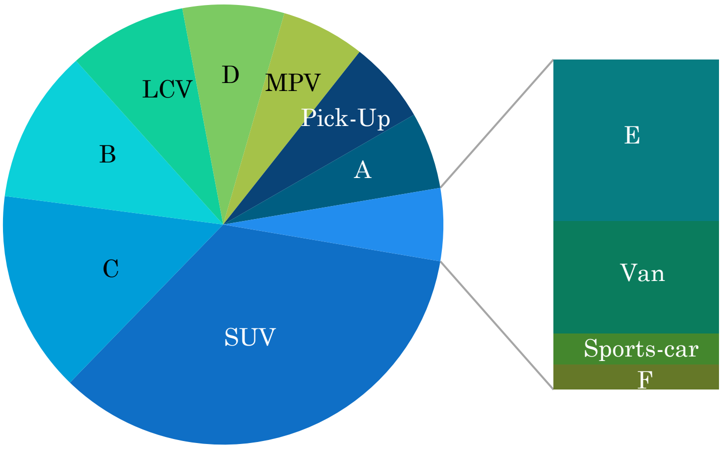


*Figure 2. 2019 Q1 worldwide PC sales by segment. Source: (Felipe, 2019). Data in Appendix Table A-2*

By analysing this graph, we see that the SUV is the best-selling body type internationally, when sales are categorized the way they have been in *Figure 2*, where the SUV represents 34.3% of sales. Despite this, one has to take into account that the SUV category in this figure includes from the smallest cross-overs to the largest SUVs. This body type categorization and nomenclature will be changed from this point onwards, as more detailed data was available regarding the SUV segment. Further analysis of *Figure 2* indicates that compact and sub-compact vehicles (A, B and C segments) represent a combined 31.5% of sales, and mid-sized and large sedans or wagons (segments D, E and F) only account for a combined 10.4% of sales.

As is discussed in further detail in *Section 2.2.1.1. Europe PC Sales and Section 2.2.1.2. USA PC Sales*, higher class vehicles (such as Audi, Infiniti, Mercedes-Benz, BMW, etc.) are more abundant in the larger segments like large SUVs, E, F or D; whereas lower class vehicles (such as Renault, Hyundai, Kia, Peugeot…) represent the majority of sales in smaller-sized segments. (A, B, and small crossovers)

*Figure 3* shows worldwide EV sales from 2013 to 2020, categorized between the key markets and the type of EV (BEV or PHEV). No data was found in relation to PHEV sales for each key country, so this category is not divided between the key markets. The data from *Figure 3*, which has been aggregated from various sources, indicates that from the 3.2 million EVs sold in 2020, around 2,235,000 of them were BEVs. This marks a 43% increase from 2019's approximated 1,675,000 BEV sales, an increase that has continued the decade's trend of growth of EV vehicles, which is clearly seen in the same figure. It is also interesting to note that BEVs have consistently had a higher share of sales compared to PHEVs since 2014, but it is important to account that HEV vehicles are not accounted for in *Figure 3*. Europe has accounted for 43% of global EV sales, while China has followed with 42%. During this same year, USA only represented 13% of EV sales. (Shahan, 2021) (MG, 2021). India has the highest growth rate for EV sales, at a current +510%. (Shahan, 2021)

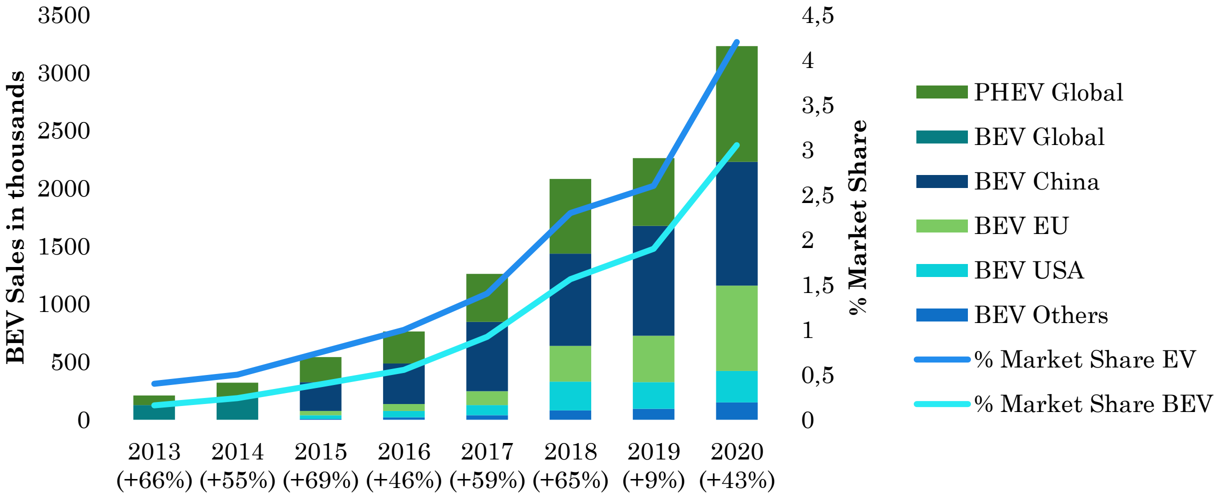


*Figure 3. Worldwide EV sales by key countries, 2013 – 2020. Source: (Gersdorf, et al., 2020); (Shahan, 2021); (Dr. Hamilton, et al., 2020), own calculations. Data in Appendix Table A-1*

Even though EV sales have continued their steady increase, BEV sales in 2020 have only accounted for 3% of worldwide PC sales, and 2% in 2019, percentages which can be considered very low when taking into account the interest and pressure to adopt this propulsion technology, which by now has had enough time to mature and be implemented in a usable manner into our daily lives.

Despite this low percentage of sales, EV sales have had a continued growth in respect to 2019, while the global PC market has decreased substantially in 2020, as discussed before. This indicates that the EV sector is in a complete phase of expansion, and the public is more predisposed than ever to attain a BEV.

As we can see in *Figure 4*, which shows the expected growth of the EV market in each key market, this trend will continue steadily, with an expected average growth of 29% until 2030, reaching approximately 30% of global PC sales in 2030. It is expected that by that year, China will be responsible for around 49% of EV sales, Europe 27% and USA 14% (Dr. Hamilton, et al., 2020)

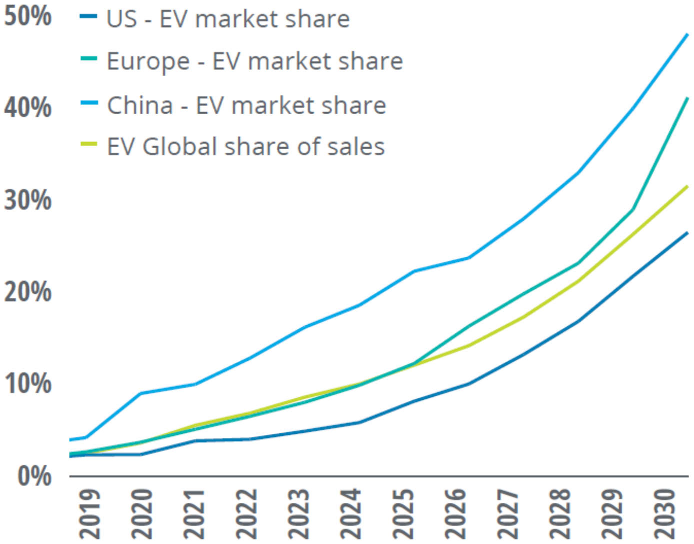


*Figure 4. EV market share outlook. Source: (Dr. Hamilton, et al., 2020)*

By analysing the distribution of worldwide BEV sales in function of their body type (*Figure 5*), one can see that the preferred body types vary substantially in comparison to the distribution found in worldwide PC sales (*Figure 2*). In the case of BEVs, there are not as many SUV/crossover sales, as the combined share of these vehicles in the BEV market has been 25%, compared to the global 34.3% share in the global PC market. Mid-sized sedans (C-segment) and minicars (A-segment) are the most popular body types, with compact cars (B-segment) closely following. This is mainly due to the fact that, as is studied in further detail in *Section 2.2.2.5. Best-selling BEVs analysis*, the BEV market has a very low number of different models that account for most sales, and therefore the body type of these best-selling BEV models greatly dictates the global distribution in relation to the body type. Nevertheless, as we will also see in the same section, mid-size sedans and minicars have a few advantages over the other body segments when the propulsion technology is that of a BEV, as is discussed in detail in *Section 2.2.2. Current BEVs benchmarking.*

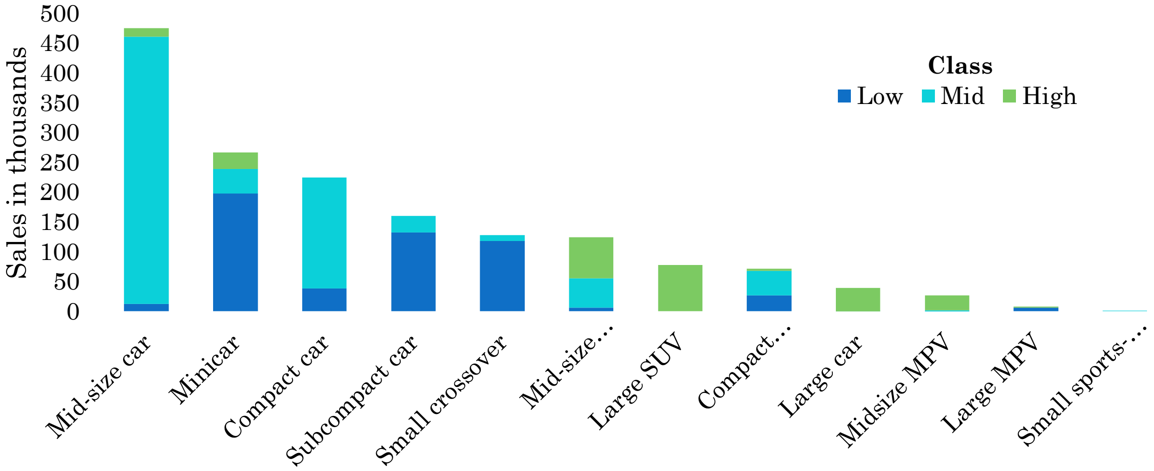


*Figure 5. Worldwide BEV sales by segment and class, 2020. Sources: (CSB, 2020) (GCBC, 2020) (Chinamobil, 2020) Data in Appendix Table A-4.*

*Figure 5* also gives insight into which levels of quality (or class) are popular for the different body types. As we can see, generally speaking the smaller the size, the lower the class will be, and vice versa. This is a trend which, as seen in the next sections, is also found in ICEVs, and the reasons for which are given in *Section 3.1.1. General.*

### *2.2.1.1. Europe PC Sales*

In Europe, during 2020, 11,797,000 units were sold, while during 2019 the total was approximately 15,350,000 units. *Figure 6* shows the sales distribution of PC in the EU during 2020 and 2019 in function of body type and class, and also shows the sales of BEVs for each body type. As can be appreciated, and as has been previously mentioned, generally speaking, the smaller the body type, the lower the class of said vehicle.

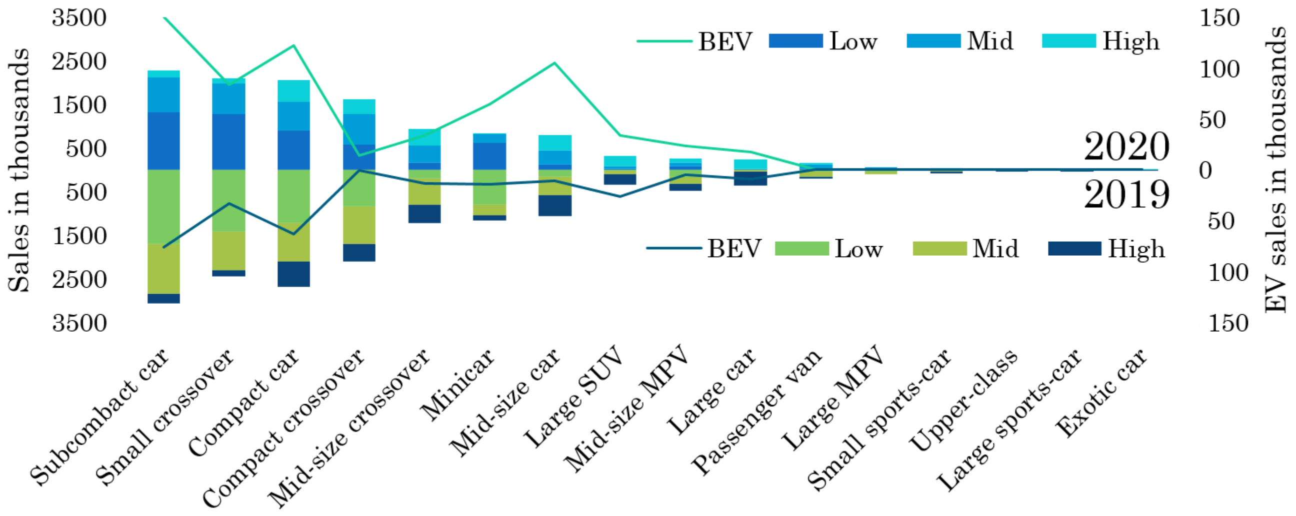


*Figure 6. Europe PC and BEV sales. Source: (CSB, 2020). Data in Appendix Table A-5.*

Following the global trend, sales of SUVs and crossovers account for a large ammount of sales (43% when combining the 4 sizes of SUV and crossovers body types), therefore the European market has a higher preference for these types of vehicles when compared to the global market situation, as seen in *Section 2.2.1. Global and EV sales*. The combination of the Minicar, Subcompact and Compact body-types equals this percentage, whereas sedans (Mid-size car, Large car and Upper-class) only account for 9.5% of sales. This means that small vehicles (A and B segments) also have a higher percentage of sales in Europe when compared to the rest of the world, while with sedans the opposite is true.

It is also interesting to point out that the European market has a higher percentage of higher class vehicles when compared to the other to key countries.

During 2020 in the EU only 5.5% of sales have been BEVs. To put it into context, of the 50 best-selling vehicles in the EU, we only find 2 BEV models, the Renault Zoe in 33rd position, and the Tesla Model 3 in the 43rd. Nevertheless, sales have increased from approximately 400 thousand in 2019 to 750,000 during 2020.

With further analysis of *Figure 6* it is evident that BEV sales distribution in the EU is not the same as its PC global sales, as the SUV/crossover body-types account for approximately 26% of BEV sales in contrast to the global 43%. On the other hand, Minicar, Sub-compact and Compact body-types increase their sales percentage, but the highest difference is seen in the Mid-size car category where, thanks to the popularity of the Tesla Model 3, this body type accounts for 16.2% of BEV sales, whereas when combined with ICEV sales, it only accounts for 6.7% of the European market. (*Appendix Table A-5*)

### *2.2.1.2. USA PC Sales*

The preferential types of vehicles in the USA are very different from the EU, as can be seen in *Figure 7*, which shows the sales distribution from the last two years according to vehicle type. Pick-up trucks account for the largest amount of sales, followed by differently-sized crossovers and SUVs. Overall, small vehicles (Minicar, Sub-compact car or Small crossover) are in much lesser demand, with the American market preferring larger vehicles, probably because of the population density being overall lower than in the EU, with more of the population living outside of densely-populated cities.

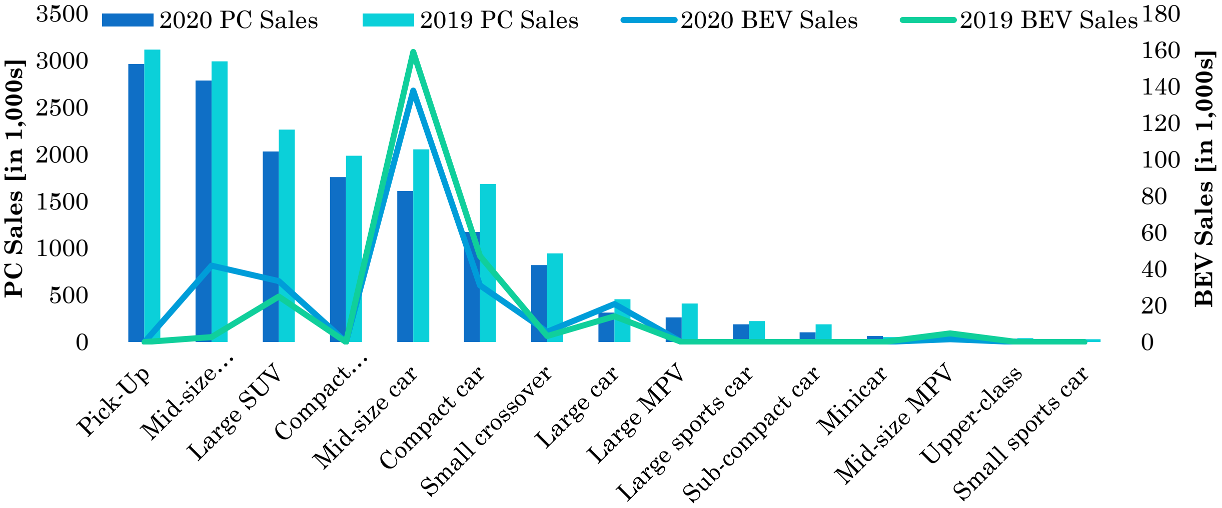


*Figure 7. USA PC sales by segment, 2020 – 2019. Source: (GCBC, 2020). Data in Appendix Table A-6*

Although the USA has overall more passenger sales than the EU, falling behind China, it is the country with the least BEV sales of the three. The distribution of BEV sales is again different from the overall PC sales, and in the case of the USA, this difference is even more noticeable when compared to the EU. There are currently no BEV Pick-up trucks in the market (although there are a couple of models expected to be released during 2021), and very low BEV sales in the crossover/SUV segments. Most of the sales come from mid-size cars, which again is the most popular BEV segment thanks in large part to the Tesla Model 3.

Even though a class analysis has not been carried out, by simple observation of different model sales (*Appendix Table X-3*) the overall preferred makes and brands are seen, these being mostly American and Japanese brands, although most of the models sold in the USA made by Japanese brands, such as Toyota or Nissan, are designed for this market in particular. No market presence is seen from cheap European brands like Peugeot or Dacia, but the brand cluster or group which owns the company always has presence in both the EU and USA market. The same can be seen with brands like Dodge or Buick, which are not available in the EU, as the group owner of the companies already has other established brands in the EU.

#### *2.2.1.3. Chinese PC Sales*

For the Chinese PC sales not enough information was available to carry out an analysis like the ones done in previous sections. Nevertheless, sales from different models can be seen in *Appendix Table X-4.* China is the country with the most PC sales, with close to 20 million units sold during 2020. These vehicles are mostly low to mid quality, with European and Japanese brands sharing the market with local emerging Chinese brands. Even though the overall EV sales are lower in China that in the EU, BEVs are more popular in China than PHEVs, especially with the arrival of BEV city minicars. The prices for all vehicles manufactured in China are much lower than those manufactured in the EU or USA, as is discussed in *Section 3.2. Cost approximation*. Therefore, as most vehicles sold in China are also catered to this market, international brands establish factories in China to manufacture vehicles affordably.

### 2.2.2. Current BEVs benchmarking

After having analysed the state of the BEV in the global automotive market, a study of the current BEV models is needed to gain insight on the capabilities, technologies, specifications and prices for these vehicles.

This section excludes any sports-car, super-car or hyper-car, as the technology scope in these vehicles isn't fitting for this study.

Various technical aspects of the car are studied in the next sections, all of which are related to the manufacturing costs as is explained in *Section 3.1. Applied methods to reduce manufacturing cost*. After these aspects are discussed, a brief overview of the best-selling BEVs and of the relevant affordable BEVs is carried out.

#### *2.2.2.1. Platform*

Platform sharing is a very common practice in the automotive industry nowadays, with manufacturers having numerous vehicles produced with the same engines, frame underpinnings and other components. These may be different models under the same brand, automotive group, or even between brands of different groups.

Regarding BEVs, platforms can be classified in 3 groups:

- ICEV – EV Platform

  These are platforms that underpin BEV, ICE, and even other EV vehicles (PHEV, HEV…). These can be under the same model name (i.e. VW Golf, which until 2020 had both ICE and battery powered versions) or under different brand or models names, like the Dacia Spring, a BEV which shares its platform with other ICEVs.

  The main advantage of this type of platform sharing is reduced costs. These arise from manufacturing a large number of identical components between models. Nevertheless, BEVs based on platforms with ICEV counterparts have to compromise on the design, meaning that it does not take advantage of the packaging advantages that the BEV powertrain offers, or at least not as much as a BEV platform-based car does.

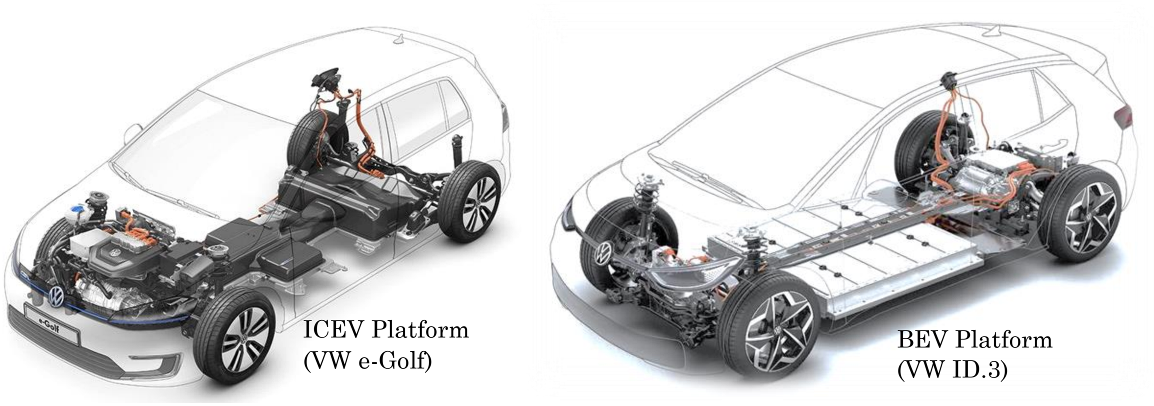


*Figure 8. Comparison between ICEV and BEV platform (BEV model). Sources: (CAR, 2017), (Motor1, 2020)*

This is seen in *Figure 8*. On the left a 2015 Volkswagen e-Golf is shown, and on the right a 2020 Volkswagen ID.3. The electric motor and inverter have to occupy the combustion engine bay in the e-Golf, and the batteries are positioned in the available spaces left from removing the rest of the ICE's powertrain components.

On the other hand, in the ID.3, a BEV platform-based car, the positioning of the electric powertrain components is much more optimized: the batteries are located flat on the floor, spanning the entire width of the car, aiding with design simplicity; and the electric drivetrain, which is smaller and more manageable, cap be positioned in the rear under the boot, and therefore the available interior space at the front of the vehicle is much improved.

Furthermore, the drivetrain components distribution in a BEV that does not share platform with an ICEV allows for a better weight distribution and centre of gravity, as the weight is more centralized, evenly distributed, and closer to the ground.

- BEV Platform

These vehicles are those that share platform with other BEV models. The advantages of these types of vehicles are, both design optimization and price reduction. The problem facing these vehicles at the moment is the lack of sales of BEVs. Although on the rise, it's still complicated to have similar BEV models under the same brand or group, as there may not be enough combined sales to meet the desired production numbers to decrease the price of each vehicle.

- Independent BEV

These are vehicles which do not share platform with any other vehicle (e.g, Renault Zoe), so they are designed from the ground up to be optimized for such model specifications. The main disadvantage of these types of vehicles is the fact that the manufacturing price will be higher than the others. This is due to the fact that not as many of the same components will be manufactured as the other two types, so production costs will be higher, as is discussed in detail in *Section 3.1.1.2. Highly versatile BEV platform. Ease of scalability*

Analysis of the 20 best worldwide selling cars indicates that the public prefer BEVs that are either based on a dedicated BEV platform, or those that are independent BEVs. This can be seen in *Figure 9*, which shows the best-selling BEV model sales and their type of platform. Although the price for BEV platform is higher, because of the reasons mentioned above, these models' designs take advantage of the BEV powertrain's packaging capabilities, which could be the main reason for which sales for these vehicles is higher than those based on existing ICEV platforms.

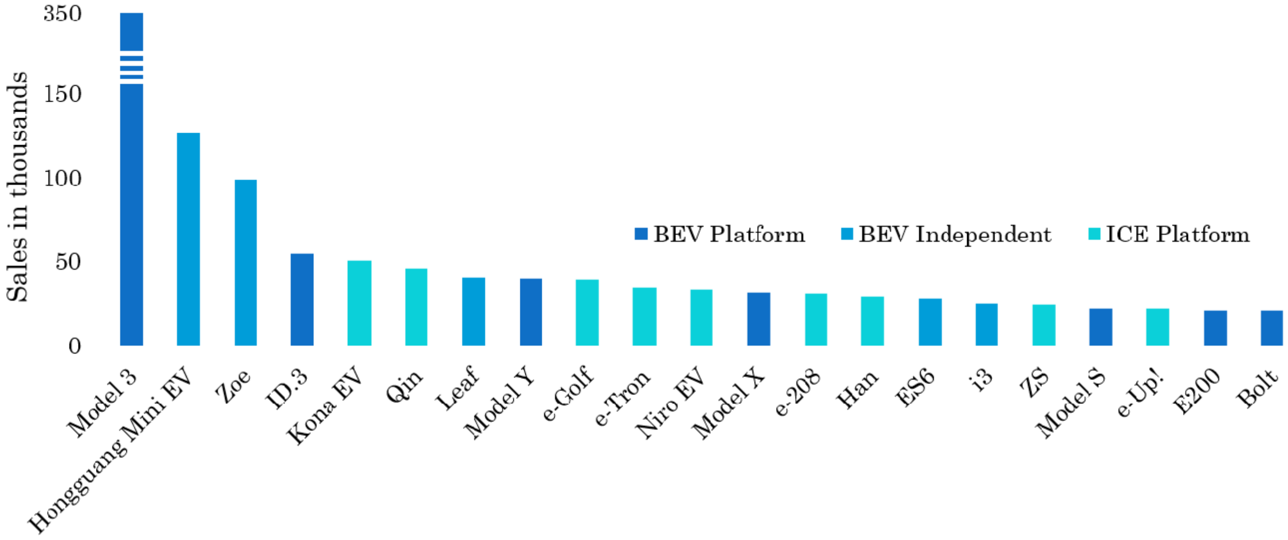


*Figure 9. Best-selling BEV models, by type of platform. Sources: (EVSpecs, 2020) (EVdatabase, 2020) Data in Appendix Table B-3.*

### *2.2.2.2. Range and battery specifications*

These two aspects of the vehicle are grouped together as range is largely correlated to battery capacity. Other factors also affect range, specifically weight, powertrain efficiency, aerodynamics and rolling resistance; these are explained in the following sections.

*Figure 10* shows the WLTP range (Worldwide harmonised Light vehicles Test Procedure) for the vehicles analysed (seen in ***¡Error! No se encuentra el origen de la referencia.***) in function of their battery capacity, measured in kWh. The weight is also graphed in function of the battery capacity, although the effect of battery capacity on weight is discussed in the next section. As is seen in the figure, range is not directly proportional to the battery capacity, as the computed average for the WLTP range slightly decreases in slope as the kWh increases. This is mainly due to the increase in weight brought by the larger battery, this is discussed in the next section as well.

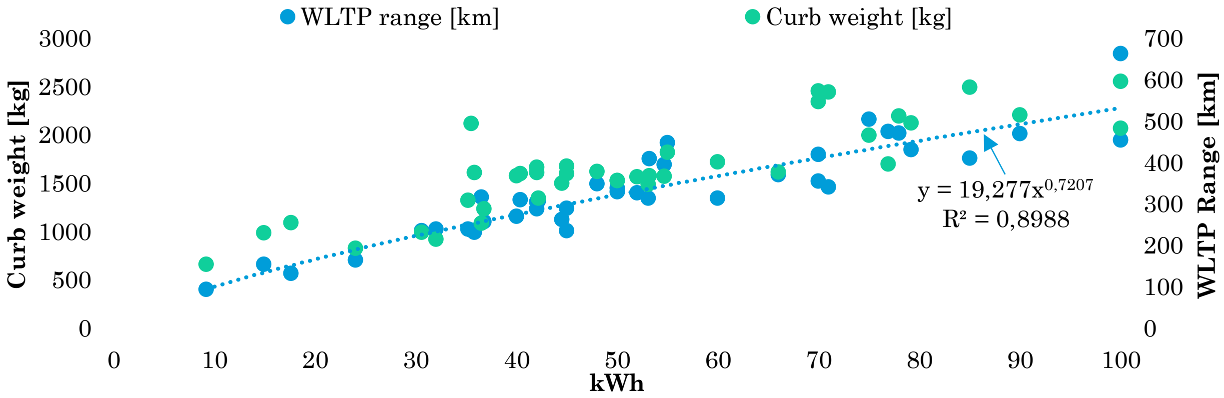


*Figure 10. Curb weight and WLTP Range in function of kWh. Sources: (EVSpecs, 2020) (EVdatabase, 2020) Data in Appendix Table B-4 and B-5*

Range is directly correlated to the battery capacity with the rated consumption (Wh/km), given by the manufacturer. This accounts for the previously mentioned factors, and depending on the specifications of the vehicle, it can range from 138 Wh/km (this being the best) to 257 Wh/km. (*Appendix Table B-5*)

Naturally, the less resistance (be it aerodynamic, rolling, mechanical or electrical) and weight, the lower the rated consumption will be, and therefore a higher range will be obtained for a specific battery capacity.

Given the fact that the battery is the largest cost contributor of vehicle manufacturing (as is discussed in *Section 3.1. Applied methods to reduce manufacturing cost*) in order to be able to have more affordable electric vehicles, some manufacturers (especially Chinese) opt for a small battery capacities, down to 9.2 kWh, to reduce costs. Nevertheless, this approach reduces range to a minimum, and limits the functionality of the vehicle. In this particular example, the model is the Hongguang Mini EV, a city minicar which has been the 2nd best-selling BEV during 2020, and is rated at just 120km NEDC range (New European Driving Cycle). Despite this, it has found a large enough market in China for this type of affordable, low-range BEV.

On the other extreme we can find batteries with up to 100 kWh on the 2020 Tesla Model S Long Range Plus, the cheapest available variant of the Model S during 2020. With a rated consumption of 180 Wh/km, it achieves a 713 km NEDC range. This approach greatly increases range, but also price, so potential buyers are reduced. (*Appendix Table B-5*)

### *2.2.2.3. Size and weight*

Currently BEVs range from small city cars to large SUVs, the only segment as of April 2021 to not have a BEV model available is the pick-up segment.

ICEVs' weight has generally depended on 2 factors: size and quality of build. As determined by the analysis done by (Lutsley, 2010), there is a difference in weight for same-sized cars which are different classes, with higher class cars having a higher mass than lower-class ones, given that higher-class vehicles are sturdier, generally safer, and use more material for the overall product. *Figure 11* shows the increase in weight of the averaged brands' model line-up, depending on the vehicles footprint. As can be seen, the average increase in weight is quite proportional to size, nevertheless, this is not the case in BEVs.

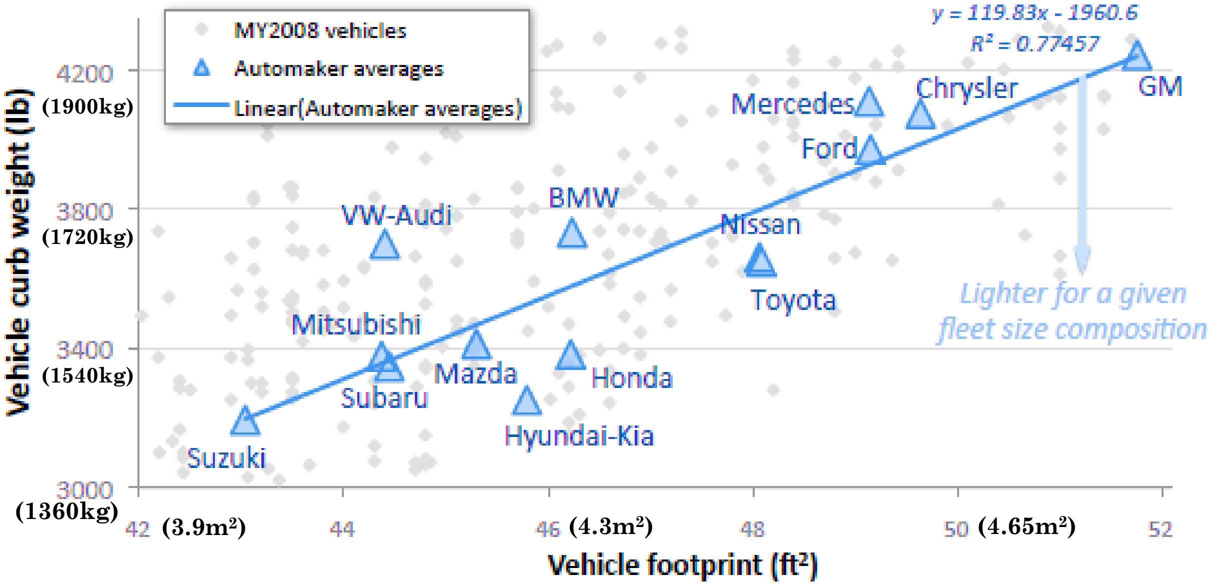


*Figure 11. Curb weight vs. vehicle footprint. Source: (Lutsley, 2010)*

In the case of ICE powertrains, the weight of the system increases relatively proportional to the vehicle's weight, size and engine power, whereas in a BEV, the largest weight contributor in the powertrain is the battery. The weight of the battery capacity is so large, in fact, that it can take up between 15 and 30% of the total vehicle weight, as can be seen in *Figure 13*. *Figure 12* shows the weight distribution of an average ICEV, and of the Tesla Model S. The weight percentage of the whole electric powertrain is much higher than that of the ICEV, apart from being overall heavier, since BEVs in most cases have a higher curb weight, which is visually represented in the pie charts by their relative size.

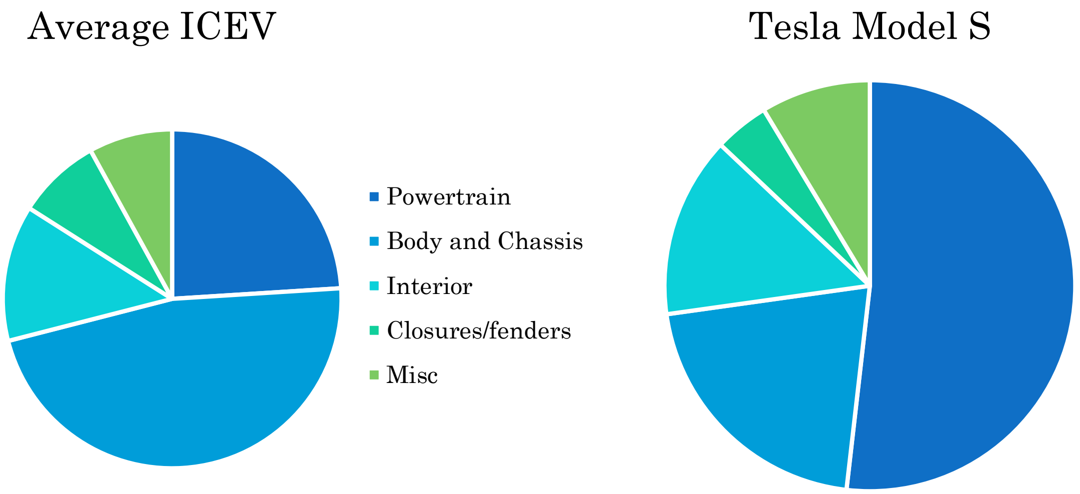


*Figure 12. ICEV vs BEV weight comparison. Sources: (Lutsley, 2010), (Kenneth, 2016). Data in Appendix Table B-7.*

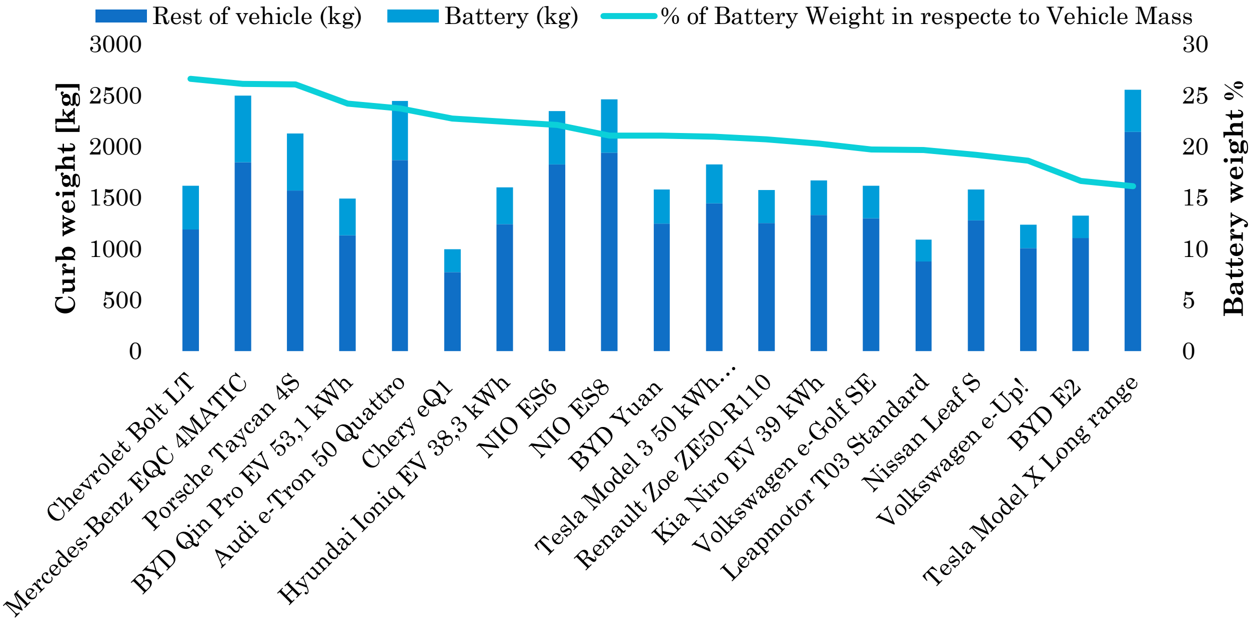


*Figure 13. BEV weight comparison. Sources: (Berjoza, et al., 2017), (EVSpecs, 2020). Data in Appendix Table B-2.*

Nevertheless, the weight of the whole battery pack is not directly proportional to the battery capacity and the energy density of the cells, as could be initially assumed. Instead, the power electronics, on-board charger and the battery structure and case also have an effect, this being that generally speaking, the larger the capacity, the better the energy density at the pack level [Wh/kg] (*Figure 14*). This is because the aforementioned devices can be considered as "fixed" masses for the battery pack, and so as the number of cells increases, the weight of these components is less noticeable, and the energy density at the pack level increases.

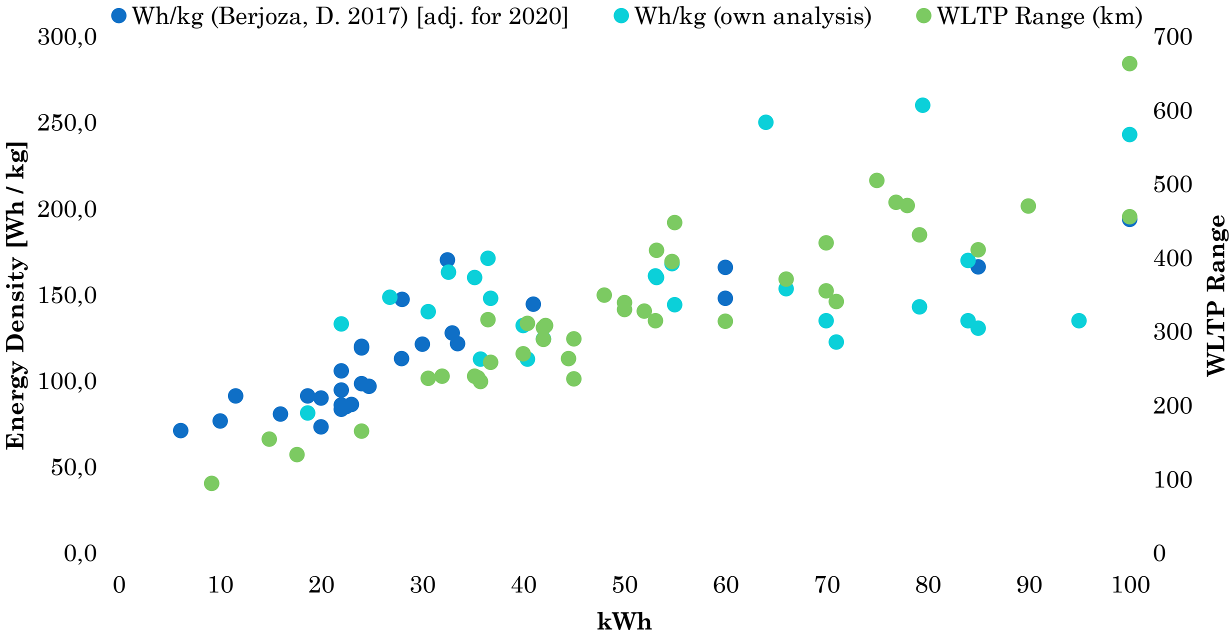


*Figure 14. Energy density (at the pack level) and WLTP Range vs. kWh. Sources: (Berjoza, et al., 2017), (EVSpecs, 2020). Data in Appendix Table B-2.*

The three extreme points in *Figure 14* regarding energy density are Tesla's Long Range variants, which claim up to 280 Wh/kg for the largest of the batteries, an incredibly good value when compared to the rest of the analysed models.

This increase in energy density does not avoid the fact that range does not increase proportionally with battery capacity, as the increase in weight from the battery when adding more cells is enough to have an effect on range, as the energy consumption increases with size. This can be seen in *Figure 15*, which graphs the calculated energy consumption ( $Energy\ density = battery\ capacity\ [kWh]/WLTP\ range[km]$ ) vs. the curb weight of each vehicle. Although disperse, because of aspects like aerodynamics or powertrain efficiency, it is clear that energy consumption is lower with a lower weight car.

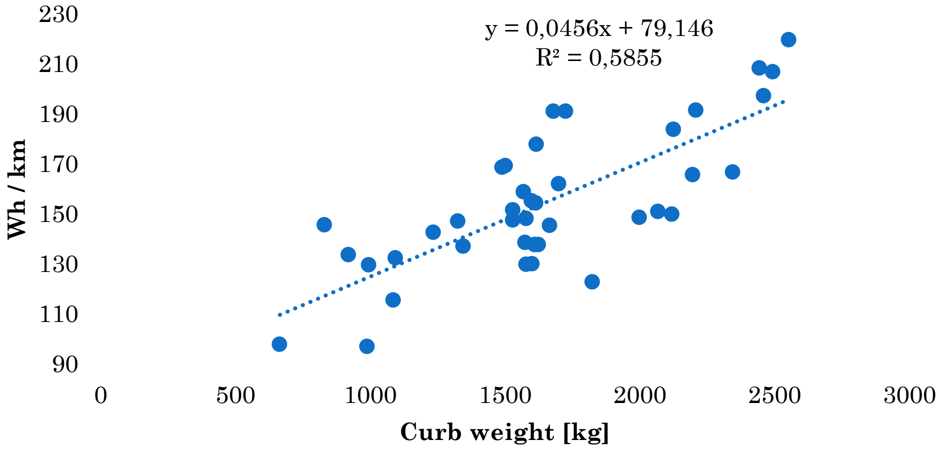


*Figure 15. Calculated consumption vs. curb weight. Sources: (EVSpecs, 2020) (EVdatabase, 2020). Data in Appendix Table B-4 and B-5.*

#### *2.2.2.4. Electric powertrain specifications*

Total power in current BEVs ranges from 30 to 700 kW, and this is achieved via a combination of 1 to 3 motors, positioned on either axle. All of the models studied have on-board mounted motors, as opposed to hub mounted motors, as you could find in an electric scooter. This is because on-board mounted motors are cheaper to design and manufacture, simplify suspension design, and have a better effect on weight distribution and un-sprung mass. Un-sprung mass is the mass which is not supported by de suspension system, and it is important to lower it as much as possible to obtain better vehicle dynamics and control. Furthermore, to have a stable and safe vehicle with hub-mounted engines, you need at least two engines, one for each side, so this option is not considered when designing an affordable vehicle.

We can differentiate between three types of electric motors used in BEVs: Induction Motors (IM), Permanent Magnet Synchronous Motor (PMSM) and Internal Permanent Magnet Switched Reluctance motor (IPM-SRM). In the case of BEV motors, all use AC current, so an inverter is always required to modify the current from the DC current from the battery pack.

- Induction Motors

Induction motors are composed of a stator winding and a rotary rotor winding, and the electric current needed to produce torque in the rotor is induced electromagnetically due to the rotating magnetic field produced by the AC current in the stator winding.

They are also referred to as “asynchronous motors”, because they operate at a lower speed than their synchronous speed, which is the speed of rotation of the magnetic field in a rotary machine, and it depends on the frequency and number poles of the machine. Nevertheless, a higher than synchronous speed can be achieved by field weakening thanks to current field-oriented vector control systems, but the higher speed comes at the cost of reduced torque.

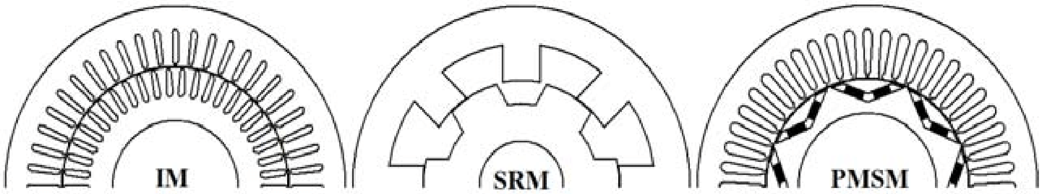


*Figure 16. Electric motor diagrams. Source: (Cheng, et al., 2015)*

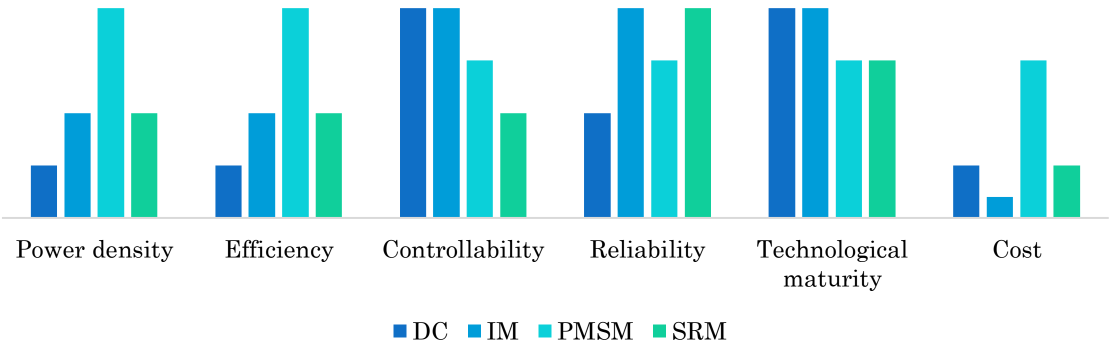


*Figure 17. Comparison between different types of electric motors. Source: (Osmanbasic, 2020)*

This design has been around since 1887 (Puiu, 2020), so the technology has had a lot of time to develop and mature, so its advantages are a simple construction, high reliability, robustness, simple maintenance, and low cost and operation in different environmental conditions. (Osmanbasic, 2020). The disadvantages of IMs are slightly lower efficiency (compared to PM motors), higher power losses derived from the cage losses from the winding, and a relatively low power factor.

- Permanent Magnet Synchronous Motor (PMSM)

In this type, the field is excited by permanent magnets that generate sinusoidal back EMF. It contains a rotor and stator, same as those from an induction motor, but a permanent magnet is used as a rotor to create a magnetic field, hence there is no need to have field winding on the rotor.

PMSM motors have a higher efficiency compared to IMs. The drawbacks of this type of motor are high costs, eddy current losses in the permanent magnets at high speed, and a reliability risk because of the possible breaking of the magnets

- Internal Permanent Magnet Switched Reluctance motor (IPM-SRM)

A switched reluctance motor produces torque by changing its magnetic reluctance stator. It has salient poles and includes windings identical to a brushless DC motor, but the rotor is made of steel cut into salient poles without magnets or windings, and the power is supplied to its stator windings.

It benefits from a low cost and good efficiency. The lack of winding or permanent magnet on the rotor means that an SRM is appropriate for extremely high speed applications, and can withstand high temperatures. Furthermore, it results in a rugged and simple structure and low manufacturing cost. At the same time, if a fault occurs in any one winding or phase, the motor can still work but at a reduced load. However, SRMs have non-linear characteristics because of magnetic saturation, which makes it complicated to accurately control its torque.

To give some examples, the Tesla Model S and Model X use conventional IMs, while the Model 3 uses an IPM-SRM. Dual-motor versions use an IM in the front and an IPM-SRM in the back. It is the opposite case for the Model S and Model X. The GM Chevrolet Bolt uses a PMSM where the magnets are placed inside the rotor. This motor type is also used by the Toyota Prius, Nissan Leaf, BMW i3, and most other models. (EVSpecs, 2020)

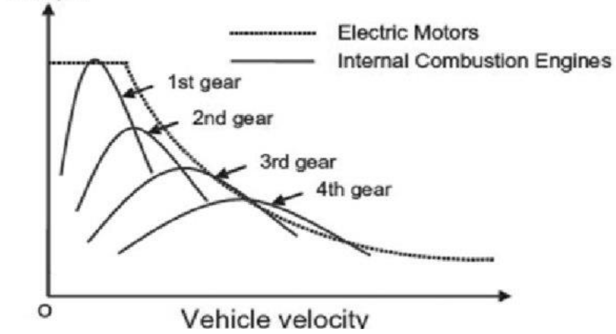


*Figure 18. Wheel torque comparison ICEV-BEV. Source: (Zhang, et al., 2017)*

Torque in electric motors is generally higher than that of an equally-powered combustion engine, and pairing this with the almost-instant torque delivery and a higher RPM limit (up to around 8,000 to 10,000 RPM), most manufacturers opt for a single-speed transmission, as more gears are simply not needed, and it lowers manufacturing cost. The trade back is a lower top-speed compared to an equivalent ICEV. Wheel torque vs. vehicle speed for both an ICEV and a

BEV is seen in *Figure 18*, and as is evident, the torque characteristics of an electric motor enables to have a single-speed transmission, whereas the torque curve of an ICEV requires various gears to achieve the desired torque over a velocity range.

### *2.2.2.5. Best-selling BEVs analysis*

In this section the best-selling BEVs are discussed. All the data discussed next is seen in *7.2 Appendix B*. *Figure 19* shows the sales of the 30 best-selling BEVs in the 3 key markets. Except for the Tesla Model 3, most models are either only available in one of the countries, or their sales are strongly balanced towards one of them.

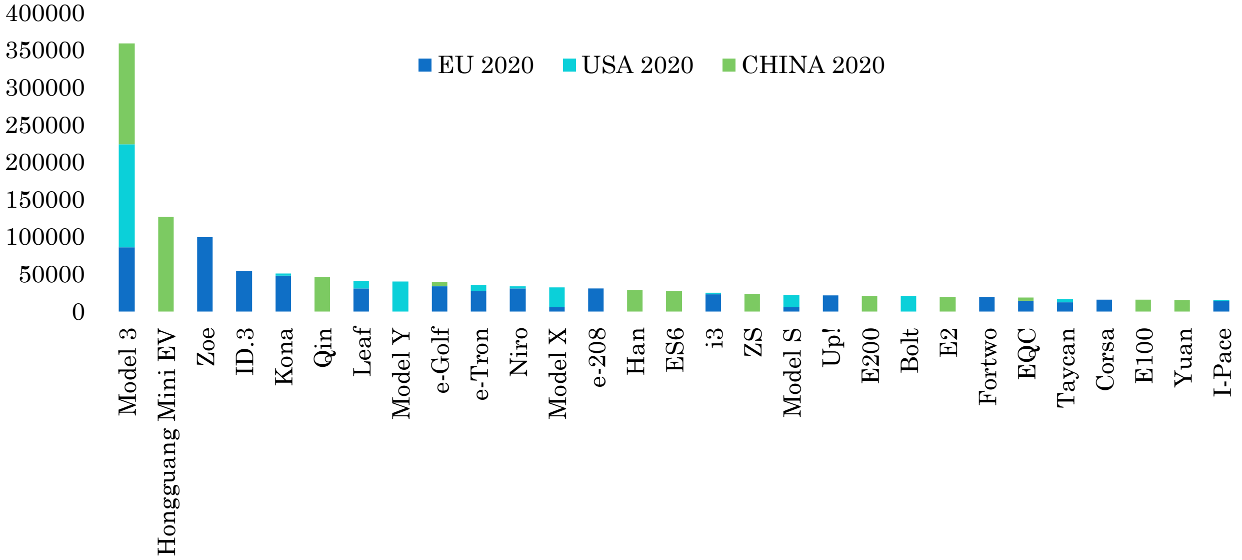


*Figure 19. Best-selling BEVs 2020. Data aggregated from Appendix Table X-1.*

*Figure 20. Tesla Model 3 [46,970€]. Source: (KindPNG)*

The best-selling BEV during 2020 has been the Tesla Model 3, a mid-size sedan which comes in three variants: Standard Range Plus RWD, Long Range AWD and Performance AWD. The lowest variant, Standard Range, has a 55 kWh lithium-ion battery, which combined with a 140 Wh/km rated energy consumption is capable of a 448 km range (WLTP). In Spain, as of April 2020, the retail price for this variant is 46,970 €. The rear IPM-SRM produces 202 kW and 404 Nm, which can propel the 1,670kg vehicle to 100 km/h in 5,6s, and up to a top speed of 225 km/h. The battery weights approximately 380kg, and has an energy density of 144 Wh/kg. It has been an international success, being the best-selling car in both the Chinese and Nort-American market.


*Figure 21. Hongguang Mini EV [3,760€ (China)] Source: (Gasgoo)*

The second best-selling BEV, even though it was only launched in November 2020, is the Hongguang Mini EV, a minicar which was only available in the Chinese market during 2020. It has a 9.2kWh battery, and a 13.4kW motor. It is designed for city use, but it can also reach 100 km/h thanks to its low weight (665kg). The objective of this vehicle is similar to the one for this project, but in the case of the Mini EV, it is much smaller and has a more limited range. The engine and inverter are located in the front, while the extremely small battery is mounted under the rear seats. These rear seats would probably not accommodate most adults comfortably, nevertheless, it is marketed a 3-door 4-seater. It is extremely affordable, priced at the equivalent of 3,760€. Nevertheless, it must be said that all Chinese-made vehicles are lower in price compared to European or American-made cars, and this is, as discussed in detail in *Section 3.2. Cost approximation,* mainly because of the cheap resources and labour that are available in China, as well as the country itself having a low currency exchange rate in order to increase exports, so direct cost comparison with Chinese-made vehicles is senseless.

The next two best-selling BEVs have been the Renault Zoe, and the Volkswagen ID.3, both only available in the EU during 2020. The Zoe in its lowest trim has a 55kWh battery and is rated at 395km WLTP, whereas the ID.3 has a 48kWh battery rated at 349km. The ID.3 is longer and wider, and therefore weighs more than the Zoe. Both are 5-door, 5 seat hatchbacks, but while the Zoe has a 80kW front mounted engine, the ID.3 uses a 110kW motor in the rear. The Zoe is currently the only vehicle produced with its platform, whereas the ID.3 is manufactured on the same platform as the ID.4, and future VAG electric models.


*Figure 22. Renault Zoe (left) [32,500€] and Volkswagen ID.3 (right) [36,145€] Sources: (A.M.), (AutoBild)*


*Figure 23. Hyundai Kona Electric [39,650€]. Source: (EVCP)*

The Hyundai Kona Electric is the 5th best-selling BEV, and the first crossover on the list, which again reaffirms how different the segment distribution is in comparison with ICEV, where many more crossovers and SUVs occupy the best-selling spots on the list. It can reach a 305km WLTP range thanks to the 42kWh battery.

The most affordable BEVs in the European market are the Dacia Spring, the Volkswagen e-Up!, and the Renault Twingo ZE. The Dacia Spring is manufactured in China, so it has a considerably low price. It has a 26,8kWh battery capable of reaching 225km. The front mounted motor produces 33kW.

The e-Up! has a 36,8kWh battery, 258km range, and 61kW thanks to the front-mounted motor. The Twingo has the same power but only 23kWh of battery capacity, reaching 190km. All three vehicles are based on ICEV platforms, nevertheless the Twingo platform is already rear-engined.

*Figure 24. Volkswagen e-Up! (left) [22,800€] . Renault Twingo ZE (middle) [22,750]. Dacia Spring (right) [16,990€]. Source: (VW), (Renault), (Teintes)*

### 2.2.3. The cost gap between ICEs and BEVs

As we have seen in the previous sections, BEV sales still represent a very small percentage of the international PC sales. Despite the increase in sales of BEVs over the years, the majority of people still buy an ICEV, even though society has clearly become more aware of the need to buy electric cars to help reduce global warming and pollution.

There are various reasons that are responsible for these low sales, and in this project focus is brought onto one of them: the cost gap between ICEVs and BEVs. The other most important reasons/factors for low sales are the limited range of BEVs and the lack of charging infrastructure, these are discussed in further detail in *Section 3.3. Product Target*

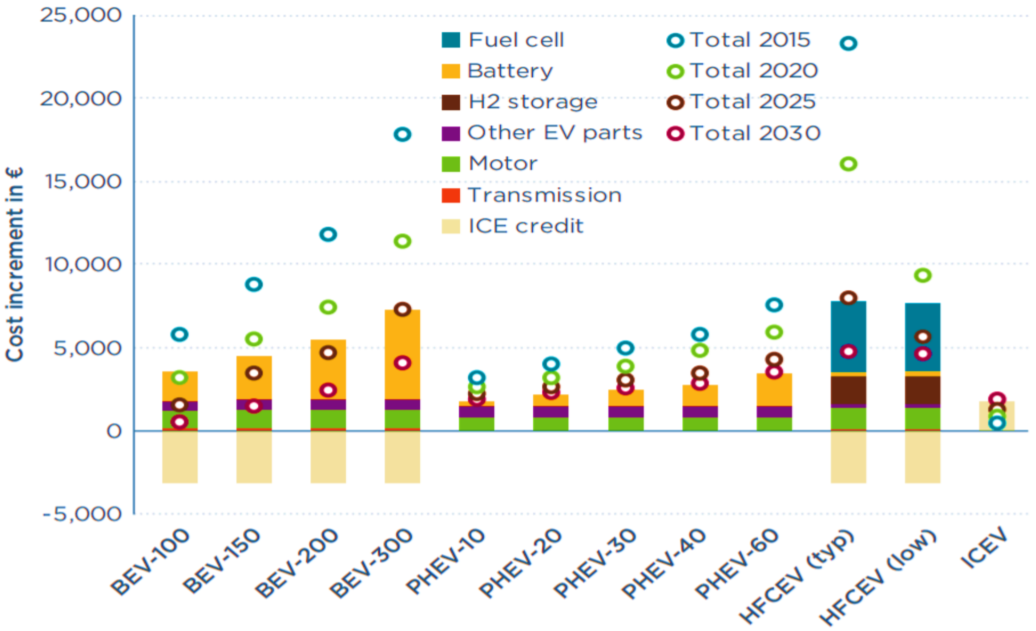


*Figure 25. Cost increment for different types of EV. Source: (Wolfram, et al., 2016)*

The problem lies in the fact that BEVs are more expensive than equivalent ICEVs, that is, ICEVs with similar size, power and build quality. This can be seen in *Figure 25* (Wolfram, et al., 2016), where the cost increment for various types of EV in comparison to an ICEV are shown for various years. The numeral suffixes in the x-axis refer to the electric-only range [miles]. As can be seen in the figure, when not considering the government BEV discount, BEVs are on average between 7,000€ and 13,000€ more expensive, depending on the range. It can also be seen that this cost increment is mostly due to the battery costs. These costs are discussed in detail in *Section 3.1.2.1. Battery capacity limitation.*

The relation between battery capacity and range has previously been discussed in *Section 2.2.2.2. Range and battery specifications*, where it is shown that range increases with battery capacity (quasi-linearly). Therefore, a higher range in a BEV increases price substantially, as is also seen in *Figure 25*, where longer range BEVs are substantially more expensive than shorter range ones.

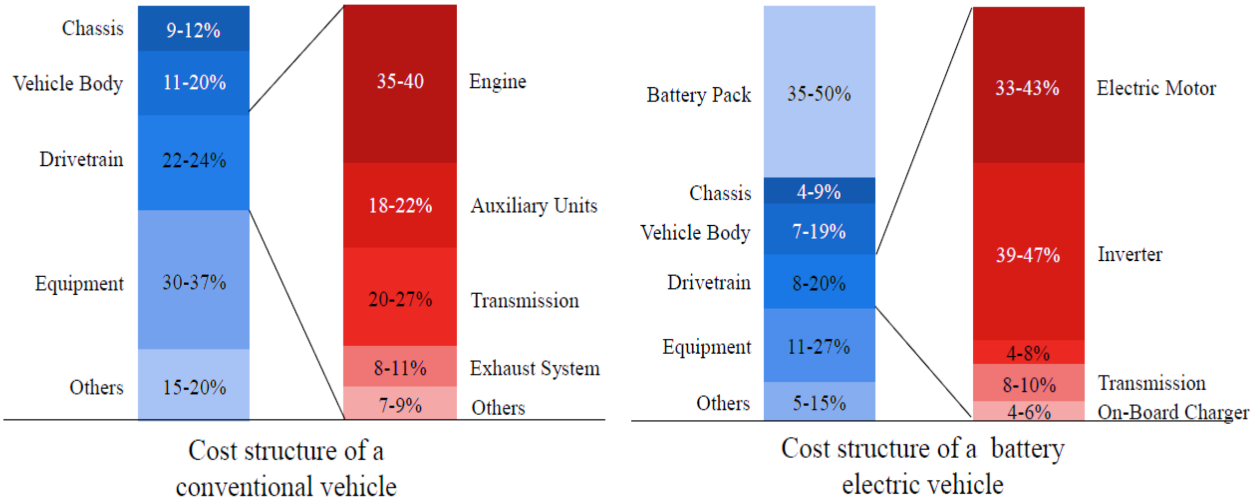


*Figure 26. Manufacturing cost comparison ICEV vs. BEV. Source: (Fries, et al., 2017)*

The effect of the battery pack cost on the overall price of the vehicle is seen more clearly in *Figure 26* (Fries, et al., 2017), where a comparison is shown between the manufacturing costs percentages of each of the vehicle's systems, both for ICEVs and BEVs. In this case, both are graphed as percentages, so the price difference is not appreciated. As seen in the figure, the battery pack can account for up to 50% of the manufacturing cost, and the electric drivetrain between 8 and 20%, whereas in an ICEV the combined cost percentage of the drivetrain is much lower, around 23% when combining all the powertrain components. It is important to mention that these percentages are in function of the manufacturing cost, and not the selling price.

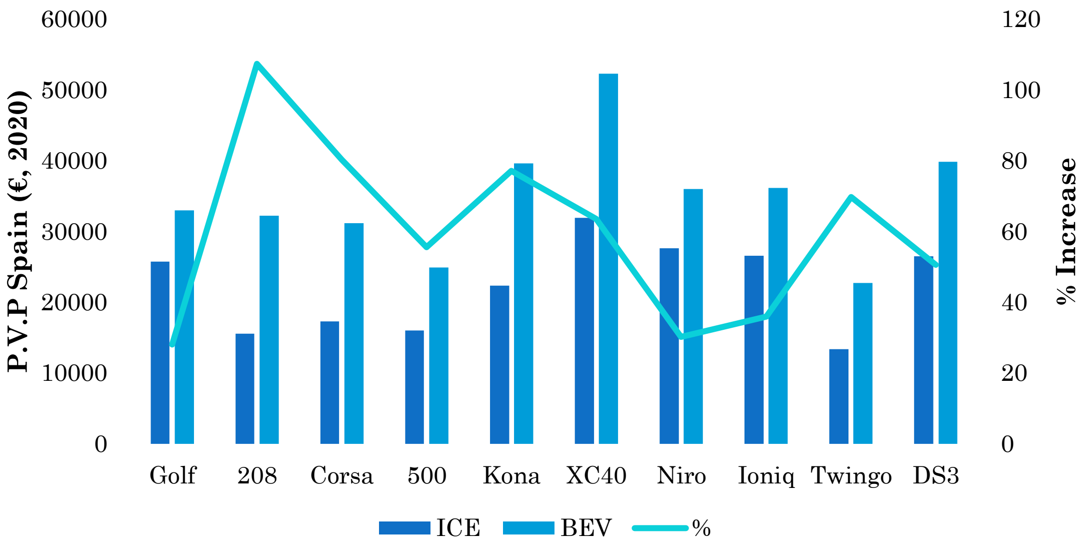


*Figure 27. Price comparison between equivalent ICEV-BEV models. Source: (coches.com) Data in Appendix Table B-8.*

By studying the MSRP price for models that have both ICEV and BEV variants, we get a clearer view of this price discrepancy. This is seen in *Figure 27*, where the prices of the cheapest ICEV and BEV variants of different models are plotted, as well as the percentage price difference between them.

As can be seen in the figure, prices vary from as little as 7,230€ for the VW Golf models, having a 28% increase; to 20,336€ for the Volvo XC40, which has a 63% increase. The highest percentage increase in price is found between the Peugeot 208 models at 108%, a 16,700€ increase in price. Another aspect to consider is that these vehicles are BEVs that share platform with ICEV models, and therefore will have an overall lower manufacturing price than an equivalent BEV which does not share platform with ICEVs. Nonetheless, it could be the case that certain manufacturers increase their selling price for BEVs, now that they are seeing a strong surge in sales, although the opposite may be true, with manufacturers reducing the BEV sales price to increase sales. This is very hard to determine, as different manufacturers will have different strategies and objectives for their models, and no information regarding this aspect was found.

It is important to mention that, although the BEVs shown are limited in range when compared to the ICEV variants, the electric motor specifications eclipse in all the cases the ICE variant specifications, and the interior and exterior trim in the BEVs are overall better or more equipped than most of the basic level ICEV variants.

A study performed in 2019 by Nic Lutsey and Michael Nicholas (Lutsey, et al., 2019) indicated that price parity for a 150km range BEV car will be achieved in 3 to 9 years (from 2020), as the price for the battery will become lower [€/kWh]. This can be seen in *Figure 28,* sourced directly from said study, where the future expected price parity for different ranged body-types is shown. The BEV150/200/250 nomenclature refers to the electric vehicle's range in miles

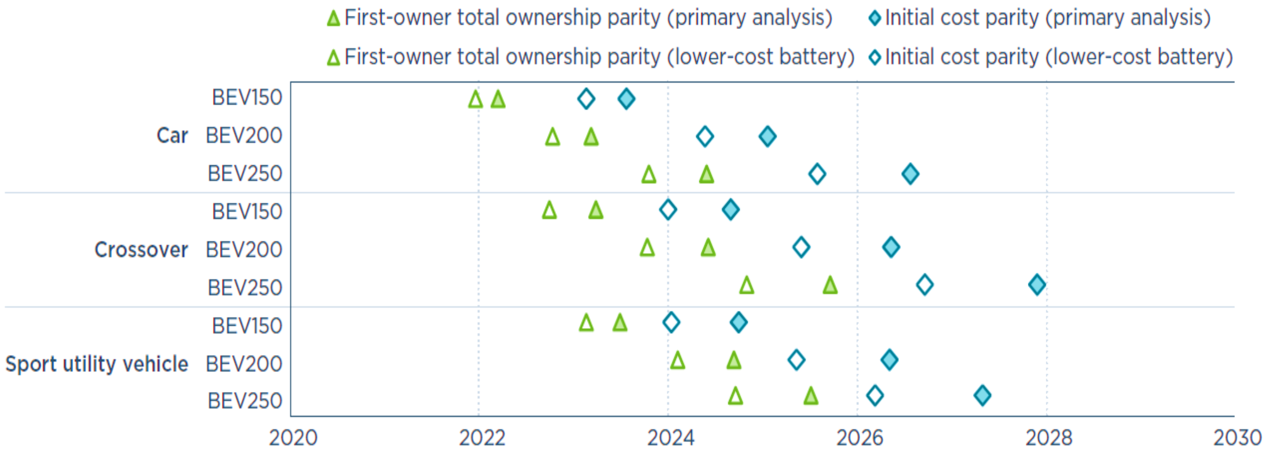


*Figure 28. Cost parity forecast. Source: (Lutsey, et al., 2019)*

From this graph, initial cost parity is the relevant value. Naturally, low range cars (BEV150) will achieve price parity first, in 2023, with low range crossovers and SUVs following a couple years later. Mid-range cars (BEV250) will start achieving price parity around 2026, according to this study.

However, one might consider this forecast slightly optimistic when looking at the previously analysed selling prices from current BEVs in comparison to ICEVs, as prices are still very high in Europe to be able to achieve price parity in the 3 years indicated in the study.

Therefore, price parity for BEVs will eventually come naturally as a consequence of reduced battery manufacturing costs. Nevertheless, as has been seen during this entire section, BEVs still have a high enough price difference to greatly reduce potential buyers, as reported by The Guardian in September, 2020. (Jolly, 2020)

# 3. Design Concept

After having analysed the current market, one can see that there are not many affordable 5-door BEV models, especially in Europe and the USA, where electric cars have a starting price of at least 22,000€, with some exceptions like the Dacia Spring. China has a wider range of affordable BEVs, but these are generally very small 3-door 2-seat models, and if they do manage to seat 4 people, the ones in the back can be quite crammed.

Furthermore, these affordable BEVs have a very limited range, as their main path to cost-reduction is through battery capacity reduction, up to a point where the low range may throw potential buyers back from choosing a BEV over an ICEV.

The large and immensely packed cities in China have given these low-range BEVs a large set of buyers, whereas in Europe potential buyers see range as one of the main factors when considering buying a BEV, so a greater battery capacity has to be implemented in this market. (*Section 3.3. Product Target*)

Now, centring the focus on Europe, as by the information explained in *Section 2.2.1.1. Europe PC Sales*, there is a substantial market in Europe for minicars, and most of the sales of these small vehicles come from lower-class models, such as the Hyundai i10, Peugeot 108, Citröen C1, Renault Twingo or Kia Picanto. The problem, as explained in the previous section, is that the cost gap is too large at the moment for someone with a budget between 10,000€ and 20,000€ to consider buying a BEV, unless their daily commute is a limited distance, or an excellent charging infrastructure is available nearby. This means a charging infrastructure which would allow you to charge at nearly every one of your daily destinations, which is currently not the case in most countries or cities.

The objective of this section, and of this project, is to explain what technical design specifications and characteristics a 5-door BEV could have in order to achieve a moderate range and be able to compete in price with ICEVs, as well as explaining the cost-reduction methods that can be applied to reach these objectives. This vehicle is specifically intended for the European market, and the material and manufacturing costs are based on European values, hence the price reduction is not accomplished by manufacturing the vehicle in cheaper economies such as China or India.

The vehicle is designed to fit up to a 95th percentile male in the front, and a 90th in the rear, relatively comfortably. The car is not performance oriented, so power and torque figures or vehicle handling characteristics are not prioritized, although the small size and weight, short wheelbase, and the instant torque from the electric motor make it ideal for urban use. Range is limited, and the vehicle is intended for short personal or work commutes, and would not be adequate, for example, to use for long-distance vacations. The target for the product are not people who enjoy driving, or whose car is a prized possession (in informal terms, *petrolheads*), but rather people who use the car as a tool to go from A to B, which are environmentally conscious, and who have a relatively low budget. (Discussed in detail in *Section 3.3. Product Target)*

A good way to understand the design objectives of this vehicle is to picture the objectives for the Citröen 2CV, the Volkswagen Beetle, the Volkswagen Golf, or the Ford Model T, all vehicles which were designed to be as practical as possible, while making them affordable for the majority of the population. In our case, the objectives are sought after in a modern, urban BEV.

All of the costs discussed in the next sections are as of 2020 or earlier, and therefore it is treated as if production could start right away, neglecting the necessary months or years of R&D and production line design and assembly. The overall costs of the vehicle if it were produced in 5 or 10 years' time would reduce noticeably, as seen in *Section 2.2.3. The cost gap between ICEs and BEVs*, due to lower battery costs.

None of the ideas or methods applied to reduce costs discussed in the next section are new, as all have been implemented in the automotive sector at one point or another. Nevertheless, there currently does not exist a vehicle with all the discussed specifications combined, and this is what makes the proposal unique.

The design shown in the next sections only serves as a proof-of-concept for some of the methods applied to reduce costs, as the 3D model is not the main scope of the paper. The objective of the proposed 3D design is to make it easier to visualize how a vehicle of the proposed specifications could be.

*Figure 29. Design proposal. Source: own elaboration*

## 3.1. Applied methods to reduce manufacturing cost

Before the explanation of the methods to reduce manufacturing costs, it's important to note that the total manufacturing cost of a passenger car is approximately 50% of the retail sales price. (Discussed in detail in *Section 3.2. Cost approximation*) The exact amount is unknown probably even to manufacturers, as it has to take into account the brand or group as a whole, which has so many variables that it is incredibly challenging to account for every one of them. (Roy, et al., 2008) This percentage over the manufacturing price comes from overhead management, R&D, marketing, logistics and distribution, dealerships margins and discounts, and other indirect costs.

The methods explained to reduce the price in the next sections are implemented in order to obtain a lower manufacturing cost, although some of them may also have an effect on the mentioned indirect costs.

Some of the design decisions have a very low impact on the manufacturing cost, but all options are considered in order to achieve the lowest price for a vehicle of the mentioned desired specifications.

In this section, these design specifications are simply explained and the reasons for the cost reduction are given, while the complete cost approximation for the proposed vehicle, with the indirect costs accounted for, is carried out in *Section 3.2. Cost approximation*, where the details for the calculations are explained.

### 3.1.1. General

This section details design specifications and decisions that affect the car as a whole, for example its size. As well as this, decisions which impact many systems of the vehicle are explained.

#### *3.1.1.1. Small size*

The first design specification is to reduce the size of the vehicle as much as possible, while still maintaining an acceptable amount of interior space, and without sacrificing safety, although small cars are inherently less safe than larger ones, due to the reduction of crash structure volume and smaller frame members and pillars.

A smaller size correlates to a lower weight, as we saw in *Section 2.2.2.3. Size and weight*, and, as we can see in *Figure 30*, weight is noticeably proportional to the price of the vehicle. Weight can be considered a more important cost contributor than the vehicle's footprint, since lower class vehicles have a lower mass than higher class ones, having the same footprint while costing less. (*Section 2.2.2.3. Size and weight*)

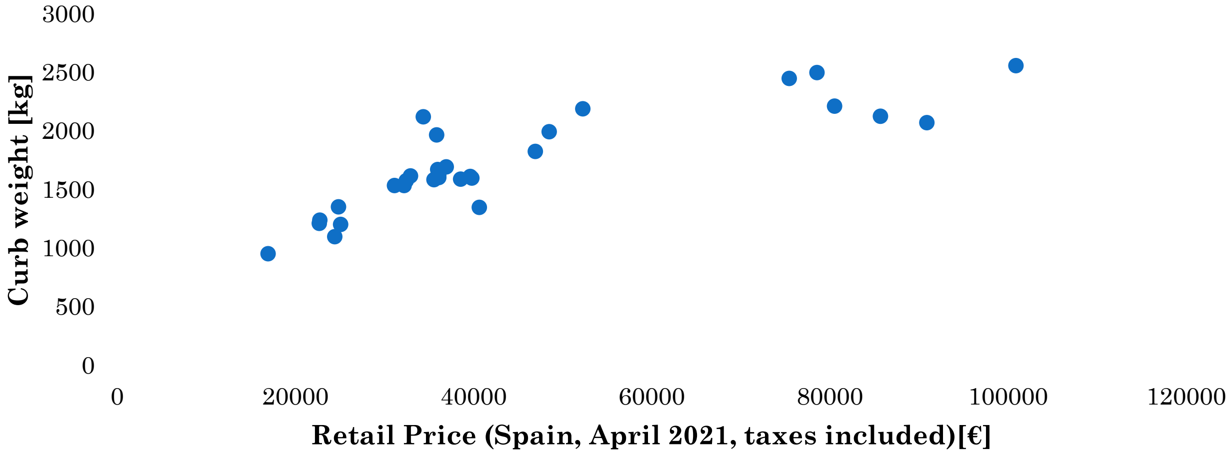


*Figure 30 BEV Curb weight vs. price. Sources: (EVSpecs, 2020) (EVdatabase, 2020), (coches.com). Data in Appendix Table B-3 and B-4.*

Even though it is not the only one, a reason for this relation of cost to weight is that, according to (Lutsley, 2010), 60% of the mass of a vehicle comes from steel, and at around 3 €/kg for the processed material (König, et al., 2021) it has a noticeable effect.

Furthermore, a small sized car needs around 25h of labour to assemble, whereas a vehicle the size of an SUV can take 50h of labour to complete. Depending on the country where the vehicle is manufactured, the hourly wages of the labour force vary, from 3€/h in China to 46€/h in Germany, in 2013 (Fries, et al., 2017). Therefore, according to this data, having a small sized car can lower the production cost from 150€ in China to up to 2,300€ in a country like Germany, when compared to a large vehicle, just from direct assembly labour costs. This does not account for the assembly of purchased parts, although these will in turn also be cheaper, as their size will also be reduced. Another impact of having a lower assembly time is lower indirect costs related to energy consumption and amortization of the facilities, as well as enabling an increase in daily production numbers.

The dimensions chosen for the vehicle are 3450 mm in length, 1650mm in width (without mirrors), 1450 mm in height, and a wheelbase of 2750mm. For reference, a Volkswagen e-Up! is 3600mm L/ 1645mm W/ 1492mm H / 2417mm WB, and the Renault Twingo is 3495mm L/ 1665 mm W/ 1554mm H/ 2494mm WB. These two vehicles can also carry 4 occupants, and are as compact as possible, but they are based on an ICEV platform. In this design this is not the case, because the BEV architecture enables a better optimization of the interior space, as was discussed in *Section 2.2.2.1. Platform.* This is seen in *Figure 31*, where a comparison of the interior distribution between a VW Up! and our proposal is shown. For the VW image, the percentile used for the shown passengers is unknown, and for this design a 95th percentile European male is used in the front, and a 90th in the rear. Both front and rear passengers have enough space to be seated, although the rear has a high floor due to the battery positioning. The biggest benefit is being able to move the front passengers forward thanks to the lack of a font-mounted ICE.

*Figure 31 Interior space comparison. (Models not to scale between each other). Source: (CARICOS), own elaboration.*

*Figure 32* shows a size comparison between different BEVs and this design proposal. As can be seen, it is a bit smaller than a Renault Twingo, and quite smaller than both the Model 3 and Model X.

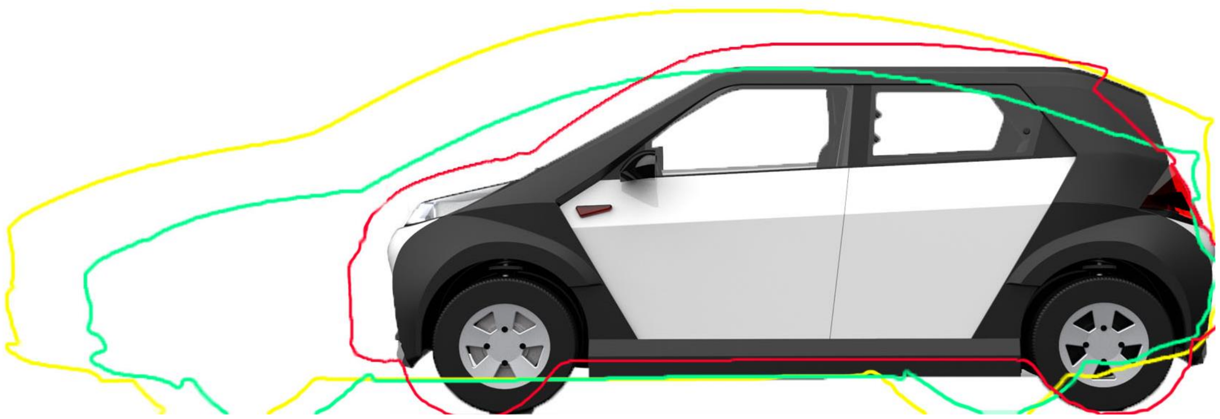


*Figure 32. Size comparison of Model X (yellow), Model 3 (green) and Twingo (red). Source: own elaboration*

A reduction in the overall size of the vehicle also scales down most of its components, and also reduces their weight. This, logical as it is, also means that all the tooling and equipment needed for the fabrication of the frame and body components is cheaper. This can be seen in *Figure 33* (Veloso, 2001), where tool investment costs are estimated according to the components' weight and complexity for a steel stamping line. This does not directly influence manufacturing costs, but the cost of the tooling and equipment is more quickly amortized.

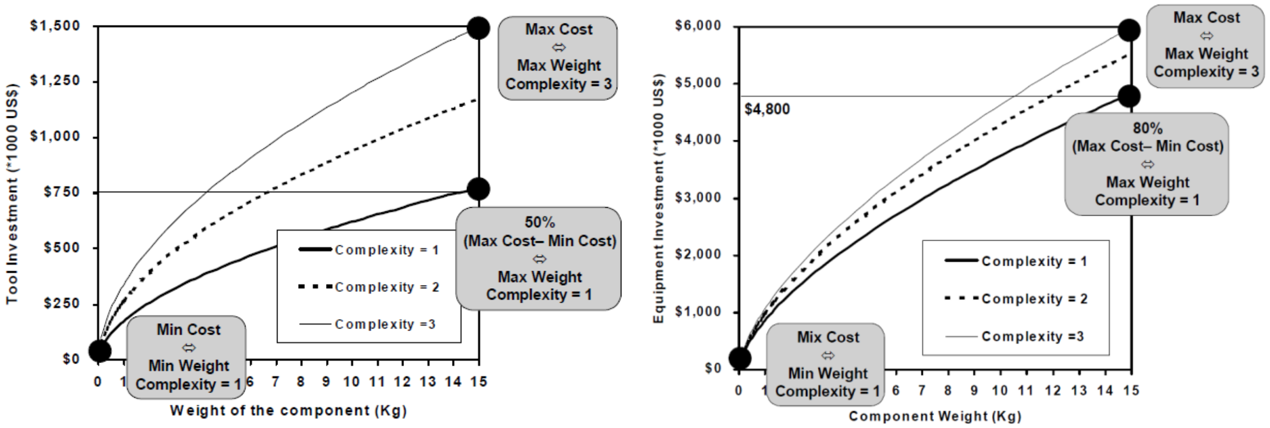


*Figure 33 Equipment and tool investment vs component weight. Source: (Veloso, 2001)*

Although the cost difference for one stamping line may not vary dramatically, one has to take into account that a compact vehicle has around 70-100 different stamped parts just for the frame, ranging from 150g to 15kg, as has been observed professionally. Therefore, the impact of the lower cost would be much greater when considering all the stamped components in the frame, body, and other assemblies.

Reducing the weight of the components also reduces cycle time in stamping lines, as seen is *Figure 34*. This reduction in cycle time allows for lower labour costs and indirect facilities costs, as well as allowing to manufacture more components in the same amount of time.

As well as this, as has been observed empirically, larger components require larger assembly lines, not only for stamping, but also for welding and other necessary operations, so a smaller vehicle will need less factory area, therefore decreasing facilities costs.

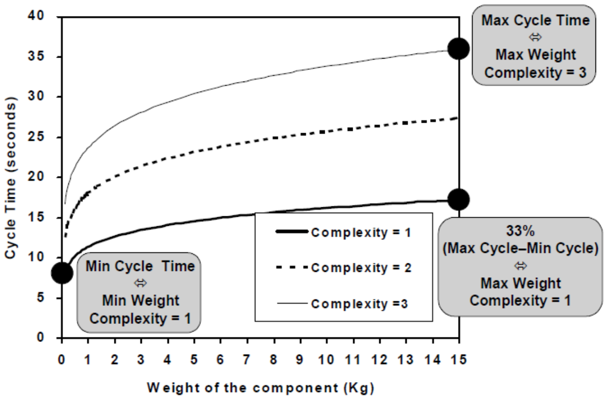


*Figure 34, Cycle time vs. Component weight. Source: (Veloso, 2001)*

As well as stamping lines, welding production lines also require a lower tooling investment when the weight and size of the component is reduced, as the robots required to move the components can be smaller and cheaper, as can the grippers, fixtures, and any pneumatic or electronic actuators needed in the production line, as has also been seen professionally.

Another side effect of lower weight in a BEV vehicle is that, as we saw in *Section 2.2.2.2. Range and battery specifications*, the energy consumption is better, as less power is required to accelerate and decelerate a less massive vehicle, and rolling resistance is lowered. That means that for a lighter vehicle a particular range can be achieved with a lower-capacity battery than one found in a heavier car, and a lower battery capacity greatly reduces cost, as explained in *Section 3.1.2.1. Battery capacity limitation*. Furthermore, a smaller, less powerful electric motor can be used, which also reduces costs as explained in *Section 3.1.2.2. Electric motor specifications*

Finally, and also related to range, is that frontal area is reduced with a smaller-sized vehicle. Even though in this specific design the drag coefficient ($C_D$) would not be very good, since it is wedge-shaped and angular, in the drag equation the frontal area (A) multiplies at the same level as the $C_D$, so a smaller vehicle achieves lesser aerodynamic friction losses.

$$Force\ of\ Drag = \frac{1}{2}\rho v^2 C_D A\ [N]$$

*Equation 1. Drag Formula*

### *3.1.1.2. Highly versatile BEV platform. Ease of scalability*

As seen in *Section 2.2. Automotive sector analysis*, ICEVs have the advantage of being easily implemented in platforms shared with other models since there is a large enough market to accommodate different models. Nevertheless, BEVs have to choose between sharing an ICEV platform, a BEV platform, or be a completely independent model, each option with its advantages and drawbacks, as discussed in *Section 2.2.2.1. Platform*.

By having more components shared between platforms, the price for each component that is shared is lower, an example of which can be seen in Figure 35, where the cost of kWh and the cost of the electric motor is graphed in relation to yearly production.

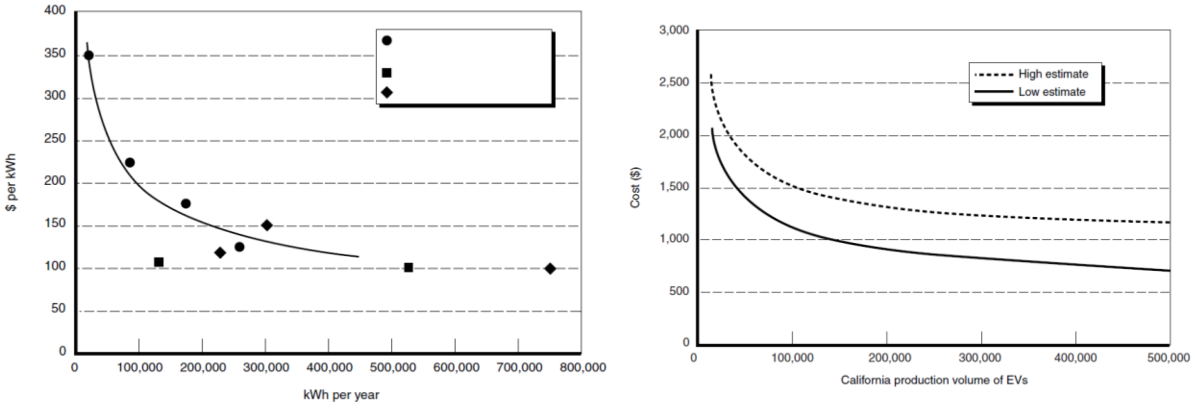


**Figure 4.3—PbA Module Cost as a Function of Production Quantity**

**Figure 4.5—Combined Cost of 50-kW Motor and Motor Controller at Different Production Volumes**

*Figure 35. Powertrain cost reduction vs. Production quantity. Source: (Lloyd, et al., 2002)*

Data of the full vehicle manufacturing cost in relation to yearly production has not been found, and even less so when accounting for platform sharing, the exception being *Figure 36*, which shows the Tesla Model 3's total cost as a function of weekly units produced. In this case, it doesn't account for shared costs between other models, nevertheless the production cost is reduced when more weekly units are produced. With this information, and a general understanding of the fabrication process, one can guarantee that sharing as many components between vehicles will reduce cost, although quantifying how much so is extremely complicated as, again, quite a few aspects and variables come into consideration.

When more weekly, daily or yearly units are produced of a specific component, a few important factors are the ones responsible for reducing cost. Firstly, similar to the effect a lower mass has on production cost as explained in the previous section, the facilities and energy costs are amortized as more units are produced. This is because the equipment and tooling investment for the component is amortized as more of them are produced. Also, less factory floor area is needed when considering other models are also produced with the same platform, since a lower number of different components have to be manufactured. Design and R&D indirect costs can also be reduced, as the design volume in a fleet of vehicles that shares platform is lower overall, since less components and manufacturing lines have to be designed and evaluated; and in case of the manufacturing lines, less overall equipment investment is needed for the same reason.

Lastly, in production lines that share different components, which are used extensively in the automotive sector, as has been observed professionally, there are not as many intervals to prepare the production line for the next component, and so production can be more continuous.

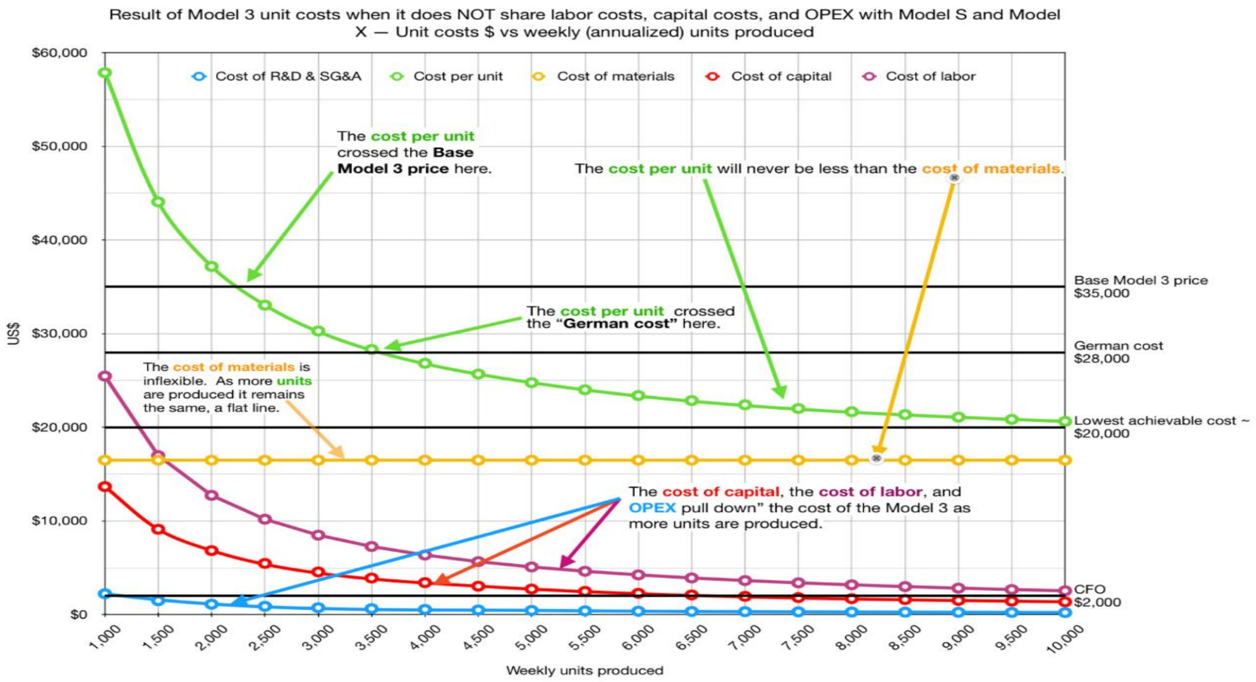


*Figure 36. Tesla Model 3 cost vs. weekly units. Source: (Kosak, 2018)*

In the case of BEVs, the problem is, as discussed in previous sections, that there may not be a large enough market to share amongst similar models. Deducing from the previous sources, and data obtained from analysing different existing vehicle platforms *Table B-3*, the minimum desired units for a shared platform to have an effect is around 100,000 yearly units. As seen by the 2020 BEV sales figures *Section 2.2. Automotive sector analysis,* this may be complicated to achieve with a BEV platform which isn't scalable, as there currently isn't enough demand to accommodate similar models from one brand. Apart from the technology being easily scalable, this reason is why newly introduced BEV platforms can scale up or down to fit different body styles, like the Tesla platforms or the Volkswagen MEB platform.

Therefore, a platform that can accommodate various body types is needed for this proposal to be as affordable as possible. These other body styles are not the scope of the project, nevertheless they have to be considered as the design has to take them into account. As they would also be affordable designs, their size and weight would also be on the medium-to-low category, therefore it has been concluded that the other body styles that could share this platform to achieve a broader target are, apart from the Minicar, a Compact Crossover, a Midsize Sedan, and a Small Van. A similar concept to the idea proposed is seen in the next image, where the concepts for different platform from an EV start-up, Canoo, are shown.

For this particular affordable design proposal, this versatility and scalability needs to be taken advantage of as much as possible, by sharing between models:

- Complete underside of the frame
- Electric powertrain
- Suspension and brake systems
- Front and rear bumpers
- Fenders
- Body stamping presses

- Flat window geometry
- Interior elements

As is evident, a Minicar will not have the same footprint as a Mid-size Sedan, so here is where a high scalability is necessary. Different-sized frame undersides and body components have to be manufactured and, to lower costs even more, this design implements a geometry along the two mid-planes that cut the vehicle perpendicular to the ground, which allows for the design to be easily modified between models, meaning that along the cutting planes, all geometries are perpendicular to the planes. This has two important effects: firstly, design and R&D costs are reduced, as the design process is overall quicker, and secondly, less tool investment is required, as nowadays movable fixtures for welding operations are extremely precise, and a single fixture could hold both sizes of underside steel plate in the manufacturing process of the underside.

*Figure 37. Canoo platform vehicles. Source: (Canoo)*

### *3.1.1.3. Materials*

Many types of materials are used in a vehicle's construction, as each component has technical specifications that require different materials. A standard ICEV material distribution is shown in *Figure 38*, and as can be seen, steel and cast iron are the predominant materials used. In most cases, material selection for a specific component comes down to the function or geometry of the component, and most importantly cost. Therefore, most of the materials seen in cars are already the cheapest material they can be, however in some cases, preference for aesthetics, a lower weight, or a better quality feel may lead to a more expensive material being used.

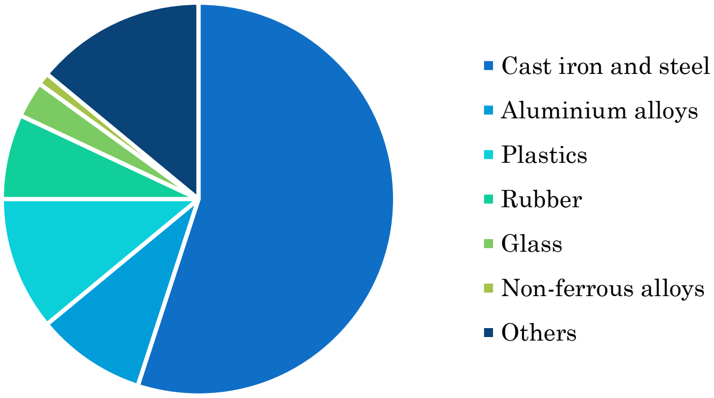


*Figure 38. Material distribution in an ICEV. Source: (Modern materials for automotive industry, 2017)*

For the overall structural components, steel, aluminium or composites are available. The chosen primary material for our application is steel, as it is the cheapest of the three, and the easiest to manufacture of the three. As the vehicle is already small in size, has a moderate battery pack, and is equipped with basic interior elements, it will not have an excessive weight, so the weight reduction advantage brought by using alternatives to steel is not necessary. For the doors and bonnet, the same material is used because of the same reasons.

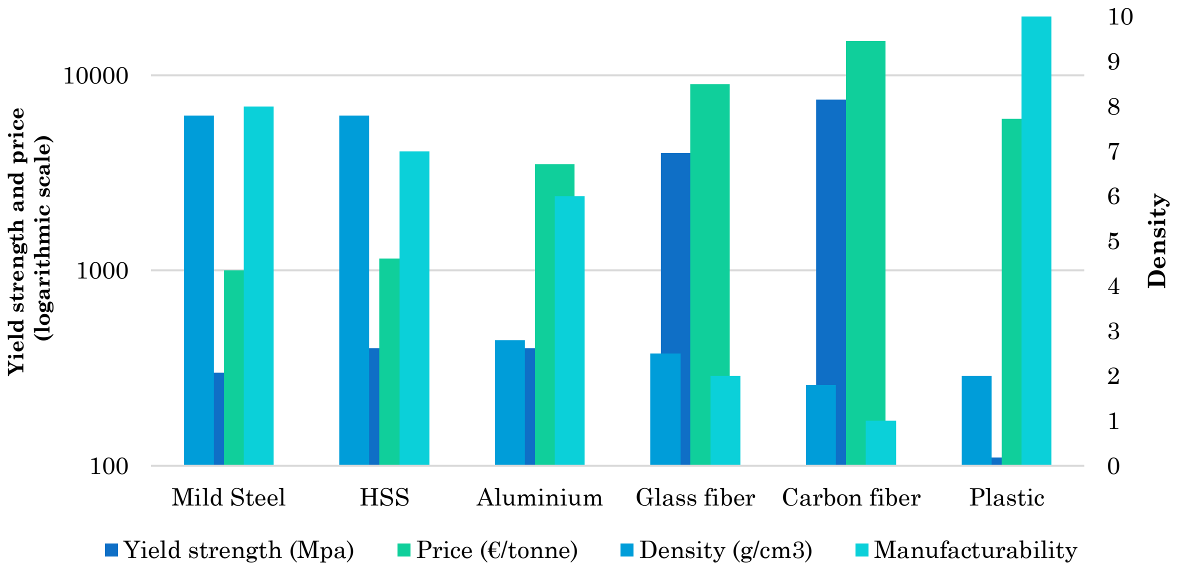


*Figure 39. Material properties. Source: (Lutsley, 2010)*

All other components that are eligible to be manufactured out of injection-moulded plastics, meaning components that are not structurally important, are manufactured out of it. Although the price per tonne is higher than steel, the lower density and ease of manufacturability allow for reduced component costs.

### 3.1.2. Powertrain

In this section the main specifications of the powertrain components are defined. The components included in the powertrain assembly are, for our purposes:

- Battery pack
- Electric motor
- Power electronics (DC on-board charger, DC-AC inverter, battery management system, control modules)
- Transmission and driveshafts
- Cooling systems

The sizes of the shown powertrain components are similar to vehicles like the VW e-Up, Dacia Spring, or Renault Twingo ZE, all BEVs with similar powertrain specifications.

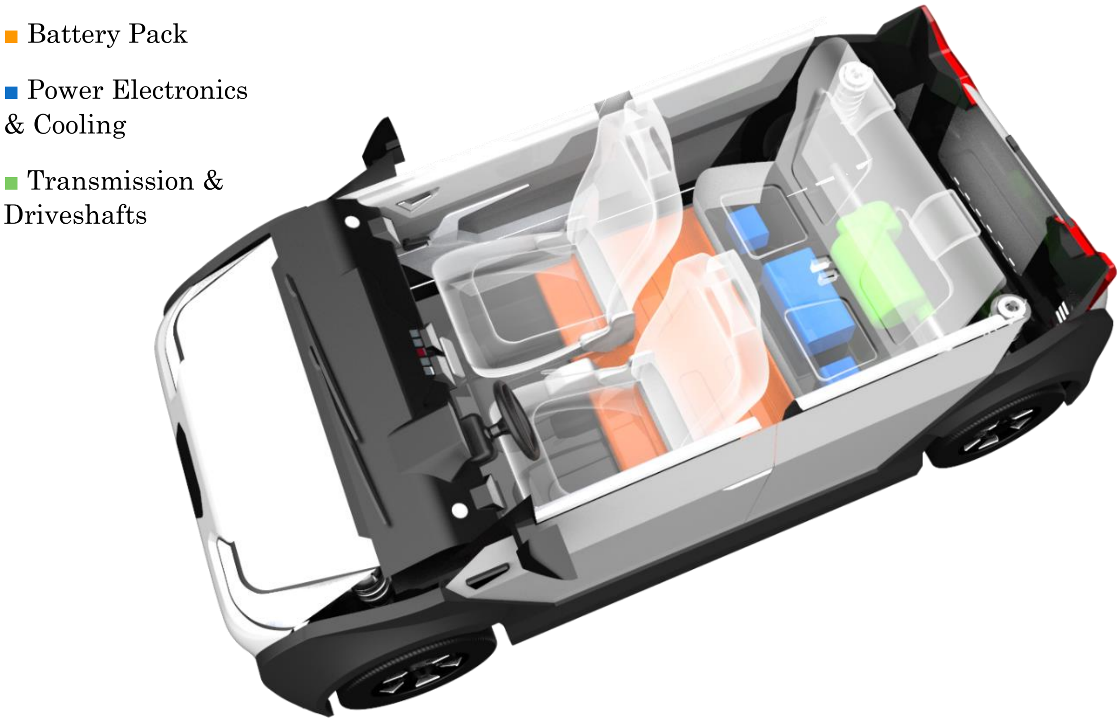


*Figure 40. Powertrain components distribution. Source: own elaboration.*

*Figure 40* shows the positioning of the powertrain elements. The battery is mounted in the floor, so it raises the rear interior floor height, nevertheless the lost space is gained back by moving the front row forwards, thanks to the lack of a front-mounted ICE, as seen previously in *Figure 31*. The power electronics and cooling systems are mounted under the rear seat bench, and the electric motor and transmission under the rear boot.

The power electronics and cooling are not discussed in this section, as the their cost is considered fixed or proportional to the engine power in the cost calculation, according to the data from (Fries, et al., 2017).

### *3.1.2.1. Battery capacity limitation*

As discussed in *Section 2.2.2.2. Range and battery specifications* the battery is the largest cost contributor in a BEV. KW/h costs are lower the larger the capacity, but at around 125€/kWh the price increment that comes from having a larger capacity is very noticeable, as seen in *Figure 41*, so even though the price per kWh is lower in a larger battery, the price increases substantially.

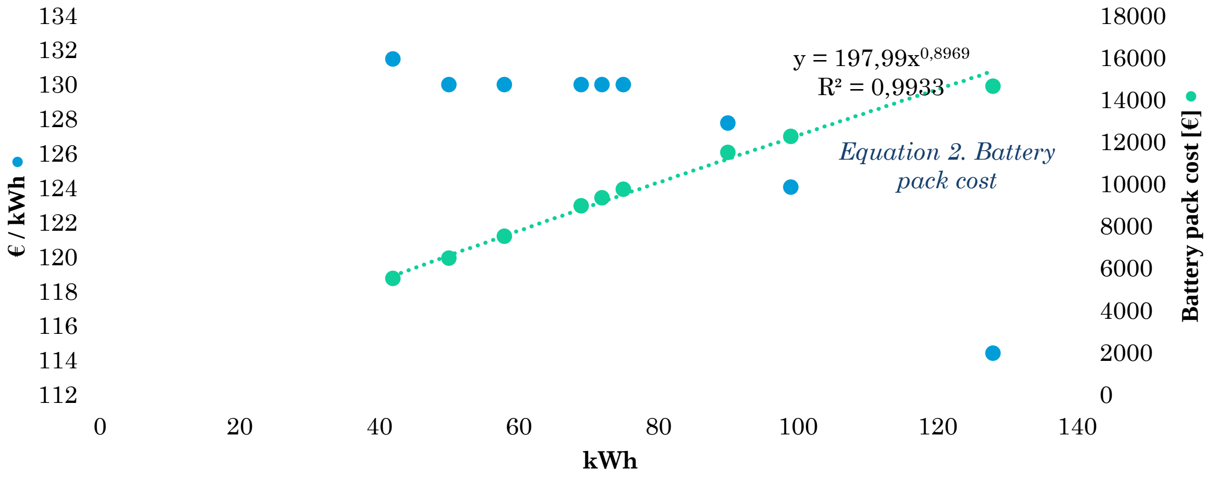


*Figure 41. Battery pack costs. Source: (Lutsey, et al., 2019)*

For this reason, a 25kWh battery is chosen for this design. With an approximated weight of 1150kg, by looking at *Figure 10* from *Section 2.2.2.3. Size and weight*, and accounting for bad aerodynamics, the approximated consumption can be approximated at around 140 Wh/km, and so the vehicle would achieve a WLTP range of around 180 km.

According to *Figure 10*, the cost at the battery pack level for a 25 kWh pack is 3,552€. For comparison, applying the equation from said figure to the 55kWh batteries found in the Zoe or Model 3 Standard Range equates to approximately 7,200€. These vehicles have a 400km and 450km WLTP ranges respectively, so range is greatly reduced in comparison to these models. The hope is that this, combined with all the other methods to lower costs, would lower the price enough to attract a large enough customer base that could live with this approximated 180km range.

The three cell architectures used for BEV battery packs are cylindrical cells, prismatic cells, and pouch cells, seen in the *Figure 42*.

The cylindrical cell has high specific energy, good mechanical stability and its manufacturing is relatively cheap. The cell design allows added safety features that are not possible with other formats, and it cycles well, so it offers a long life-span. Nevertheless it has less than ideal packaging density, and it requires more heat management than the other designs.

Prismatic cells are encased in aluminium or steel for stability. The cell is space-efficient and has the best energy density of the three, but the manufacturing process is more expensive than the other designs, therefore, it is not appropriate for our application, as the design proves that there is sufficient space under the occupants to fit a large 25kWh battery.

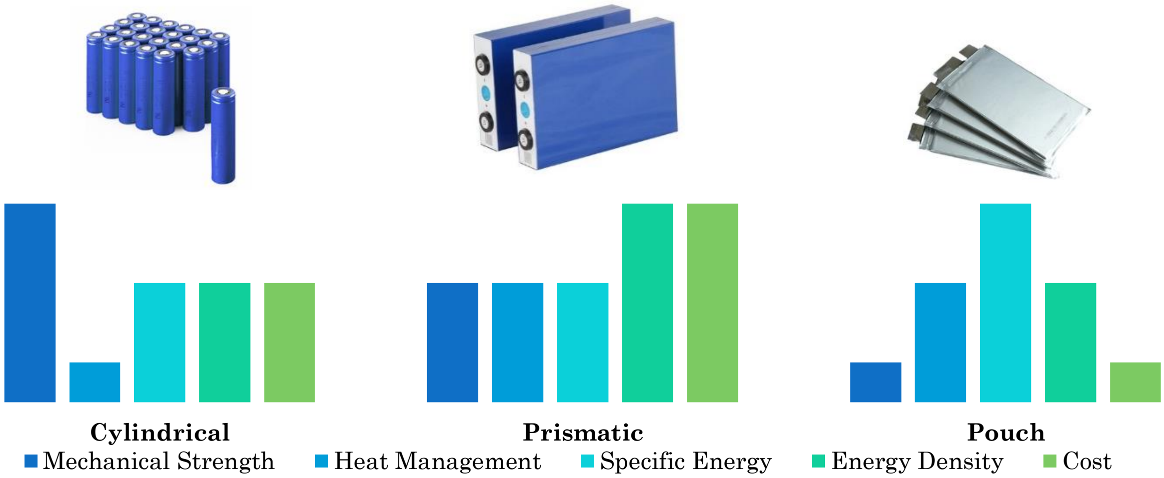


*Figure 42. Battery cell types properties. Source: (BatteryU, 2020)*

Pouch cells use a laminated architecture in a bag. They are light and cost-effective but exposure to humidity and high temperature can shorten life. The main disadvantage is that some cell designs can swell in size after a large number of cycles, and they are the most prone to cause electrical failures, if not well controlled. The pouch cell is growing in popularity and serves similar applications to the prismatic cell. (BatteryU, 2020)

The best option for our application would be the pouch cell, as it the most cost effective, although the battery management system would need to be extremely well calibrated to the cycles and swelling of the batteries, in order to supress the danger of electrical failures or battery failure.

Various types of cell chemistries are used currently in BEV cells, the main characteristics of each seen in the next figure. Nevertheless, the decision of choosing cell chemistry is left out of the scope of the paper, as it requires an extended analysis and background which elude the objectives of this proposal.

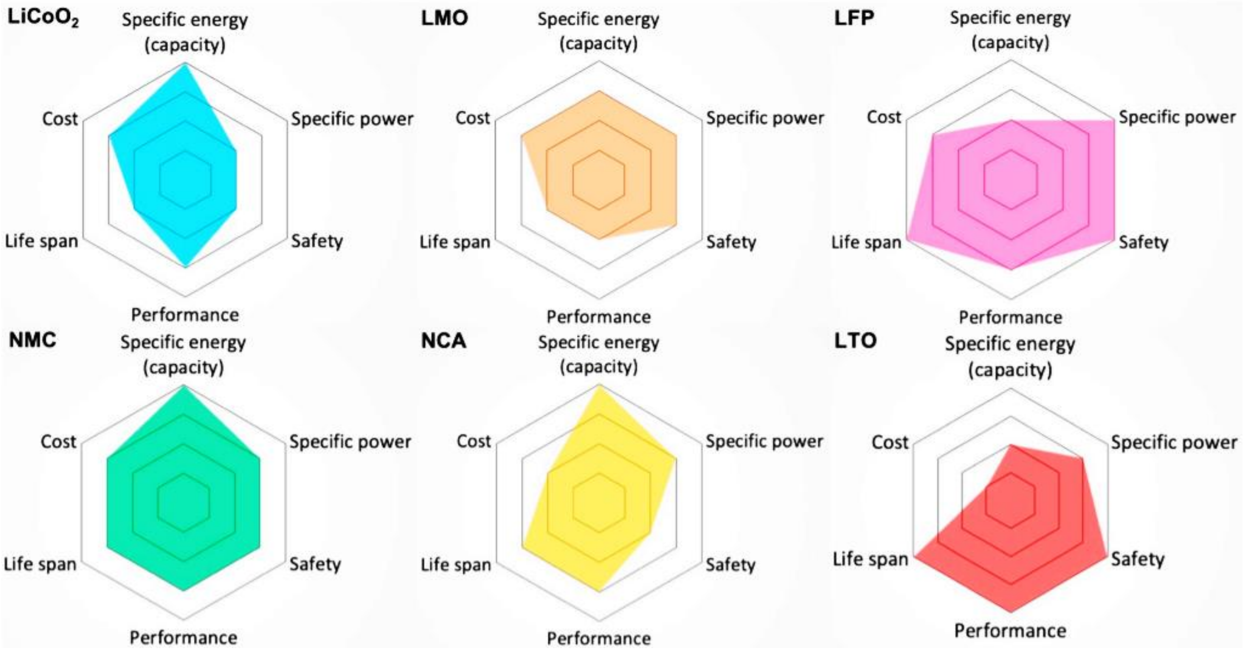


*Figure 43. Cell chemistry properties. Source: (Yu Miao, et al., 2019)*

### *3.1.2.2. Electric motor specifications*

In regards to the electric motor power, this vehicle does not need large amounts of it, as it is not performance-oriented in any way, and its mass is comparably less than the European competitors'. Therefore, a 50kW motor would be sufficient. For comparison, this is 10 kW less than the 2019 Volkswagen e-Up! and Renault Twingo, which are around 100kg heavier than the approximated weight of this vehicle. The e-Up! can achieve a 130km/h top speed, an reach 100km/h in 12s, producing 210Nm of torque.

If a similar motor and transmission-ratio were used, the exact details of which were not found, this design could achieve an approximated top speed of 115km/h, considering that the $C_D$ would be higher than the e-Up!'s.

The other aspect that this section addresses is the type of electric motor. As discussed in *Section 2.2.2.4. Electric powertrain specifications*, the two possible architectures are an IM or a PMSM motor. According to (König, et al., 2021), an IM motor has a cost of 8€/kW, while a PMSM has a cost of 10€/kW. The other advantage of the IM is that R&D costs are lower, as this technology is extremely matured and is easily controllable. Nevertheless, one has to factor in the fact that IMs have a lower efficiency. That means that if you had two identical vehicles, and one had a PMSM and the other an IM, the IM vehicle would need a larger battery capacity to achieve the same range.

To see the effect this has on the overall BEV powertrain cost, it has been assumed that the PMSM has a 95% efficiency, and the IM 90% (Hanejko, 2020). Then, the 25kWh battery is assigned to the PMSM, and afterwards, with a fixed 140 kWh/km consumption, the extra kWh needed to compensate for the IM's lower efficiency are calculated. The result is 26,32 kWh for the IM motor to be able to achieve the same range, which increases the battery price by around 150€. When combined with the lower price of the IM, the total combination is just 30€ higher (*Figure 44*), so the price difference in this case is not really noticeable enough to be the factoring aspect when choosing between the two. Another effect that is not considered here, as the energy consumption is fixed, is that the larger battery would increase the weight, and therefore would in turn increase consumption, which would also decrease range.

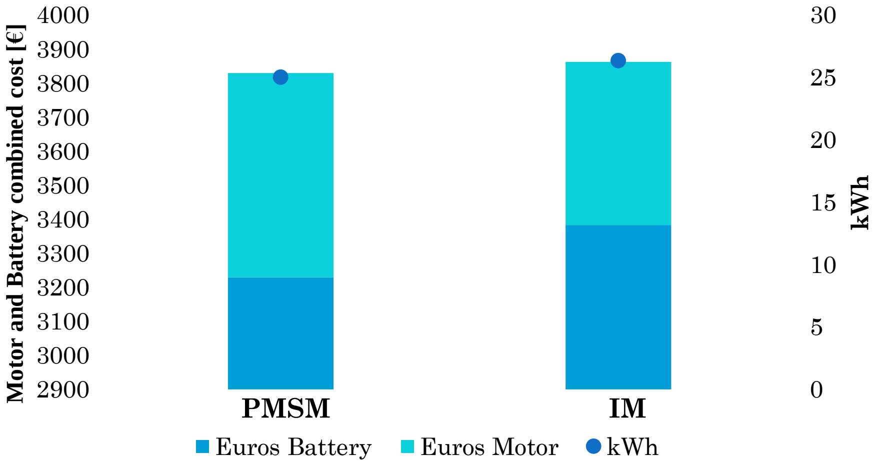


*Figure 44. PMSM and IM cost comparison*

Therefore, the deciding factor in this case is packaging size. As discussed in *Section 2.2.2.4. Electric powertrain specifications,* PMSMs are more compact than their IM counterparts, so in the case of a small vehicle, it is really beneficial to be able to have a smaller motor. Furthermore, as the battery is also smaller, although not by a lot, it allows for an easier positioning of it. So even though the R&D costs may be slightly higher for PMSMs, it is compensated by a higher efficiency and by the packaging capabilities of this type of motor, which make it the adequate one for this design.

Other costs of the BEV powertrain are the inverter and power electronics, the high-voltage cables, and cooling systems. As these are mostly fixed or proportional to power (König, et al., 2021), they are not discussed in this section, although they are considered in the cost estimation in *Section 3.2. Cost approximation.*

#### *3.1.2.3. Rear mounted motor*

Thanks to the motor being a PMSM and low power, it has a very compact size, so the motor can be mounted in the back, under the rear boot, behind the rear occupants. This is also enabled, in part, thanks to the use of a single-speed transmission, detailed in the next section. Positioning the motor in this area has indirect cost reduction since the front end of the vehicle can be shortened, and therefore slightly less material is needed for the overall manufacturing of the vehicle. Furthermore, front suspension and steering elements can be simplified and compacted, reducing their cost. The rear driveshafts are also cheaper, as they do not need to incorporate large hub joints to enable for steering angle.

A side-effect of positioning the motor in the rear is that the centre of gravity is moved rearwards, so a rear-balanced car is obtained. This is considered beneficial for stability and car control, and is generally considered complicated to achieve with an ICEV, but is easily achieved with this BEV powertrain architecture.

#### *3.1.2.4. Single-speed transmission*

Finally in the powertrain area, the transmission needs to be addressed. All BEV vehicles under 50,000€ use a single-speed transmissions. The reason for this is because, as discussed in detail in *Section 2.2.2.4. Electric powertrain specifications,* the instant and high torque of the electric motor, combined with their high RPM limit, enable for highway speeds with a single speed, as well having enough torque for low-speed acceleration. (KIA) Only a few high-end BEVs have more than one speed transmissions, for example the Porsche Taycan. The purpose of having a 2-speed automatic transmission is to have a higher top-speed, and make better use of the engine torque curve (Wandewerp, 2019). Although this does make the vehicle more efficient overall, the increased size and cost is not worth it in this application, so a single-speed transmission is used for this design.

### 3.1.3. Bodywork

The methods explained to reduce manufacturing costs in this section are related to the bodywork panels. Exact data of the cost of these components was unattainable, so the objective for all these methods is that, all combined, they could potentially decrease the cost by the amounts detailed in *Section 3.2. Cost approximation*.

It is important to reiterate that, especially in this section, a design with this bodywork specifications could be much improved, and the model shown only serves as a template for the concepts which are proposed.

*Figure 45. Bodywork design. Source: own elaboration*

#### *3.1.3.1. Reduction of bodywork components*

The first step to reduce bodywork-related manufacturing costs is to reduce the number of necessary components. Reducing the number of components logically reduces overall price as it lowers the different components that need to be manufactured or purchased from suppliers, and as well as this, assembly time is reduced, and therefore the vehicle requires less man-hours of labour and less energy resources to assemble. Furthermore, similar to the reasons explained in *Section3.1.1.2. Highly versatile BEV platform. Ease of scalability*, less factory space is required, and a more continuous production can be achieved, lowering indirect costs related to manufacturing.

Consequently, for this design, the entire bodywork is limited to the following panels:

1. Front and rear bumpers
2. Fenders
3. Lower side protection
4. Upper side protection
5. Hood
6. Doors
7. Front windshield
8. Side windows (driver and passenger front and rear windows)
9. Rear hatch (window)
10. Roof
11. Side window trim

12. Single-unit head and tail lights
13. Front badge holder and rear charging port lid

*Figure 46. Bodywork components comparison. Source: own elaboration, (topseed)*

If we take a look at one of the best-selling affordable models, the Renault Clio (*Figure 46*), we can see that, although it has a simple design, there are still a few elements which can be supressed to lower the number of components. Naturally, the manufacturer will have chosen this slight increase in cost to achieve a better-looking design, but for the objectives of this project, all possible cost-reducing methods are considered.

In the rear, the rear boot lid structure is completely replaced by an abatable window, like the mechanism seen in *Figure 47*. This greatly reduces the number of components needed, and although it limits loading capacity, the boot size is already smaller than usual because of the rear engine layout.

*Figure 47. Older generation Citroën C1 rear hatch. Source: (Commons)*

The number of components needed for the front and rear bumpers is minimized. The fact that it is a BEV makes it easier to achieve, as the powertrain components require less cooling, as a conventional ICE converts about 60% of its energy into heat (Ruffo, 2020), which has to be expelled, whereas a PMSM achieves around 95% efficiency, as discussed in detail in (Section 2.3.2.4.). Cooling is still required, especially for the batteries, which have to be maintained at a specific range of temperatures to maintain battery life and not cause failures. As the rear bumper needs attachment points for the mandatory rear red reflectors, this also means that the front bumper will have the same attachment points, as it is identical. Therefore, that means that an extra aesthetic component is needed, the one that covers said attachments. The charging port is also located in the rear, and the lid is replaced in the front with a badge holder.

As can be seen in *Figure 48,* in the case of some vehicles, like the Renault Clio seen earlier, the side bodywork is a single stamped steel piece welded onto the frame, whereas in this design it is comprised of three separate plastic components: the rear fender, and the upper and lower side plastic panels. In this case, the cost reduction for these components comes from the chosen material, which is explained in detail in *Section 3.1.3.5. Extensive use of plastic in bodywork components.*

*Figure 48. Conventional PC frame. Source: (Hexagon)*

### *3.1.3.2. Simple geometry for stamped steel components.*

To further reduce the bodywork's manufacturing cost, the shape of the exterior stamped steel sheet components (Doors, bonnet and roof) is simplified. The simplification of the geometry of these panels has the objective of reducing the raw metal sheet stamping process cost, because as seen in *Section 3.1.1.1. Small size,* a lower complexity lowers both equipment cost and cycle time. Complex bodywork geometries usually need more than one die, usually a stamping die, two cutting dies, and a measurement and final conforming die, meaning that in most cases, at least four dies are used for each stamped component. These are usually positioned in a single, large stamping press, with robots moving the sheet from one die to the next.

*Figure 49. Stamped Steel panel with simple geometries. Source: own elaboration.*

The simplified components are highlighted in *Figure 49*. For this design, in the case of the doors, a simple one edge design is implemented. This geometry allows the panel to be cut in a single operation, and also allows for the same die to stamp the symmetric side, as explained in detail in the next section, as well as being used for different models, as discussed in *Section 3.1.1.1. Small size*

For the bonnet and roof panel, a flat sheet is used, therefore only the cutting process for the exterior panel is needed, simplifying a lot the production process and line. A flat panel loses a lot of rigidity, but in the case of the bonnet, it is a very small size and has another piece that makes it more rigid. In the case of the roof, hopefully the central middle beam of the frame would give it enough strength. If it were more flexible than expected, an option would be to thicken that steel sheet, but that in turn would slightly increase price and weight.

This simplification of the geometry greatly affects styling, and since no direct data of the cost of bodywork components in function of geometry has been found, it is difficult to know if the price reduction would be worth the potential buyers that are put off by the trigonometric looks. Furthermore, the doors and the bonnet also have separate interior structural stamped metal pieces welded together, and the complex geometry of these is hard to reduce, as the curves give rigidity, and different supports and anchor points are positioned in various planes and positions, so the full manufacturing cost of these components cannot be directly linked with the exterior geometry.

For reference, the shortly available Tesla Cybertruck has similar bodywork geometry to this design, and although Tesla claims it is for price reduction, it is also done because the stainless steel used in the bodywork cannot be stamped into complex geometries (Engheim, 2019).

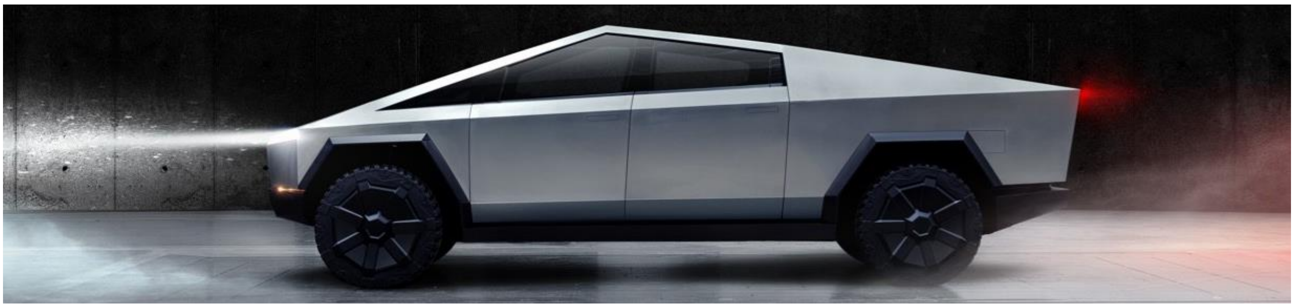


*Figure 50. Tesla Cybertruck. Source: (Tesla)*

### *3.1.3.3. Identical bodywork components*

The reason identical components found in the bodywork reduce manufacturing cost is the same as in *Sections 3.1.1.2. Highly versatile BEV platform. Ease of scalability* and *3.1.3.1. Reduction of bodywork components* so it will not be further discussed in this section.

*Figure 51. Identical components groups. Source: own elaboration*

The identical components found in the bodywork are the following:

- Front and rear bumpers

This is challenging from the design point of view of the vehicle, but it has been implemented in the automotive sector, an example of which is the Citroën AMI (*Figure 52*), a super affordable BEV rated for A1 (Spain) license. For this design, both sides are more distinguishable between each other, as the lights and windshield shape are different, unlike the AMI.

Using identical bumpers allows for the fenders to also be the same, as is explained next.

*Figure 52. Citroën AMI. Source: (Citroën)*

- Fenders

Fenders are naturally symmetric side-to-side, and because of this, if a front-to-back symmetry is also implemented, the driver's side front fender can be used in the rear passenger's side, and vice versa. This can also be seen similarly implemented in the AMI, although the shape and positioning of the fender panel is quite different. For our implementation, urban mobility has been prioritized, and the fenders cover the most-often scratched zones, to keep component replacing costs low.

By maintaining the lower door edge horizontal, the identical fenders also allow the use of an identical lower side impact protection panel.

- Lower side impact protection

This component, also known as "*side-skirt*", is, as seen before, not usually needed in cars, as this piece is a stamped metal part that goes up to the roof, which is welded and part of the car's frame. Nevertheless, as in this design plastic is chosen for this component, the symmetry is applied to lower costs.

- Side windows

As all windows of the vehicle are flat, the reasons for which are discussed in the next section, all side windows are the same as their opposite side.

- Door stamping press

Although the exterior panels of the doors aren't exactly the same at each side because of the angle, the stamping die can be designed to be used for both sides, as the angle is the same, and therefore only separate cutting and measurement dies would be needed for the 4 doors of the vehicle. As well as this, both doors from a single side can be stamped in a single operation and separated afterwards, thus reducing equipment investment and cycle time.

#### *3.1.3.4. Flat Windows*

The process of window fabrication for cars is quite straightforward. After manufacturing or obtaining the flat glass sheet, which is laminated for the front windscreen and tempered for the rest, it is cut to the required dimensions. After this, it is positioned on a mould and heated in an oven so it can form the desired shape. (Glass, 2012)

By having flat windows the oven moulding operation can be eliminated. Consequently, only the cutting and the application of the contour decals is required before assembling the windows to the vehicle, meaning that the amount of equipment and cycle time needed is drastically reduced.

#### *3.1.3.5. Extensive use of plastic in bodywork components.*

As seen in *Section 3.1.1.3. Materials,* it is usually cheaper to manufacture a component out of plastic compared to steel. For this design's bodywork, plastics are used in the fenders, the lower side impact protection, the bumpers, and the higher side impact protection, as well as the window plastic trim (*Figure 53*). Bumpers and front fenders are already made out of plastic in most passenger cars, but that is not the case for the other three components, as these are usually made from one stamped metal piece welded to the frame as discussed previously. Plastics are also much cheaper to conform into complex geometries than metal stamped sheets, so for these components which have complex geometries, making them out of plastic makes them even less costly.

*Figure 53. Plastic bodywork panels (orange). Source: own elaboration.*

A necessary advantage that comes with making the higher lateral impact protection out of plastic is that it makes it possible to use the same fenders between platform models, as the higher lateral piece will be the one with a different shape between different models of the platform in order to accommodate for the different body styles. It also enables, styling-wise, to have a continuity of the shapes when looked at from the side, a design cue currently very popular in minicars when combined with various body colours. Lastly, the use of plastic in these components makes them easy and cheap to replace, so it improves the utilitarian design objective for this vehicle.

Nevertheless, using plastic in bodywork components has two important disadvantages. The first one is a reduction of overall quality, be it feel, look, rigidity or noise level, but as mentioned before, this lower quality has to be accepted if the price of the vehicle is to be able to compete with ICEVs. The second disadvantage is that, while metal is easily recyclable, plastic is not, so the carbon footprint of the vehicle is increased. A possible solution to this would be using recycled plastics, but these are more expensive than virgin plastics so the manufacturing cost would increase, though the difference is small enough to consider using the environmentally-friendly option.

The remaining metal stamped pieces could potentially also be made out of plastic, but it was decided against it, as these components have already had their manufacturing cost reduced thanks to their simple geometry, and it has been assumed that a full plastic-bodied vehicle would repel more customers than the customers gained from the given cost savings.

#### *3.1.3.6. Paint scheme*

Finally, in the bodywork section, the paint scheme is addressed. The direct cost of painting is really low, as it is an automated process and a cheap material. Nevertheless, it requires quite a substantial amount of time to paint and dry the vehicle. Because of this, for this proposal, the fenders and lateral plastic panels are left unpainted. Current automotive-grade plastics are able to withstand UV and environmental effects, and also allows for cheaper repair in case of needing a panel change, as is common is dense, urban environments.

Nevertheless, these panels should still need to be offered as a painted optional extra, as many people would still pay a bit more for a better paint-job.

### 3.1.4. Interior and safety systems

In this section, the methods to reduce costs which are applied in the interior elements are explained. This is mostly carried out through elimination or simplification of components.

*Figure 54. Interior design. Source: own elaboration.*

#### *3.1.4.1. Simple interior*

Fort the interior panels, the number of components is reduced to a minimum, therefore reducing costs for reasons mentioned in previous sections. That does not necessarily translate directly into bland-looking panels, because as mentioned in *Section 3.1.1.3. Materials*, plastics are easily conformable into complex shapes, and plastic is, in this case, the most used material for the interior, as it is the cheapest.

This means, for example, using a single-piece dashboard, and deleting the central console. The front door trim has only 3 panels, and the rear 2, as no door storage is implemented.

#### *3.1.4.2. Reduction of electronic components*

Electronics account for approximately 1% of the total vehicle manufacturing, according to (Cuenca, et al., 1999). This may seem like a small amount, but to reiterate, all possible cost reduction methods are pursued. Therefore, electronic components are either deleted, or changed for a more cost-effective solution.

*Figure 55. Dashboard unit. Source: own elaboration.*

In this design simple speaker system is still included in the vehicle, as it has been considered necessary considering that the noise level is expected to be higher than normal due to the lower quality. Couple this with the silent PMSM, which produces less decibels than an ICE, and the speaker system becomes a beneficial system, as it is a low-cost system that in this case is considered worth the value, as it would distract drivers from road and vehicle noise. This speaker system consists in front speaker tweeters and sub-woofers, while no speakers are included in the rear.

The infotainment system, or radio, is deleted, and instead to control the speakers and heating a direct cable connection to a smartphone is used. Currently this makes sense, as it is safe to assume that any person who could be able to buy this vehicle also has a smartphone. As the vehicle still needs electronic control modules, it would not be hard to assign the task of smartphone connectivity to one of said control modules. This would also enable the car to have internet connectivity, as long as the user had roaming services, which is largely the norm in the EU.

Therefore, the dashboard of the vehicle only includes the driver's display, and the necessary buttons for the systems which, because of safety reasons, cannot be controlled from the smartphone (e.g. Door locking mechanism / Emergency lights / Drive selector). The smartphone holder and connection is positioned where the infotainment system is usually found.

The front windows are operated via a manual rolling mechanism, as these are more affordable, and the rear windows use the lateral-hatching mechanism found in some vehicles such as the Smart Forfour.

Naturally, no extra electronic devices are implemented, as could be electric seat adjusters, electric steering wheel adjuster, electric wing mirror adjusters or similar.

Regarding the driver's display, since the vehicle has digital data that is important to display, for example battery charge, state of health or temperature, an analogic display would not be adequate for a BEV. Therefore, a low-cost LCD display is chosen for this application, in contrast to more expensive RGB displays found in other BEVs.

Lowering the number of electronic components also reduces the amount of cabling needed, which is normally around 500€ (Fries, et al., 2017), and also reduces the assembly time of the components and of the entire vehicle.

### *3.1.4.3. Simple seating*

The seats are also simplified, as the front seats have longitudinal and rotation adjustability, but the height is not adjustable and the headrest is fixed, in order to reduce the number of components needed, and the assembly time of the seats. The seats are made as compact as possible while retaining some cushioning, as this also enables to achieve better rear legroom. These would need to be thoughtfully designed to comfortably accommodate a wide range of percentiles, which is clearly possible having seen that models like the Renault Twingo or Peugeot 108 have similar seats.

The rear is a simple 2 piece foldable bench, with adjustable head supports, as fixed-height headrests could impair rear visibility too much.

*Figure 56. Seating view. Source: own elaboration.*

### *3.1.4.4. AC deletion*

Air conditioning is a large cost contributor in the interior of the vehicle, as the AC compressor system costs around 200€ (Kolwich, 2012) (Adjusted for inflation). So for this application, in the cheapest configuration of the vehicle the AC is deleted, but it is left as an optional extra. This is unusual in most passenger cars, but not unheard of, as is the case with the base variant of the Dacia Sandero or the Kia Picanto, to name a few examples. The heating unit costs around 50€, and in an ICEV uses hot engine coolant as the heating source. In a BEV, the battery heat exchange system can be used in a similar way, and the warm air can be easily routed into the cabin using flexible plastic tubes. It has been concluded by looking at other affordable models like the Sandero that the base trim version should at least include heating, and AC is left optional as an extra, to be able to achieve a wider target.

#### *3.1.4.5. Safety and driver-assistance systems*

Currently many advanced vehicle safety systems exist, such as level 2 autonomy in a few vehicles. Nevertheless, these systems require various sensors and cameras, a powerful electronic on-board computer to compute the complex tasks of autonomy, and a lot of software R&D.

Therefore, in this vehicle only the systems required by the EU from 2022 onwards are fitted, which are: (EWMG, 2019)

- Daytime Running Lights (DRL)
- Anti-Lock Braking System
- eCall
- Intelligent speed assistance
- Alcohol interlock installation facilitation
- Driver drowsiness and attention warning systems
- Advanced driver distraction warning systems
- Emergency stop signals
- Reversing detection systems
- Event data recorders
- Accurate tyre pressure monitoring.
- Advanced emergency braking systems
- Emergency lane-keeping systems
- Enlarged head impact protection zones capable of mitigating injuries in collisions with vulnerable road users, such as pedestrians and cyclists

Apart from these systems, it is decided that airbags are necessary in the front, as small vehicles have a lower safety rating than larger cars as a consequence of their size. So driver and passenger airbags are installed, as well as frontal side airbags for lateral impact protection. These are still not required in all the countries in the EU, but are required in the USA.

Furthermore, a very simple form of traction control could be implemented via software calibration, which would come at a reduced extra cost. It would consist in managing the supplied current in a moderate manner in the case the driver stepped on the accelerator pedal from a standstill. This would reduce potential accidents in bad weather conditions, as the instant torque of the electric engine could spin the rear wheels.

Having said this, if you consider the possible progress autonomous vehicles can have, it seems like a good idea to pre-design the vehicle so it can accommodate the necessary sensors for level 5 autonomy, which would be extremely useful to have in a ride-sharing vehicle, one of the possible product target market. (*Section 3.3. Product Target)*

### 3.1.5. Suspension elements

The size of the suspension system elements is often proportional to the vehicle's size and weight, so in the case of a small vehicle like ours, these elements are already compact. Nevertheless, for this design, the objective of the suspension system is to be as compact as possible, while maintaining design simplicity. The objective for this compactness is to be able to achieve the necessary foot room at the front in order to position the occupants as needed, as well as reducing material and equipment costs, as discussed in previous sections. A disadvantage of the reduced suspension system size (in relation to a usual proportionally sized system) is that the vehicle dynamic characteristics of the car will be negatively affected, nevertheless, as this is a vehicle with urban use in mind, and a low top speed, it is considered an acceptable trade back.

A McPherson suspension geometry is used in the front axle (*Figure 57*), as it is the most compact design, and although not the most cost-effective (which would be leaf springs), it maintains a low cost thanks to its reduced number of components. In the rear, a semi-independent, or torsion beam system is used, as is common with small, compact cars.

*Figure 57. McPherson suspension system (left) and torsion bar (right). Source: (RideBuster)*

The wheel size is 14”x4”, and the tyre 155/65/R14. This choice has been made by analysing existing similar-sized PCs, and choosing a small but standard size. The tyres are chosen to be narrow to reduce friction losses and therefore maintain a higher range, and the fact that is has low power and low mass should maintain a good level of traction with tyres this size. An advantage of having small radius tyres is that the transmission unit can reduce in size, since the smaller tyre needs a lower transmission ratio, and therefore lowers the cost of the transmission unit.

The front brakes chosen, based on current model analysis (EVSpecs, 2020), are 250mm steel disc brakes with two pistons for each calliper in the front axle, and 180mm drum brakes at the rear. Rear drum brakes are extensively used in small vehicles, but the unusually small size of 180mm can be achieved thanks to engine regeneration, which is easily implemented, and can be used to generate most of the rear axle’s braking force.

Finally, the power steering is electric, with a direct collapsible mechanical connection to the steering wheel. Even though in an ICEV a hydraulic power steering system is cheaper, in a BEV you would need an external hydraulic pump, which would increase costs and lower efficiency. The direct mechanical connection is chosen as a drive-by-wire system would need an extra electric motor for the steering wheel, and more sensors and safety systems to guarantee redundancy.

## 3.2. Cost approximation

As has been seen in the previous section (Section 3.1. Applied methods to reduce manufacturing cost), many factors have to be taken into account to be able to obtain an exact cost approximation for any vehicle. As reported by (Roy, et al., 2008) detailed knowledge of the product, facilities, workforce, overheads, suppliers and logistics network is necessary, just to name a few. This is data which is obviously not publicly available, and even if it were, the amount of time needed to encapsulate the information into a cost approximation would exceed the extent of this project.

Therefore, the cost approximation carried out is based on percentages, and the result of which is majorly in function of the battery pack cost, which can be estimated quite accurately from the previously seen data (Section 3.1.2.1. Battery capacity limitation). Nevertheless, the total amount is merely indicative of the price range, and as has been mentioned before, the assumption is that the approximated costs can be achieved thanks to the combination of all the proposed ways to reduce manufacturing costs (Section 3.1. Applied methods to reduce manufacturing cost).

The approximated price of the proposed concept would be around 17,300€, taxes included and without government subsidies. With government subsidies taken into account, which in Spain as of 2021 are 4,500€ for BEVs (González, 2021), this price is reduced to approximately 12,800€. The subsidies are even higher for light commercial BEVs, which get a 7,000€ reduction in price.

A brief summary to explain how said price has been reached will now be carried out, nevertheless, the complete details for the cost calculation can be found in *7.3 Appendix C*.

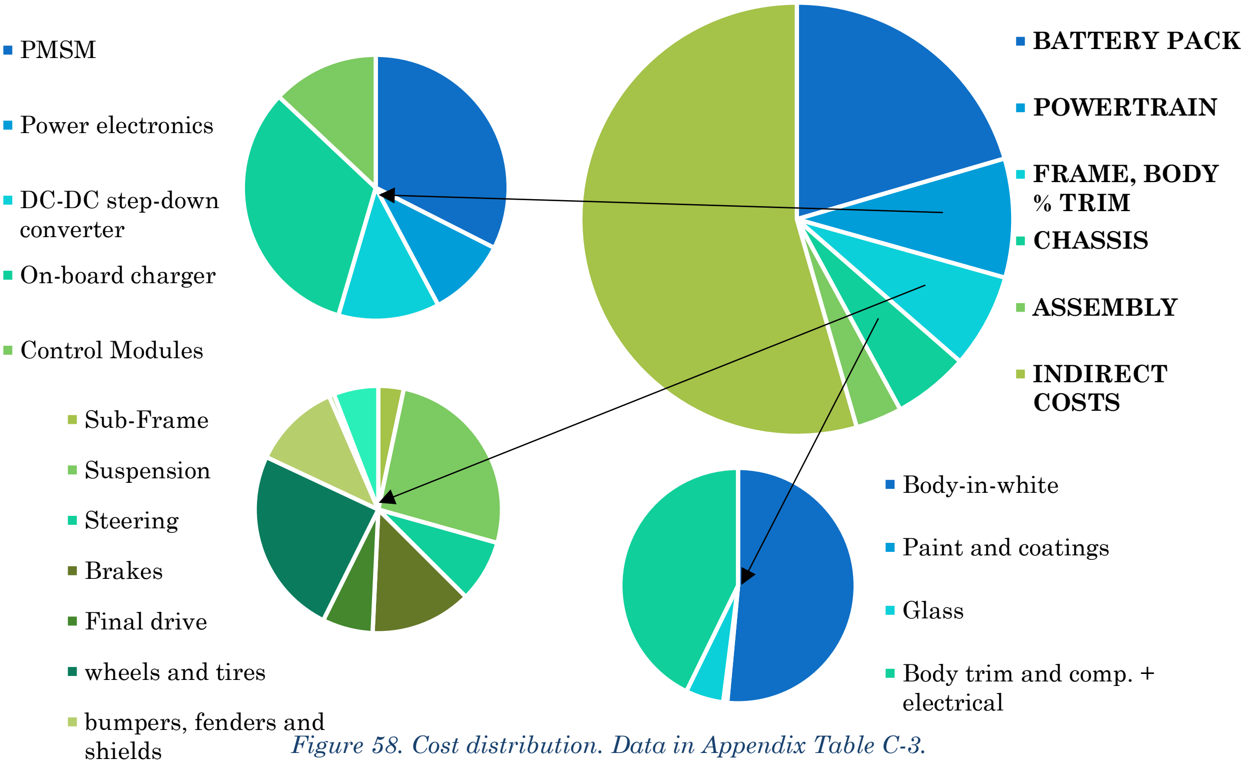


*Figure 58. Cost distribution. Data in Appendix Table C-3.*

To obtain the MSRP price, an indirect cost multiplier (ICM) of 1.815 has been applied on the manufacturing cost. This ICM is an addition of indirect cost group multipliers, as seen in *Appendix Table C-2*. This value lies in the mid-range from various ICM from different sources (See *table C-3* to *C-8*). It is used to calculate the price before taxes from a given manufacturing cost. It accounts for production overheads, management overheads, distribution and selling.

Once the pre-tax price is known, a 1.21 multiplication is done, corresponding to the 21% tax in Spain.

In *Figure 58*, the total cost distribution is shown. The total calculated indirect costs account for 54,5% of the selling price, and manufacturing for the remaining 45.5%.

The 25kWh battery pack is the largest manufacturing cost contributor, as is expected, and has been calculated with *Equation 2*, for a total cost of 3,550€, accounting for 20.5% of the total selling price.

The powertrain cost has been calculated according to the information from *Table C-9*, and as we can see, the Permanent Magnet Synchronous Motor (PMSM) and the on-board charger account for the majority of the costs.

In the Body and Trim systems, the body-in-white (name given to the frame and steel body components, such as doors) is responsible for more than half the cost of the system, and body trim and electrical components (which include all the interior elements and electrical components) account for most of the remaining cost. The glass cost is lower than the industry average, thanks to the simplified window geometries.

The chassis components include all the remaining components not included in the previous sections, which are all attached to the frame, such as the suspension system, steering system, bumpers and fenders, etc. In these systems, the suspension system, wheels and tyres account for around half the costs.

The cost for these systems (Body & Trim, Chassis) has been calculated by applying the manufacturing cost percentages seen in *Table C-12* to an approximated manufacturing cost from a Kia Picanto. The Picanto has been chosen as the reference vehicle to calculate frame, body and chassis components cost, as it has a similar size, is low cost, and the base model includes little extras. Furthermore, the units produced in 2020 for the Picanto and its platform-sharing models are very similar to the ones discussed in *Section 2.2.2.1. Platform*. The manufacturing price for the Picanto has been calculated using the same tax (21%) and ICM (1.815) as before. From this, and approximation for the components in each of the two subsystems has been done (Frame and Body, Chassis), and from this information, deletion of the components or a percentage reduction is used to calculate the cost for these subsystems for this design proposal. The details of the components and reasons for the percentage reduction are explained in *Table C-13* and *C-14.*

It must be said that the method applied for the cost approximation for these two categories is not as precise as initially desired when conceptualizing the methods for reducing cost. Nevertheless, after thorough research into real manufacturing prices for these system's components in function of quality, units produced, geometry or size, it became clear that not enough information is available for certain components, or that the cost methods were too complex or involved too many variables to fit into the scope of this project. Therefore, the percentage approximation method is used. The percentages applied to reduce cost (*Table C-13* and *C-14*) are considered conservative, and they have been chosen as such given the lack of information, and as to not reduce the price indiscriminately. To put it into perspective, the sum reduction of

*Figure 59. Kia Picanto. Source: (Motor1, 2020)*

manufacturing cost for these two categories is just 800€ when compared to the Picanto approximation. The final manufacturing cost approximation is in the range of those seen in *Figure 26*

After having analysed the method to obtain a selling price, it is clear that the proposed price of 17,300€ only serves the purpose of giving an idea of the price range of the car, since especially for the indirect costs, small variations in the ICMs would lead to a noticeable final price variation. For comparison, if the lowest ICM sourced were used (*Table C-7*), at a value of 1.48, the total selling price would be of 14,150€; whereas if the largest ICM were used (*Table C-6*, value of 2.14), the total price would amount to 20,450€. Therefore, the managing of the company, distribution and sales system all greatly influence the final selling cost, and manufacturing cost reductions can be undermined if these parts of the company are not efficiently run or carried out.

It is also evident that some of the methods applied to reduce manufacturing costs, such as identical bumpers or flat panels, have a barely noticeable effect on the overall selling price, and one might argue that given the aesthetic compromise it is not worth the cost difference, but the objective for this project is to contemplate all possible cost reduction methods to attain the cheapest BEV of these characteristics.

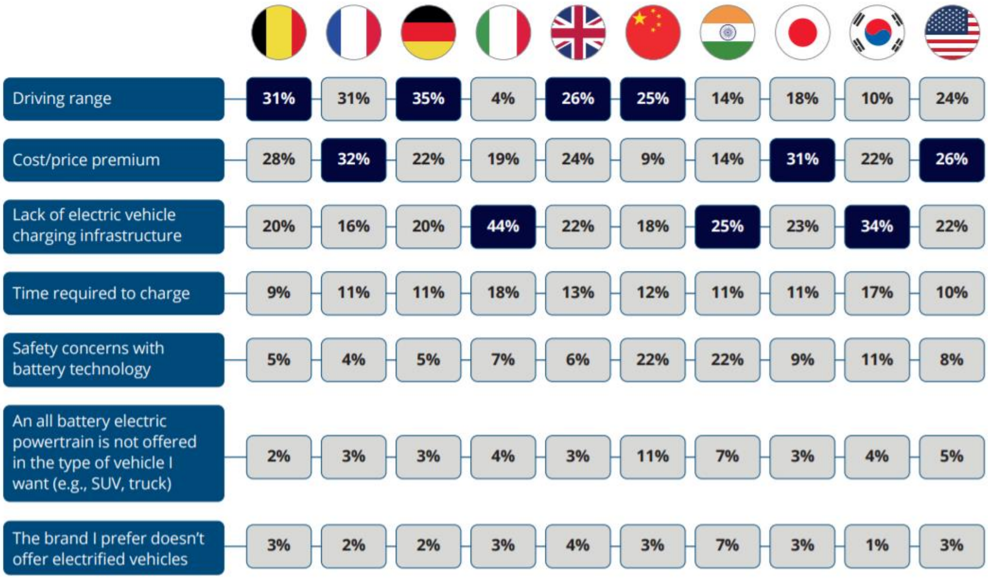
The implications of these costs on the overall product are discussed in the next sections.

## 3.3. Product Target

After having specified the characteristics of the vehicle and its approximated price, the possible potential customer target can be defined.

As reported by the surveys conducted by Deloitte (Dr. Wu, et al., 2019) and Consumer Reports in 2019 (Reports, 2019) , the high price of BEVs compared to ICEVs is one of the most important factors affecting sales, together with range and lack of charging infrastructure. This can be seen in *Figure 60*, where different factors affecting BEV sales are represented for the major BEV markets.

In this case, the proposed vehicle addresses the cost problematic in sacrifice of, among other things, a better range, as was discussed in *Section 3.1.2.1. Battery capacity limitation.* Since the battery pack costs are the highest cost contributor in the manufacturing price, evidently both issues cannot be completely solved at the same time with the current state of the technology.



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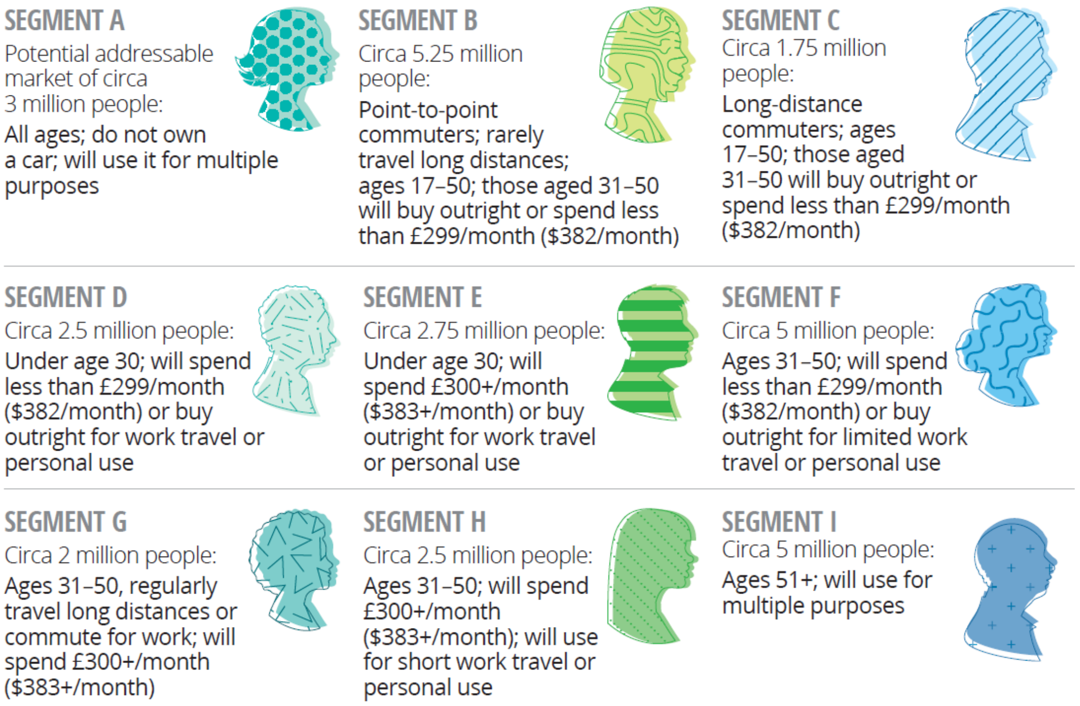
|---|---|---|---|---|---|---|---|---|---|---|
| Driving range | **31%** | 31% | **35%** | 4% | **26%** | **25%** | 14% | 18% | 10% | 24% |
| Cost/price premium | 28% | **32%** | 22% | 19% | 24% | 9% | 14% | **31%** | 22% | **26%** |
| Lack of electric vehicle charging infrastructure | 20% | 16% | 20% | **44%** | 22% | 18% | **25%** | 23% | **34%** | 22% |
| Time required to charge | 9% | 11% | 11% | 18% | 13% | 12% | 11% | 11% | 17% | 10% |
| Safety concerns with battery technology | 5% | 4% | 5% | 7% | 6% | 22% | 22% | 9% | 11% | 8% |
| An all battery electric powertrain is not offered in the type of vehicle I want (e.g., SUV, truck) | 2% | 3% | 3% | 4% | 3% | 11% | 7% | 3% | 4% | 5% |
| The brand I prefer doesn't offer electrified vehicles | 3% | 2% | 2% | 3% | 4% | 3% | 7% | 3% | 1% | 3% |

*Figure 60. Deciding factors in BEV sales. Source: (Dr. Wu, et al., 2019)*

A different report by Deloitte (Dr. Hamilton, et al., 2020) gives insight into the personal profiles of the potential BEV buyers (*Figure 61* and *Figure 62*). From the proposed buyer segments, this vehicle would be primarily targeting segments A, B, C and D, which are categorized as having a more limited budget and travelling short distances. For the latter reason, segments F, H and I could also be potential buyers, although they would be able to afford a more expensive BEV. Example persona profiles are included in *7.4 Appendix D*.

The combination of the A, B and D segments results in a consumer base of around 10 million people in the UK, or about 15% of the population, according to the report's data. The potential for the percentage for national consumer targets to increase in lower wage countries, such as Italy, France or Spain; is evident when contrasting the information with that from *Figure 60,* since in lower income countries, the cost/price premium is a larger factor than range.



**SEGMENT A**
Potential addressable market of circa 3 million people:
All ages; do not own a car; will use it for multiple purposes

**SEGMENT B**
Circa 5.25 million people:
Point-to-point commuters; rarely travel long distances; ages 17–50; those aged 31–50 will buy outright or spend less than £299/month ($382/month)

**SEGMENT C**
Circa 1.75 million people:
Long-distance commuters; ages 17–50; those aged 31–50 will buy outright or spend less than £299/month ($382/month)

**SEGMENT D**
Circa 2.5 million people:
Under age 30; will spend less than £299/month ($382/month) or buy outright for work travel or personal use

**SEGMENT E**
Circa 2.75 million people:
Under age 30; will spend £300+/month ($383+/month) or buy outright for work travel or personal use

**SEGMENT F**
Circa 5 million people:
Ages 31–50; will spend less than £299/month ($382/month) or buy outright for limited work travel or personal use

**SEGMENT G**
Circa 2 million people:
Ages 31–50, regularly travel long distances or commute for work; will spend £300+/month ($383+/month)

**SEGMENT H**
Circa 2.5 million people:
Ages 31–50; will spend £300+/month ($383+/month); will use for short work travel or personal use

**SEGMENT I**
Circa 5 million people:
Ages 51+; will use for multiple purposes

*Figure 61. General BEV target categorization. Source: (Dr. Hamilton, et al., 2020)*

Further insight into the segments can be obtained by analysis of *Figure 62*. Here, the percentage of the population from each segment who would consider a BEV purchase is shown. Segments A, B, D are shown to be quite favourable towards BEVs, nevertheless, the segment which is more inclined towards BEV purchases (segment G) cannot form part of the possible consumer base, as the segment is categorized by commuting long distances regularly, and also by having a higher budget.

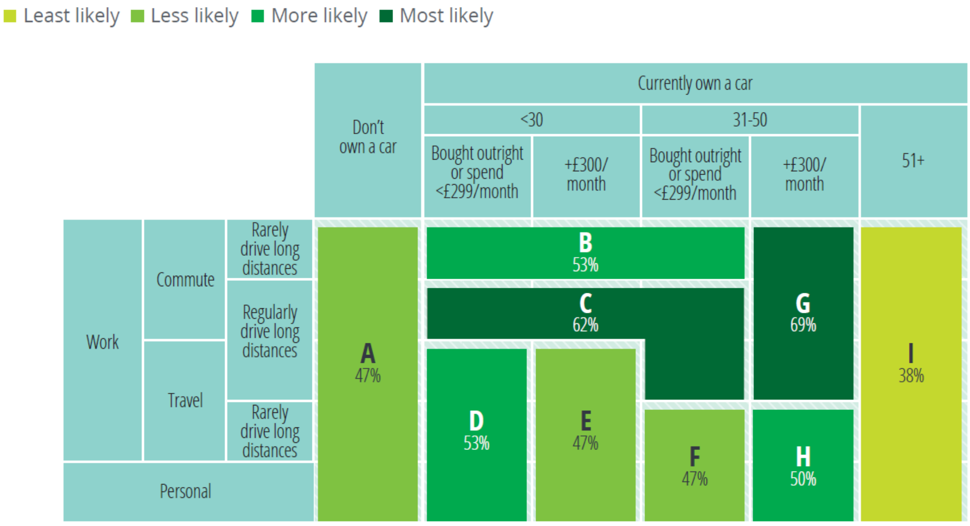


*Figure 62. Tendency to purchase a BEV. Source: (Dr. Hamilton, et al., 2020)*

Said report also mentions the importance of enabling low-cost monthly payments for new BEV purchases, as a majority of the consumer base is not able or not willing to pay the full price of the vehicle outright.

The fact that, as specified in *Section 3.1.1.2. Highly versatile BEV platform. Ease of scalability*, this vehicle would have to be sold in combination with other body types, means that the public from these segments can be more easily reached when considering that preference for body-styles is quite varied regardless of the group or category.

So, assuming that 50% of the potential buyers that may switch to a BEV are put-off by either the vehicle's looks or extreme simplicity, this still leaves 5% of the UK's population being potentially addressable. Standardising this for the main potential countries in the EU (UK, Belgium, Germany, Norway, Sweden and France, for a total of 240 million inhabitants) amounts to around 12 million potentially addressable customers.

It is also important to note that, as seen in *Figure 6* in *Section 2.2.1.1. Europe PC Sales*, Minicars are the sixth largest segment in Europe, with approximately 800 thousand sales in the EU during 2020.

Another possible market for this proposal is the Free-Floating Car-sharing Systems market (FFCS). This is still an emerging market in big cities, and it consists of by-the-minute car rentals, which you pick up around the city and park at you destination. An example of such service is the Daimler company ShareNow, which is available in 16 major EU cities, including Madrid, and which is starting to include BEVs in its fleet of vehicles.

This market has proven itself with electric scooter rental services, which use very simple and affordable electric scooters which are extremely easy to use. The proposed vehicle has these exact qualities but in a car, with cheap, interchangeable and easily replaceable bodywork components. The simple interior would be much easier to maintain, and simplified electronics would make electrical repair jobs much easier for the company. ShareNow currently offers a 0.19€/min fee for the cheapest option, the Smart Fortwo. The operation costs would most likely be lower for the proposed electric vehicle, as long as the charging infrastructure were sufficient to allow for on-spot parking charging.

FFCS is still an emergent market, but as reported by an analysis on various services around the EU and USA in 2016, the daily bookings for these services are continually growing year after year, especially in EU cities (Kortum, et al., 2016). Therefore, by offering a cheap electric alternative for the rental vehicles, the lifecycle costs for each vehicle would be reduced (Brennan, et al., 2016), therefore offering the possibility to reduce rental price, which can lead to a higher use of the service. It could also impact noise and environmental pollution in city centres, nevertheless all of this is only possible given that the city where the service is located has an extensive EV charging infrastructure, a problem discussed in the next section.

## 3.4. Product analysis and comparison

The previous category does not take into consideration the unusually low build quality, very basic comfort systems and unusual styling, as these aspects are discussed in this section in comparison to other existing ICEV and BEV vehicles.

No comparison with Chinese market vehicles will be carried out, as these benefit from very low manufacturing costs and sell at very low prices, meaning that in a direct cost comparison, these have an obvious advantage.

As the calculated price is just for indicative purposes, no direct cost comparison will be done, as the cost approximation is too inaccurate to do so. But as mentioned in *Section 3.2. Cost approximation*, the given price helps establish a price range for the vehicle to be positioned in.

All the data discussed in the next paragraphs and its sources are seen in *7.2 Appendix B*. *Figure 63* shows a comparison of the European BEVs under 35,000€ in Spain, as of April 2021, with tax included, with the design proposal also included.

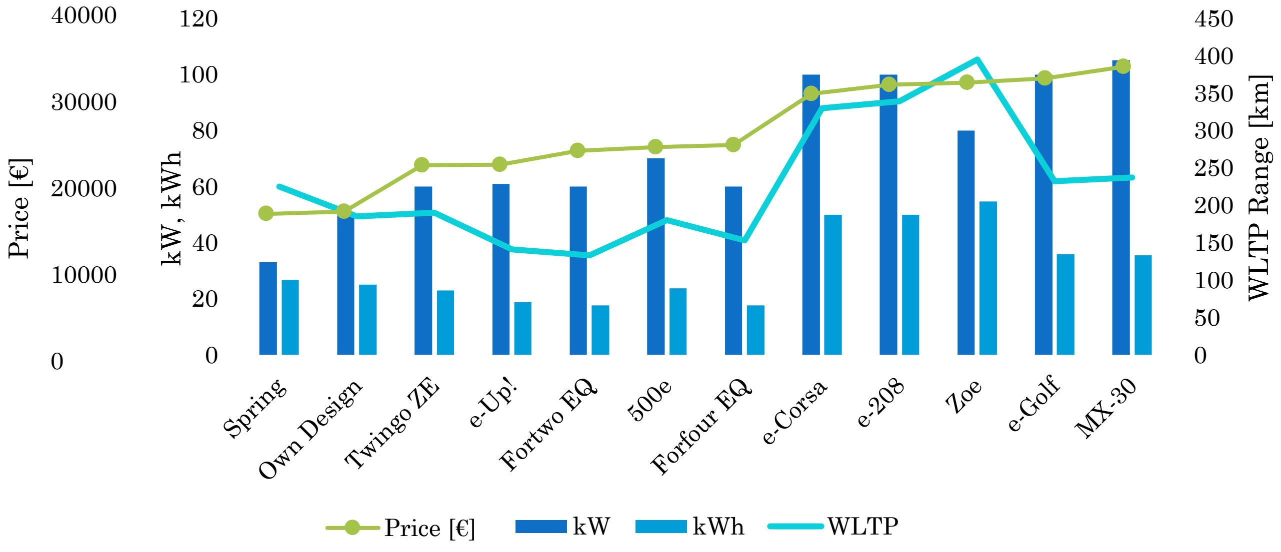


*Figure 63. Technical and price comparison with affordable European BEVs. Data aggregated from Tables B-3 to B-5*

*Figure 64. Dacia Spring. Source: (Dacia)*

The closest European BEV currently in the market is the Dacia Spring a small city crossover priced at 16,990€ (Spain 2021, tax included). It has a very similar battery pack capacity, at 26.8kWh, reaching a WLTP range of 225km. It is remarkably light, at 921kg, as it is actually quite a small vehicle, only 120mm longer than a Renault Twingo, and 40mm narrower. It is based on the Renault-Nissan CMF-A platform, which underpins other small ICEVs and BEVs available in China and India, models which have had quite good sales these last two years (EVdatabase, 2020). This, combined with the fact that it is produced in the same Chinese factories as the other platform models, are presumably the main factors which allow it to attain such a low selling price. As in our case indirect costs, labour and electric technology costs are based on European figures, even though the Dacia Spring is available in Europe, this comparison definitively weighs in favour of the Chinese-made model for the reasons mentioned above. Therefore, no further comparison is carried out for this model, and all the next BEVs compared are both available in Europe and manufactured in a UE nation. Furthermore, no 2020 sales data is available for the Spring, as it launched during the early parts of 2021.

The next closest price competitor is the Renault Twingo ZE, which is priced at 22,750€. It is based on the Twingo-Smart platform, which until 2020 included BEV models. It still takes advantage of the BEV architecture, as the ICE was originally made small enough to be positioned in the back, to allow for better interior space. It has slightly more power but less battery capacity, nevertheless it achieves a very similar WLTP to our approximation. For a reminder, the calculated WLTP range for this project's design is deliberately lower than a vehicle of similar characteristics because of its worse aerodynamics. It also seats four occupants and comes with only 5 doors. The differences in features are small, with the Twingo benefiting from a (standard in all the next vehicles) infotainment display, an AC controller, and electric front windows. It is 90mm higher at the highest roof point and 300mm longer, and weighs 1250kg, therefore it is larger, to possibly accommodate with ease the highest percentile passengers, an advantage which the proposed design does not achieve as well as the Twingo.

*Figure 65. Renault Twingo ZE. Source: (Renault)*

The Volkswagen e-Up! also closely matches the Twingo's characteristics an price, and therefore is also a strong contender in the affordable BEV market. These vehicles sold approximately 27,000 units in Europe combined, with the e-Up! accounting for 22,000 of them. Nevertheless, the Twingo-ZE only started receiving orders in the fourth quarter of 2020, so its sales are not representative of a full year. With an approximate 5,000€ reduction in price (nearly a quarter of the selling price), as is the case of our proposal, sales of vehicles like these could potentially increase noticeably, allowing to meet the yearly unit production goal for this proposal.

*Figure 66. Fiat 500e. Source: (Fiat)*

Vehicles like the Fiat 500e or the Smart EQ stand at a higher price point, and offer higher quality finishes with very similar battery and range specifications to the previous vehicles. Our proposal does not target this market, as these have a higher premium factor. The customers for these vehicles have a slightly larger budget, between 20,000€ and 30,000€, and are looking for a higher quality feel and finish, as well as the premium factor, which our proposal does not possess. These vehicles have very similar technical specifications to the previous ones, while costing more.

The next price range starts around 30,000€, with vehicles like the Opel Corsa-e, the Peugeot e-208, or the Renault Zoe. All of the vehicles in this price range, except the Zoe, are based on existing ICEV models, so they do not benefit from the packaging advantages of the BEV architecture, but it does result in lower costs. These models have upwards of 35kWh batteries, and their quality is also better, so considering this and the large price difference, it becomes clear that these do not interfere with our target demographic.

*Figure 67. Opel Corsa-e. Source: (Opel)*

So the direct competition for an affordable city BEV in the European market is quite limited, with 6 different models offered, only two of which (the Dacia Spring and the Renault Twingo) are exempt from any premium value, and are offered with very basic trim and features. Nevertheless, as seen in *Section 3.3. Product Target*, there exists a large enough percentage of the population to increase demand, given that the prices for these BEVs were low enough to compete with the most affordable ICEVs. When government benefits are included, the only BEV to exist in this price range is the Dacia Spring, which again benefits from being produced in China, in contrast to the rest of the vehicles seen in *Figure 63*, which are produced in the EU or Japan.

Regarding the sought after objective of achieving price parity with the most affordable ICEVs, even with all the cost reduction methods applied, the cost parity for a usable, utilitarian city BEV cannot be fully achieved. To put it into context, the Kia Picanto used to derive part of the vehicle's cost is priced at 12,650€, taxes included. That is a marginal decrease in price when compared to approximation, while the ICEV counterparts retain a better design, better interior trim and features, and the convenience of a combustion engine.

Nevertheless, when government subsidies are taken into account, the approximated cost for the designed vehicle starts to be in par with the ICEV A-segment models, such as a Citroën C1 or a Hyundai i10, while retaining a usable battery capacity for short-to-medium journeys. Hence that with government subsidies, a vehicle like this proposal would be able to be positioned as a price competitor with the most affordable ICEVs, although the proposed BEV would still lack in range, features and styling.

*Figure 68. Citroen C1 (Left). Hyundai i10 (Right). Sources: (Citroën), (Hyundai)*

After having analysed the possible competition, it is necessary to reiterate that, even though the manufacturing cost approximation has been considered reliable enough, the indirect costs have been estimated at the mid-range from values from various sources, which vary drastically, resulting in a noticeable price difference if the ICM is modified.

# 4. Environmental effects

Assuming the 100,000 yearly platform units sold came from 95% current ICEV owners, a figure which as we've seen in *Section 3.3. Product Target* could be easily achieved given the potential market, this would leave us with approximately 95,000 PC that switched from ICEVs to BEVs in one year.

The next figure shows the average CO2 emitted for different types of propulsion technologies. "Electric car-clean" refers to charging with energy produced from renewable energy sources or low CO2-emitting sources. The emissions shown are therefore not only from exhaust gasses, but are the total carbon footprint of each vehicle, including manufacturing and energy production.

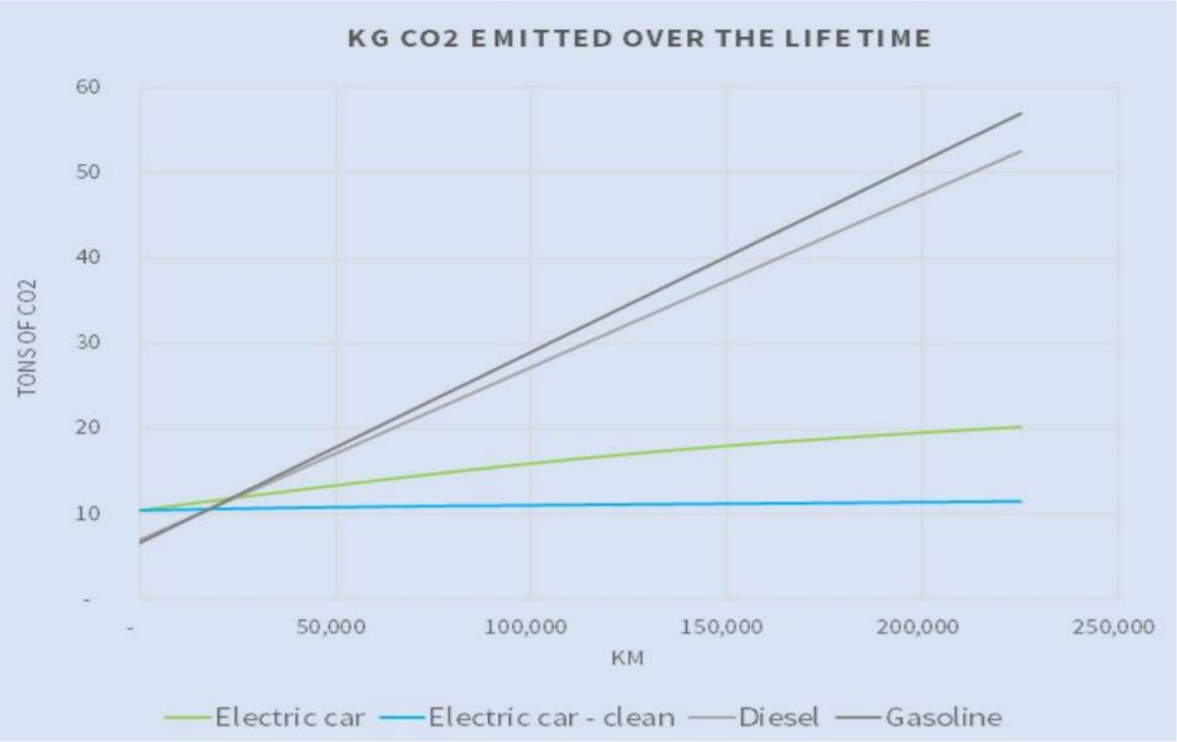


*Figure 69. Average PC carbon footprint. Source: (TandE, 2020)*

The average European drives 12,000km every year (Enerdata, 2020), so after 10 years of ownership a BEV will have produced an average of 16 tons of C02 (green "electric car"), in comparison to the 30 tons emitted by a diesel vehicle, for each individual vehicle (*Figure 69*). Nevertheless, during the first 20,000km, a BEV has a bigger carbon footprint due to the mining and shipping of the lithium for the battery manufacturing.

The 14 ton difference over ten years of ownership would mean that the vehicles sold in one year would decrease carbon emissions by 1.3 thousand tons over these ten years, when compared to diesel cars.

This is a very small amount compared to the overall worldwide pollution, but if such a vehicle were implemented in the market and it worked as proposed, it would most likely generate further competition which would make the BEV market grow even further, further reducing worldwide emissions.

Nevertheless, if recycling of lithium-ion batteries is not addressed (currently at around 5%), it will become an environmental threat with the rise in popularity of BEVs. (Jacoby, 2019)

# 5. Conclusions

The objective of this proposal was to achieve a BEV which, thanks to an array of cost-reducing methods, would cost the same as the most affordable A-segment European ICEVs.

Despite the final price being an approximation, it can safely be said that this cost parity cannot be currently achieved for a BEV with a usable range, even with all the cost-cutting measures combined. The final price is higher than the initially desired, nevertheless, the price is substantially lower than similar European BEV models, so a noticeable price decrease is still achieved with this design.

It is disputable if specific cost-reducing measures would be beneficial given the slight cost reduction, for example the exterior bodywork metal geometry. Despite this, one has to consider that the aim of this vehicle is to explore and combine as many of these measures, even if they may seem to make a very small difference in the overall cost. As well as this, the design shown is only for visualisation purposes, as it is not the main scope of the project, and has been done by an engineering student without background in graphic design or exterior car design. The design could be much improved even with the given bodywork characteristics, although the vehicle would still look quite different from anything currently seen in the EU.

It must be said that the initial expectations for the bodywork and interior design specifications were that they would reduce the cost of the vehicle much more dramatically, but after further research it became apparent that automotive brands are able to manufacture these components much cheaper than initially expected. Furthermore, the current high cost of battery manufacturing means that the only way to reduce price to around 12,000€ would be by limiting range severely, up to a point where the vehicle would be unusable for the majority of the target demographic.

Despite this, as mentioned before, a noticeable price decrease is achieved, and it has been concluded that a vehicle similar to the one theorized in this project would be a beneficial addition to the BEV market, as it could help with the transition from fossil fuel mobility to electric mobility for the masses by offering a lower starting price. A vehicle like the one proposed could cover the entry-level BEV gap in the European BEV market, and if manufactured in a few years, it would be one of the first vehicles to achieve price-parity with ICEVs without the need for government subsidies. Furthermore, it could also make the electric FFCS market grow in a similar way that has been seen these last with electric scooter rental services, since it is cheap, has a basic interior, and would have easy and cheap maintenance and repair, for the bodywork and interior components.

It is important to restate that a vehicle like the one proposed would only be able to be usable as long as the area of residence of the owner had an extensive charging infrastructure, which needs to be installed with the help and regulation of local governments, as the private sector does not have the backing or interest to create the necessary infrastructure.

Finally, the importance of clean energy production, clean lithium mining and transportation, and lithium-ion battery recycling cannot be understated, as BEVs depend largely on these external factors to reduce pollution when compared to ICEVs, and embracing one without the others is illogical if the objective is to reduce our carbon footprint during the next decades.

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