POLITECNICO DI TORINO

Department of Management and Production Engineering

Engineering and management course (Innovation path)

Master’s Degree Thesis

# Battery Swapping Systems:

From a Business-oriented Analysis to a Practical Case Study

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*"You can't connect the dots looking forward; you can only connect them looking backwards. So, you have to trust that the dots will somehow connect in your future. You have to trust in something — your gut, destiny, life, karma, whatever".*

- *Steve Jobs*

Alla mia famiglia, ad Adriana e ai miei amici. Che sia la fine di un duro percorso e l'inizio di una vita colma di felicità, successi e rivincite.

# Abstract

*This master's degree thesis deals with the concept of Battery Swapping System (BSS). A BSS is an alternative technological infrastructure to the charging process of Electric Vehicles (EV) of any kind and dimension, trying to solve problems affecting many stakeholders in the process while obtaining equivalent final result.*

*I decided to address this specific topic driven by a strong commitment to safeguard of the planet. I believe the problem must be solved together and even the smallest symbolic contribution from younger generations may help.*

*In this paper I tried to blend more abstract and general considerations to business-oriented concepts and practical applications and implications.*

*Nowadays, Electrification of powertrains is increasing year on year and it is quite clear that this scenario in the long term will dominate market sales, imposing itself as the dominant paradigm of green alternative mobility. On the other hand, the electrification process brings the attention to some issues to be solved, first of all which infrastructure and complementary technology to invest in, in parallel with EVs diffusion curve. Today, plug-in charging, private or public, is the most widespread form of charging, however it has many drawbacks and probably will not be able to support the rapid growth of EVs, leaving the door open to other solutions for the future. Among all possibilities, explained in the paper, the decision to focus on Battery Swapping was taken since this solution, right now, allows to gain the highest benefits, satisfying simultaneously the needs of all the stakeholders and maximising the process efficiency from almost all points of view.*

*The paper can be virtually split into two parts, a first section whose aim is to collect and put together information on the topic from online and offline sources, exploiting a funnel approach starting from the broader concept of EV state of art and paradigm and ending with detailed battery swapping dynamics, passing through complementary technologies' comparison as alternatives as well. After bringing the attention to the chosen technology, the second section focuses on an ideal practical application of BSS, introducing a specific case study on heavy-duty trucks (commercial road transport) in Italy with a deep dive on market sizing and business model analysis. The choice of this mean of transport was made considering how well and easily could it fit a battery swap infrastructure. The goal of this case study is to simulate heavy-duty trucks driving on two paths across the whole country (long-haul trucks), exploiting a BSS built using FlexSim software, under many ideal assumptions clearly stated. The final aim of the simulation itself was double, on one side to test the maximum traffic flow the basic model could bear and, on the other side, to modify the model so as to find the best solution based on monitored output parameters, solution to be then approximately compared to the outputs that would ideally come from a traditional plug-in fast charging solution or even a traditional powertrain (ICE), in terms of cost, time and energetic demand.*

*Therefore, based on quantitative results obtained from the specific simulation and analyses under all the assumptions and based on the qualitative more general academic research on the topic as well, I have been able to draw some conclusions. The battery swap solution provides benefits to many stakeholders involved and may be able to provide the same results for drivers as a plug-in solution, however other obstacles are probably hindering its rise in the short term. In the long term, due to the rise of other shaping trends, battery swap may become an optimal complementary solution, thanks to the possibility if offers to improve energy management and timings, two key factors in the future connected smart communities.*

*This paper addresses a highly innovative topic for our country, really practical and useful for our immediate future. This work opens the door to further investigation, in particular to the building of more customized and accurate models, able to resemble real processes applied to many different vehicles and situations. Further research may be conducted on the renewable energy options applied to battery swapping stations as well on the net present value (NPV) of a network of BS stations' project. The kind of results ideally coming from those experiments would be extremely beneficial for the final evaluation of the adoption and investment of such a technology in our country. Today is the perfect timing, investment and development decisions can't be postponed anymore.*

# Acknowledgements

*Vorrei esprimere i miei più sentiti ringraziamenti al Professor Franco Lombardi, alla ricercatrice Giulia Bruno e al dottorando Emiliano Traini per la disponibilità e per aver permesso la realizzazione di questo elaborato.*

*Ringrazio il dipertimento di Ingegneria gestionale e della produzione (DIGEP) del Politecnico di Torino e per aver concesso l'utilizzo del modello di base (risultato di una tesi di laurea magistrale precendente), utile ai fini delle simulazioni e l'osservatorio del traffico dell'ANAS (Gruppo FS Italiane) per la concessione dei dati esemplificativi inseriti nel modello di simulazione.*

*Un grazie infine ai professori Neirotti e Cantamessa per avermi introdotto e fatto appassionare all'analisi strategica di soluzioni innovative.*

# Table of Contents

# 1. Introduction

Subject of this paper is an in-depth analysis of the Battery Swapping System technology, an alternative technological infrastructure to the charging process of electric vehicles of any category and dimension, providing improved benefits to all involved stakeholders while obtaining the same final result.

This master degree's thesis is virtually split into two parts, the first one more theoretical, based on a massive research from online sources and a second part more practical and personal, in the attempt to develop a case study complete with simulations on FlexSim software and analyses.

I decided to address this topic since the choice of the optimal technology/infrastructure to invest on is such an actual, practical and strategic issue for our country, giving it the possibility to finally take a relevant step towards green mobility innovation. Electric mobility is growing quickly year on year and a solid efficient infrastructure must be built in parallel in order to reduce range anxiety and in general all the bias in users' mind. All these are preventing the society from a mass adoption of EVs, even if it is expected to happen in the next ten years. The main objective of my work is to collect as much information as possible on electrification process and complementary available technologies and, most of all, understand how to evaluate a battery swapping project in Italy compared to other solutions and if it could really be implemented under certain assumptions. In other words, some of the biggest questions still open today and partially addressed in this paper are: "Is, right now, BS the right technology to invest in?" or "Is it suitable for our market and society?" Or, again, "For which category of transport and service should we start designing and realizing it?" And, finally, "Which business model (pricing, partnerships…) should we adopt?"

For sure battery swapping has many drawbacks as a solution, it requires a massive upfront investment as well as an accurately planned business model and partnership support so as to be sure not to fall in the past trials' traps. Both from supply side (carmakers, battery manufacturers…) and demand side (electric vehicles owners) this solution needs full support and backing, making the idea commercially sustainable. Modularity and standardization of batteries today are hot topics, strongly affecting the technical feasibility and diffusion of such a technological infrastructure. On the other side, the benefits coming from the adoption of this solution are, according to me, more than compensating all these odds in the long term, increasing my commitment to it and my desire to evaluate its actual suitability and feasibility. A battery swapping project, for instance, allows an enormous cutting of time from electric vehicle (EV) owner's perspective compared to traditional plug-in charging process and it also allows for a better energy management in terms of peaks and valleys flattening with a bidirectional energy exchange with the power grid, in a unique optimized power system of the future.

The first part of the work is made up of three chapters developed following a funnel approach, I read and collected a huge amount of information on the topic from academic papers, industry reports, consulting companies reports and newspapers. I start, in the first chapter, form the global concerns about transport sector's impact on emissions, moving to the rising of electric powertrain as the dominant paradigm shaping global mobility future and concluding reporting the problems linked to this kind of solution. In the second chapter a description of the main complementary technologies for EV available and trending on the market today is developed, trying to decline them to specific means of transport (public, private, commercial…). Among them figures the battery swap which has a fully dedicated chapter (e.g. the third). In this chapter I provide a deeper analysis of stakeholders involved in a BSS project, advantages and disadvantages as well as business model insights of successful or ruinous past examples and the key issues related to batteries (typologies and standardization of modular batteries).

The second part starts from the widely explained concept of BSS and its application to commercial transport on the road and deepens this analysis through a specific case study on heavy-duty trucks for long hauls. The choice of this specific vehicles was not random, it was, instead, driven by how well and easily this category could fit a battery swap infrastructure, in terms of logistics, vehicle technical design and monitoring of benefits. I collected, analysed and reported information about market sizing, trends, BSS applications and I proposed a business model. The last chapter, before conclusions, aims at simulating some BSS scenarios and analysing its output data. The simulation has been run on FlexSim, while the output data has been collected and analysed exploiting Excel in order to optimize the model, find the desired solution and make some coherent considerations. The experiment consists of two paths (crossing the whole country) travelled by two typologies of heavy commercial trucks in a three traffic flows scenarios simulation (best, middle, worse), based on a personal estimation derived from data collected online. Paths are fixed, simulations are on a 24-hours basis and a consistent number of ideal assumptions had to be stated. Each path has four to five battery swap stations almost equally spaced on the map. I focused on the first (and most critical) of these stations to perform some analyses. My intention with this case study was to simulate heavy trucks driving without experiencing battery problems by optimizing the station model. For this purpose, after a market research on key numbers shaping this sector, I exploited the model of a BS station built by another master degree's student in the university and I performed a discrete event model simulation based on the trial-and-error principle and what-if analysis, modifying the model by setting the inputs parameter so as to optimize the trade-off among outputs required. Output key indicators to be monitored and analysed mainly include time, State of Charge of the batteries (SoC) and energy consumption. The specific final aim of the simulation itself was double, on one side to test the maximum traffic flow the basic model could bear in a sort of pilot project to be hypothetically realized in the short term and, on the other side, to modify the model so as to find the best solution for a long term full project based on monitored output parameters, solution then approximately compared to the outputs that would ideally come from a traditional plug-in fast charging solution or even a traditional powertrain (ICE), in terms of cost, time and energetic demand.

What comes out of simulations' results is that a battery swapping station design is affected by many possible variables, however, if wisely designed, it may bear high traffic flows and provide comparable results with respect to plug-in solutions both in terms of SoC (%) and timings, all this relying on normal charging (22 kW) with all the benefits implied by this choice.

Therefore, thanks to the quantitative results obtained from the specific simulation under all the assumptions and relying on the qualitative more general academic research on the BSS topic as well, I have been able to draw some interesting conclusions.

First of all, the battery swap solution provides benefits to many stakeholders involved and may be able to provide the same results for drivers as a plug-in solution under certain design specifications, however other obstacles are probably hindering its rise in the short term (initial investment requirements, standardization problems, revolution in business model…). In the long term, instead, due to the rise of other shaping trends, battery swap may become an optimal complementary solution, thanks to the possibility if offers to improve energy management and timings, two key factors in the future connected smart communities.

I hope that this paper can arouse the reader's attention and stimulate the desire to keep on developing further research and simulation on the topic, since this is the perfect timing to focus on such an innovation.

# 2. Electric vehicles state of art

## 2.1 Environmental trends - transport sector’s role and incentives

Greenhouse gases are responsible for our planet warming since they trap heat. In the last century the increase in greenhouse gases is almost all due to human activities, mainly coming from burning fossil fuels for electricity, heat and transportation. Here below, the primary sources of GHG emissions, taking the U.S. as reference country to give an idea:

- Transportation (28.9% of 2017 greenhouse gas emissions) – The largest part of greenhouse gas emissions is generated by transport sector. Transportation caused emissions mainly come from burning fossil fuel for cars, trucks, ships, trains, and planes. Over 90 percent of the fuel used for transportation is based on petroleum (e.g. gasoline and diesel).
- Electricity production (27.5% of 2017 greenhouse gas emissions) –second in the rank. Approximately 62.9 percent of our electricity comes from burning fossil fuels, mostly coal and natural gas.
- Industry (22.2 percent of 2017 greenhouse gas emissions) – Greenhouse gas emissions from industry primarily come from burning fossil fuels for energy, as well as from certain chemical reactions necessary to produce goods from raw materials.
- Commercial and Residential (11.6% of 2017 greenhouse gas emissions) – Greenhouse gas emissions from businesses and homes derive primarily from fossil fuels burned for heat, the use of certain products and the handling of waste.
- Agriculture (9.0% of 2017 greenhouse gas emissions) – Greenhouse gas emissions from agriculture come from livestock such as cows, agricultural soils, and rice production.
- Land Use and Forestry (remaining 11.1% of 2017 greenhouse gas emissions) – Land areas can act as a sink (absorbing CO2 from the atmosphere) or a source of greenhouse gas emissions.

The total Emissions value in 2017 amounts to 6,457 million metric tons of CO2 equivalent. [1]

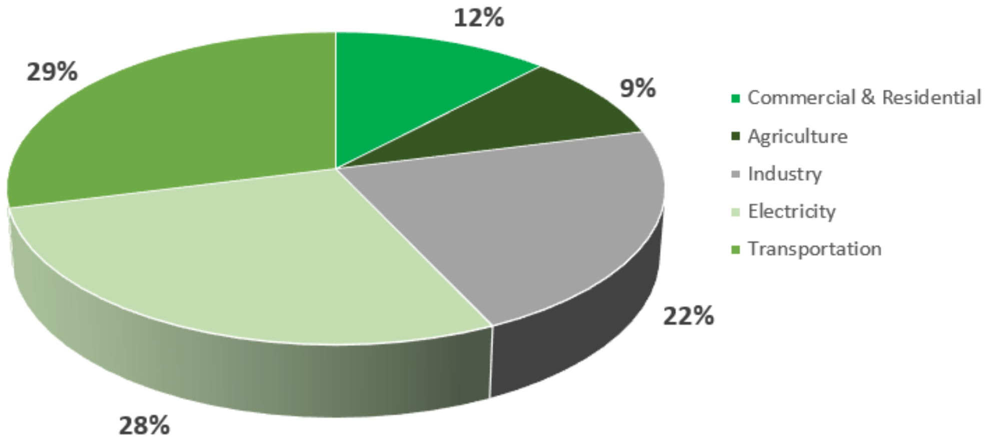



Figure 1. Total U.S. greenhouse gas emissions by economic sector in 2017, Source: [1]

Giving a look at the European situation we find very similar results and percentages, suggesting how critical the situation is and how quickly it must be addressed. Here I reported the percentage breakdown of GHG emissions and the energy demand both referred to 2014 in Europe in 2014. It is clear how road transport is dominating both pie charts. [3]

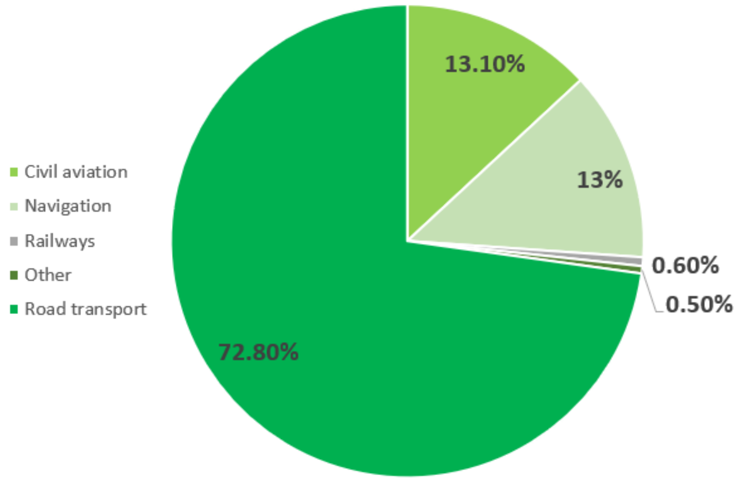



Figure 2. U.S. GHG emissions by mean of transport, 2014. Source: [2]

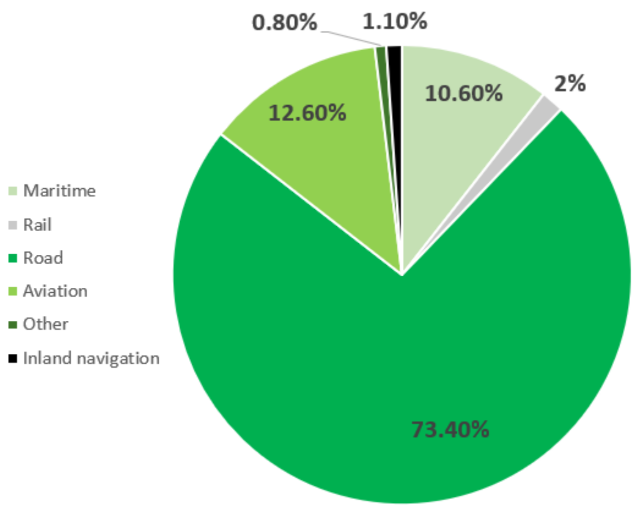



Figure 3. Share of energy demand for means of transport, 2014 (%) Source: [2]

From 1990 to 2016, in EU28 countries, as we can see from the Figure 4., the unique sector with an increasing trend is the transportation. [2]

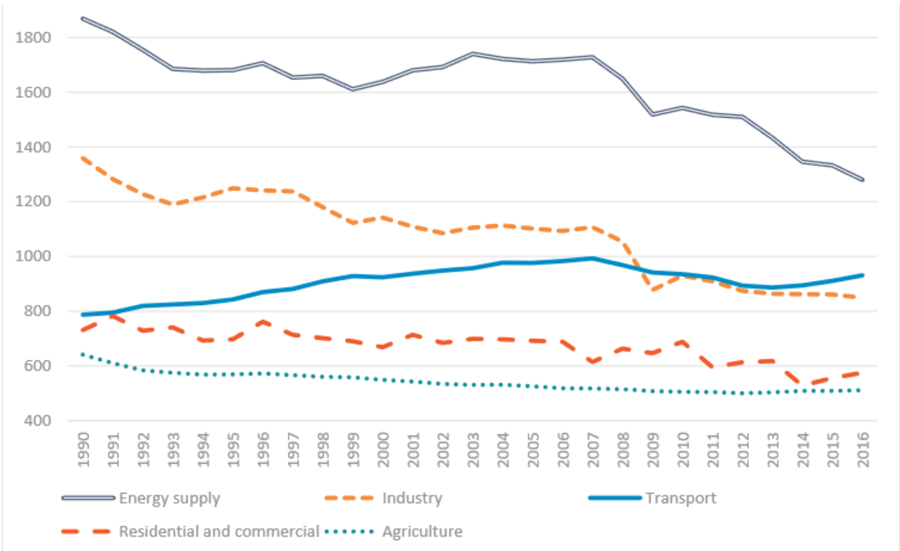



Figure 4. GHG emissions by sector in the EU28, 1990-2016, Source: [2]

The great majority of GHG coming from transportation sector are carbon dioxide, known as CO2, due to movement of cars, trucks, trains, ships, airplanes and any kind of vehicle. These emissions are the result of the combustion of petroleum-based solutions (e.g. gasoline), in ICE. Later in the report a further breakdown highlighting the main sources of GHG emissions by typologies of transportation is provided. Road transport takes by far the biggest responsibility. Fuel combustion produces relative little quantities of methane ($CH_4$) and nitrous oxide ($N_2O$). In addition, a small amount of hydrofluorocarbon (HFC) emissions are present in the transportation sector, due to the use of mobile air conditioners and refrigerated transport. [2]

Analysing the trend, during 1990-2017, total emissions of transportation have raised due to many factors. For sure, demand for travel increased and so did the vehicle miles travelled, boosted by population growth, economic growth and urbanization.

According to European Parliament, “Transport is also a major source of noise pollution. High - levels of noise can lead to hearing loss, sleep disturbance, poor mental health and well-being, increased risk of heart disease and change in blood pressure, among other effects. According to 2018 data from the European Environment Agency, almost 88 million people living in urban areas and almost 41 million people living outside urban areas in the EU are exposed to road, rail and air traffic noise levels exceeding EU thresholds.” Generally speaking, electric vehicles are much less noisy (and, so, harmful) than a traditional vehicle, thus reducing this kind of emissions on one side but, on the other side, increasing risk of not being heard by other people while coming.

A great variety of possibilities to reduce emissions coming from this sector are available.

- Fuel switching – Exploiting alternative sources of power (fuels) emitting less carbon dioxide compared to current ones.
- Improving fuel efficiency thanks to advanced design, materials, and technologies
- Improving maintenance and driving practices
- Reducing the need to travel by non-green means of transport

A strong collaboration is in act today between EU and member states, who want to stimulate electric mobility using local, regional and national incentives like reducing taxes or giving free public parking. Eu, on the other side, tries to improve recycling efficiency, increase transport sector efficiency, break the strict dependency from oil, promote renewable electricity and sustainable fuels.
In 2016, the Commission published a European strategy for low-emission mobility. It was highlighted the importance of public recharging points for EVs and the use of renewable electricity in transport sector.
Part of the strategy was a review of taxes and introduction of subsidies and incentives for low emissions vehicles and energy made by member states. European parliament strongly supported from 2017 the introduction of electric vehicles in parallel with long-term initiatives for batteries improvement and infrastructure deployment.
In May 2017, the Commission emanated “Europe on the Move”, which is a set of legislative measures to make Europe a leader in connected and clean mobility, to be introduced between 2017 and 2018. These measures limited CO2 emissions and fostered clean vehicles sales both in private and public procurement. Usually the measures adopted in Europe come from negotiations between the European Parliament, usually calling for more strict and ambitious targets, and the European Commission.
According to the Parliament documents, “The EU provides financial support to electric mobility, for example, by making non reimbursable grants from the Connecting Europe Facility (CEF) and the structural and investments funds available for the development of charging infrastructure and the acquisition of electric buses. Projects focusing on R&D in electric mobility can obtain support from the European banking system.” [2]
A strong indication of the support that EU is giving to electric mobility is that from 2018 to the end of 2020 the Commission is investing €200 Mln in battery research and innovation, on the top of the €150 Mln previously allocated.
In a long term perspective (2021-2027), in June 2018 the Commission proposed to use 60% of the CEF €42.3 billion budget for projects helping to achieve climate goals, through an adequate infrastructure network among the others. [2]

To summarize, it is possible to identify some areas of priority for actions:

- Encourage the shift towards lower emission transports and exploiting digitalization and connectivity
- Fostering the diffusion of low-emission alternative energy for transport sector, like biofuels, electricity, hydrogen and renewable synthetic fuels and invest on a capillary infrastructure network
- Incremental innovation in ICEs and strong parallel acceleration to pass to low and zero emission vehicles
- The implementation will be largely dependent on local authorities. They are already proposing incentives for low-emission alternative energies and vehicles, encouraging active travel (cycling and walking), public transport and bicycle/car/scooter sharing to relieve cities' congestion and pollution. [2]

WindEurope report about electrification process in Europe, suggests a forecast of the future of energy consumption and transportation sector in the next 30 years, according to two different scenarios. These scenarios (accelerated and Paris-compatible) differ by the policy lever applied by EU. [4]

In the Figures 5. And 6. Below the electrification stage in the two scenarios compared to 2017 is present, broken down into the main voices.

| | SCENARIOS | |
|---|---|---|
| Policy lever | ACCELERATED ELECTRIFICATION | PARIS-COMPATIBLE |
| Energy Efficiency and Electrification Uptake: | | |
| Buildings | 1.0%/year | 1.8%/year |
| Manufacturing | 1.8%/year | 2.6%/year |
| EV fleet of passenger vehicles | 90% by 2050 | 90% fleet, 3.7% vehicles hydrogen-based |
| $CO_2$ price in 2050 | €45/t$CO_2$ | €90/t$CO_2$ |
| Coal power | Plants retired as they reach their economic lifetime<br>New plants built out where economic feasible | No new plants built after 2020<br>No generation after 2030 |

**Figure 5.** Scenarios summary. Source: [4]

| | CURRENT BASE (2017) | ACCELERATED ELECTRIFICATION (2050) | PARIS-COMPATIBLE (2050) |
|---|---|---|---|
| $CO_2$ Emissions- Energy related | -22% | -74% | -90% |
| Final Energy Demand [a] | 47,154 PJ/year | 33,460 PJ/year | 31,754 PJ/year |
| Final Energy Demand [a] | 13,098 TWh/year | 9,173 TWh/year | 8,820 TWh/year |
| Renewables in final energy demand | 20% | 59% | 66% |
| Renewables in power sector | 34% | 75% | 78% |
| Energy costs as % of GDP | 2.1% | 2.2% | 2.7% |
| Electrification of final energy demand [a, b] | 24% | 51% | 62% |
| Manufacturing goods | 46% | 65% | 86% |
| Base materials | 34% | 60% | 85% |
| Households | 29% | 39% | 59% |
| Commercial buildings | 50% | 62% | 78% |
| Transport | <1% | 46% | 51% |
| Road transport | <1% | 75% | 80% |
| Shipping | 0% | 5% | 6% |
| Aviation | 0% | 3% | 3% |
| Rail | 70% | 96% | 96% |

**Figure 6.** Scenarios comparison. Source: [4]

Focusing on the Paris-compatible scenario, in the time period 1980-2050 it is possible to gain many insights. Total energy demand is going to decrease year on year after reaching a peak on early ’00, electricity is going to get huge percentages of total energy demand by replacing oil, gas and coal. In 2025 around 18% of total electricity (5,45 TWh/year) will be used for transport sector. [4]

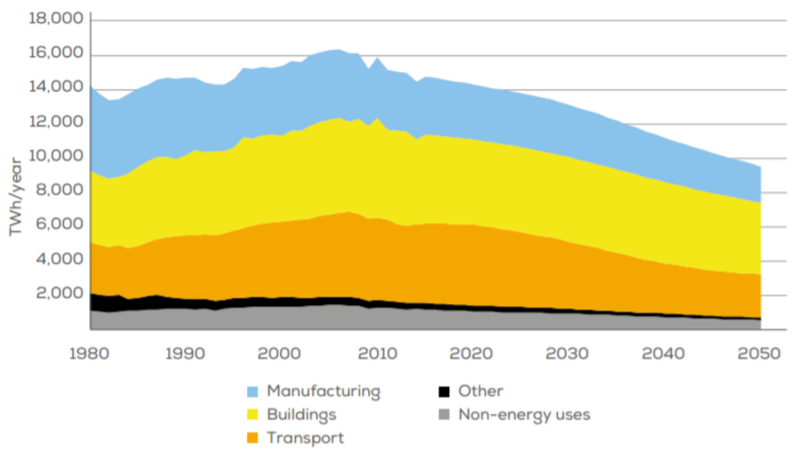



**Figure 7.** Final energy demand per sector. Source: [4]

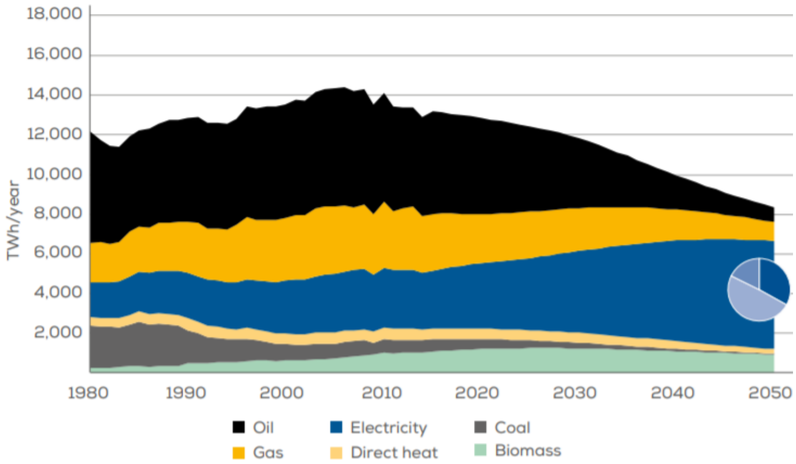



Figure 8. Final energy demand per carrier. Source: [4]

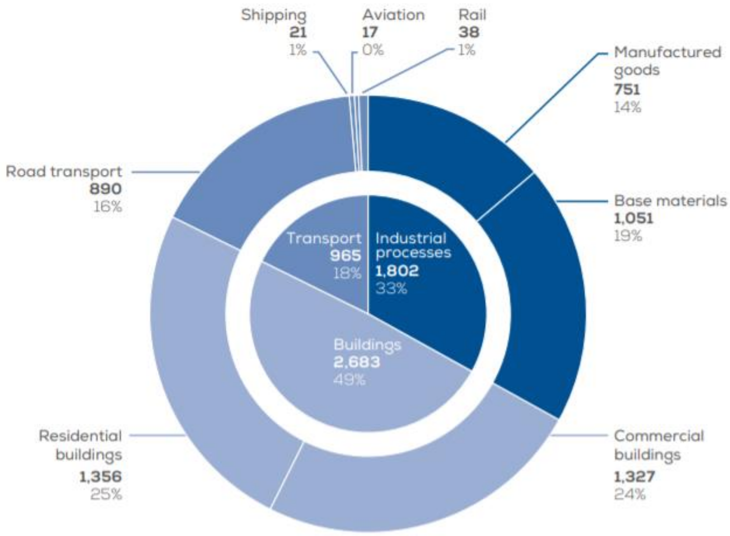



Figure 9. Electricity use by user in 2050. Source: [4]

In the Paris-compatible scenario, from Figures 10. and 11. we can, once again perceive how the road transport sector even in the next 30 years will take the biggest share of energy use in transport sector. Combining this concept with the rapid growth of electricity as main energy carrier in the long term, road transport will show the highest year on year growth rate in terms of electricity use among all sectors. [4]

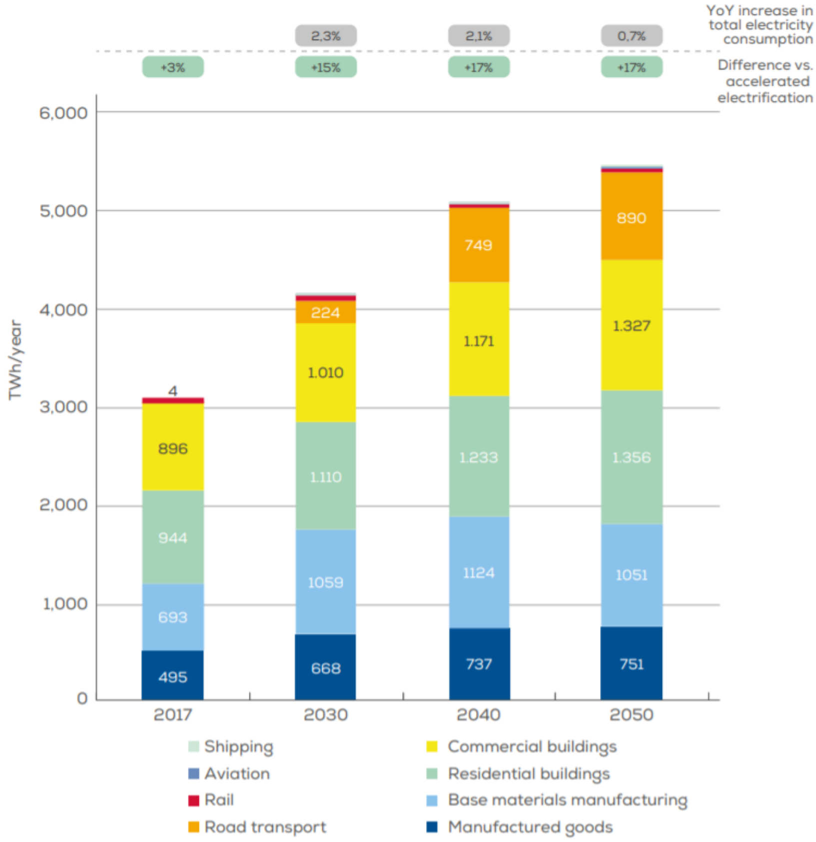



**Figure 10.** Electricity use by sector. Source: [4]

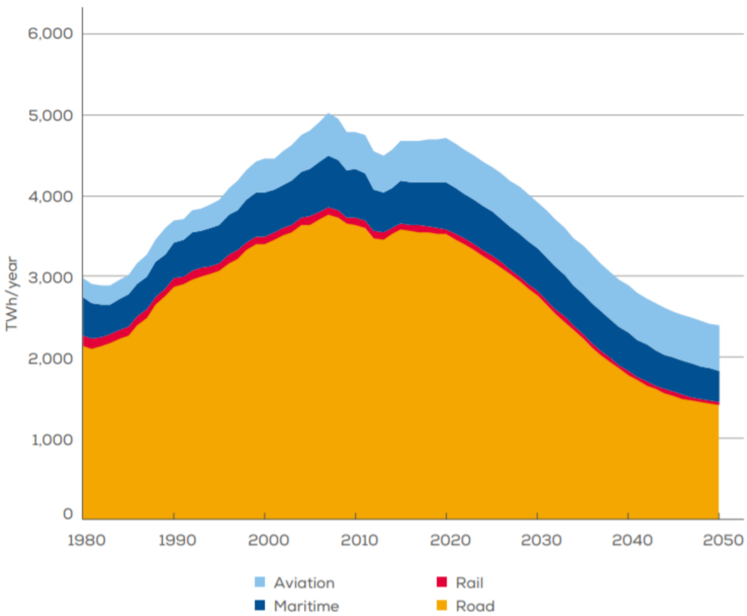



**Figure 11.** Energy use in transport per sub-sector. Source: [4]

## 2.2 Electric vehicles paradigm

Over the next years, the automobile and truck industries will diversify their powertrains considerably (i.e. the main components that generate power and transmit it to the road surface). Besides internal combustion engine (ICE) vehicles (powered by fossil fuels, synthetic natural gases or synthetic fuels), a lot of popularity will be gained by plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (fully powered by it) (BEVs) and fuel cell vehicles working thanks to hydrogen (FCEVs). It is impossible to predict with certainty future customers' preferences but strategic choices have to be made right now by all stakeholders.

All the different power systems bring with them some pros and cons (benefits and costs). The hybrid is considered to be in the middle point between Internal combustion engines and battery electric vehicles of fuel cell electric vehicles. After a comparison, in a possible portfolio of a car manufacturers' fleet today, it is possible to list the following advantages:

1.ICEs are a mature and reliable technology, a competitive price, good performances and autonomy and a capillary supply network. Its main cons instead are that it is a technology close to improvement limits and cannot satisfy the emissions levels required in the next years

2. HEVs and PHEVs, instead, can reduce emissions, guarantee lower consumptions with more efficient propulsion systems with respect to ICEs and better ranges with respect to EVs. In addition, they can exploit the existing fuel infrastructure combined with plug-in possibilities in case of PHEVs. The main odds are the weight of the powertrain, high complexity, high price, low range on just electric engine and emissions too high compared to BEVs.

3. EVs are very efficient wheel-to-wheel, ensure zero local emissions and can be charged at home/office etc. According to battery set and engine they may also prove outstanding performance and torque levels with respect to traditional powertrains. Anyway, problems related to EVs are a lot, from autonomy range to weight, passing through infrastructure underdevelopment and charging times.

4. FCVs shows the same benefits as EVs in terms of efficiency (even higher) and emissions. Differently from BEVs, they can have a very high range and really low refuelling times. Anyway, it is far from being an everyday technology even if in the last years a great progress has been made. Hydrogen production is difficult and requires a lot of energy, it comes from natural gases usually. Transporting and storing hydrogen may pollute as well. Compression and storage of hydrogen is dangerous and difficult even today. This powertrain's technology is more diffused in oriental countries, like Japan. Prices are very high, however this solution will take a relevant share in the long term panorama, it is just postponed. [5]

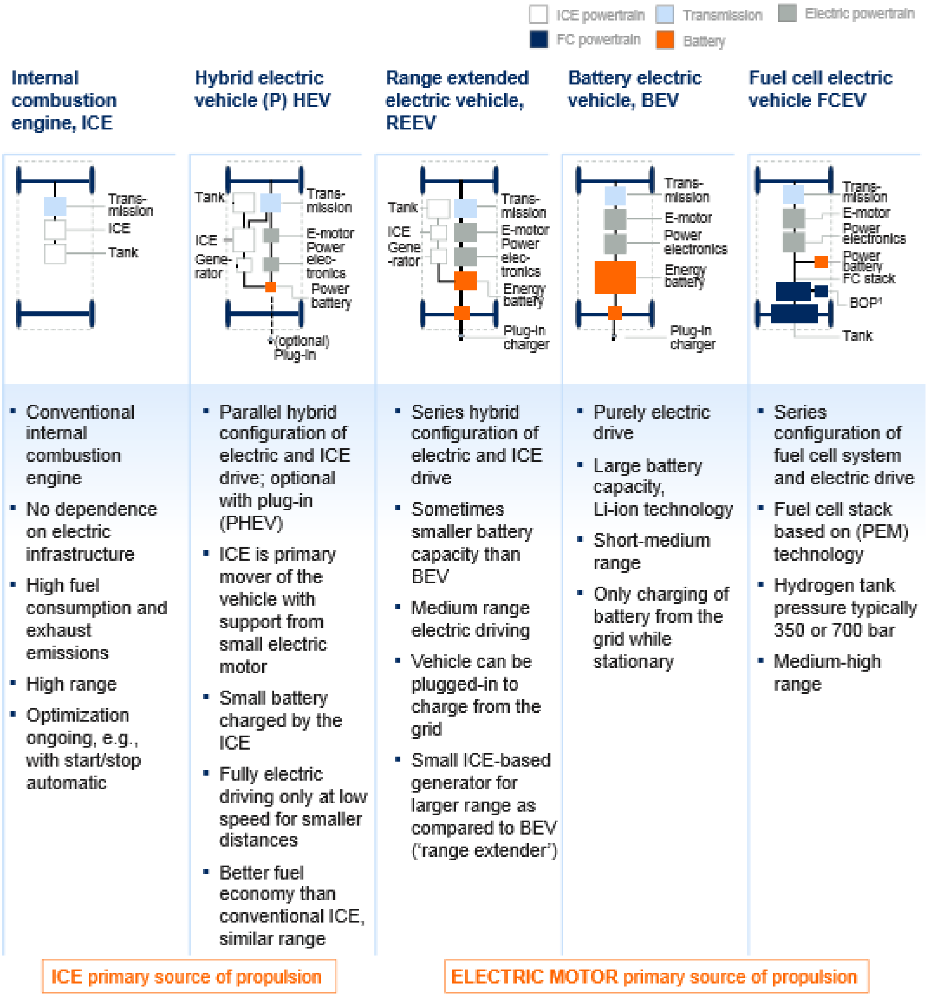



Figure 12. Different powertrain technologies in detail. Source: [5]

The figure 13. Gives an analysis in detail about a comparison of the TCO associated to each type of fuel and powertrain. The TCO consists of a car's purchase price, its maintenance and fuel costs, and the infrastructure costs over the lifespan of the vehicle. Sometimes, insurance and financing costs are also included. According to Strategy&, "the estimates are based on factors such as required infrastructure, cost of fuel, taxes, regulations, mileage requirements, efficiency improvements, depreciation, maintenance, and insurance." Strategy& reports that TCO for ICE will move up but will remain the most convenient until 2030. BEVs and FCEVs will become more and more competitive with costs progressively dropping down. In order to be ready for the future of mobility car makers should get ready to scale up the production for the vehicles they decide to produce, make product costs optimal for different powertrains, innovate and hire and train a new generation of engineers oriented to these new competences. Car makers, suppliers and all the automotive world cannot just ignore these changes, on the contrary they should plan a completely different portfolio without being stuck in the past. [6]

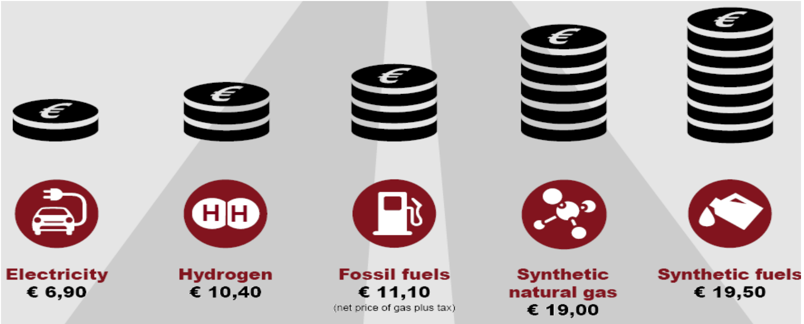



Figure 13. Fuel costs comparison of different powertrains for a distance of 100 km in a mid-range vehicle. Source: [6]

As we previously reported, with all the advances in technology and changes in society, it changed a lot how people prefer to travel and move. Mobility is going to become more and more shared, connected, cleaner and efficient. In this scenario electric vehicles are growing faster than other alternatives, gaining popularity. They are not a new invention. EVs in the first '900 were quite popular before being wiped out by fossil fuels  based powertrains due to low oil prices and battery and network problems. Interest towards electric mobility was shifted away, now, with the rising climate threats, it came back to make transport far more sustainable and smarter. As reported by EU Parliament, "the development of the EV market also depends on the level of ambition of the EU emission regulations; the incentives offered to users of EVs; fuel prices; general travel behaviour and advances in research." [2] As we can see from the Figure 14., the electric vehicle market has been subject to a great increase in performances in the last years. From 2016 to 2017 the electric vehicles in the world more than doubled reaching 3,1 Mln., 40% just in China and 250 thousands vehicles were LCVs. In 2017 again, Norway was the best country in terms of market share (39%) and vehicle stock for EVs (6,4%) thanks partially to national incentives and subsidies. [2]

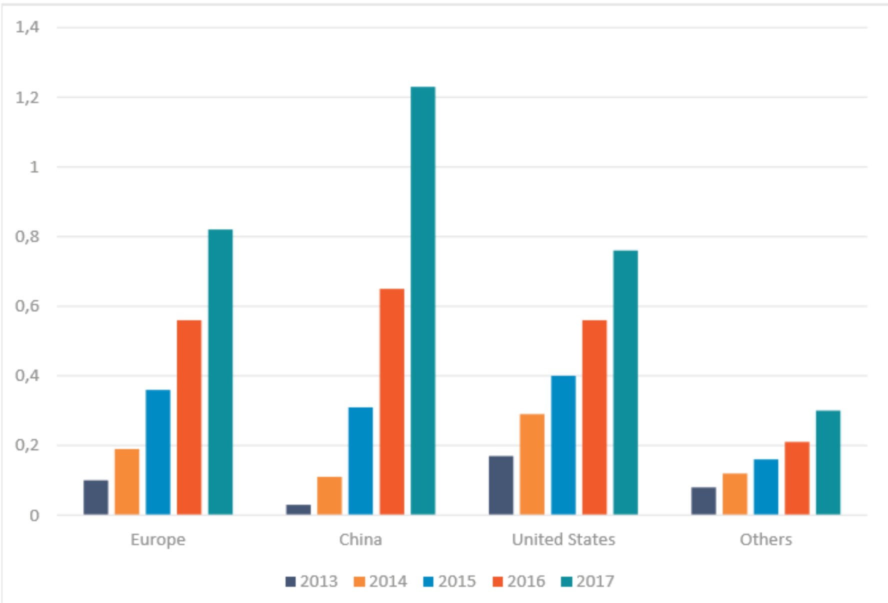



Figure 14. Number of EV circulating on the roads, 2013-2017 (MLn.). Source: [2]

These data are important and positive but we have to remember that traditional fuels and powertrains still have the largest market shares at all. According to the European parliament, "the market share of electric cars in the EU was about 2 % in the third quarter of 2018, around 30 % higher than in 2017". [2]

In terms of absolute numbers, western and northern EU member states reached higher goals but the larger growth in recent years has been registered in south-east, with hybrid which is still selling more than fully EVs. Figure 15. takes into considerations an insightful indicator, the vehicle models released by car manufacturers. They are trying to invest year on year, to offer a wider range to users, even if their numbers are still little comparable to traditional vehicles' ones.

Most of the times hybrid vehicles sales are higher that BEVs, sales are growing more in south and east of Europe in the last years, even if the most of vehicles are still circulating in north and west states. The number of available models of BEVs and PHEVs can be a good trend indicator. In 2017 the hybrid models were 33 while full electric models were 28 in Europe. However, prices for electric vehicles today are still too high compared to conventional cars, even if they are going to decrease year on year with tax breaks application helping the reduction of TCO compared to gasoline and diesel powertrains. Operating and maintenance costs for electric vehicles are lower due to less complexity in the moving components. [2]

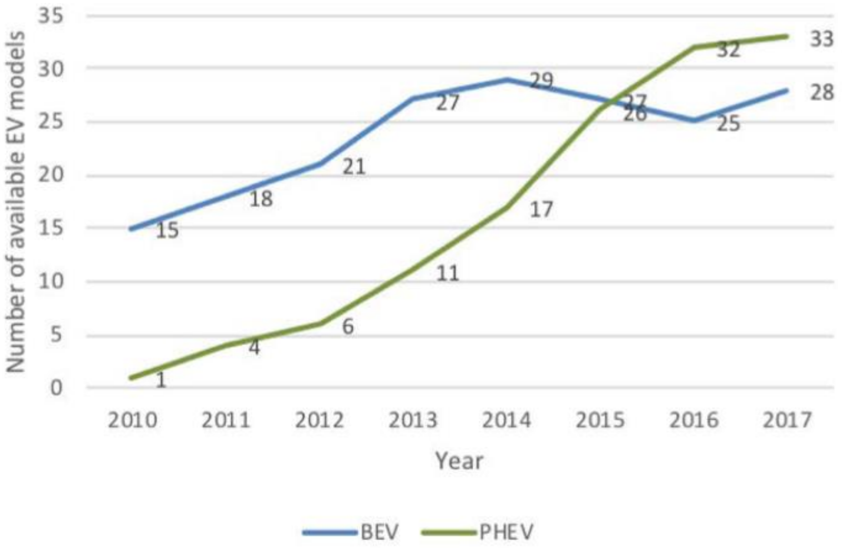



Figure 15. Number of EV models in Europe, 2010-2017. Source: [2]

Local, regional and national authorities in EU Member States provide incentives to purchase and use of EVs of any kind and dimension. Tax (ownership, registration, pollution tax…) reduction or exemption are the most widespread types of incentives. On the other side often purchase grants are promoted by governments. Each government is free to choose the amounts, how to calculate them and eligibility. France, Germany, Belgium, Norway, Austria and Sweden are examples of countries which applied a lot of measures to foster electric vehicle adoption. There are other methods to for EVs as well. Several governments have, for example, ensured that EVs are part of their public procurement contracts, or have given them access to bus lanes or to free parking. In many cities in the world the access is banned in the centre during some days and hours and, by 2030, more than 20 cities in the world are planning to ban gasoline and diesel vehicles [2]

Diesel and gasoline engines for sure will be present for the next years in global automotive markets but their market shares are going to reduce progressively as many car makers are opting for a cut in investments in these technologies. It is clear to everyone that these are examples of incremental innovation which can improve in performances but are close to their limits, not allowing to reach the hard targets of emissions and mobility that I spoke about. Improvement costs woulb be too high if compared to an electrification of the models' portfolio.

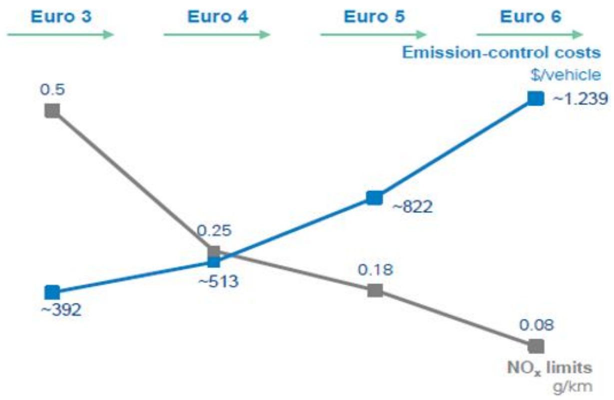



Figure 16. NOx limits of diesel cars and related emission control costs. Source: [7]

## A past, actual and future snapshot of EV market

From 2007 on the idea of electrifying the transport system from passenger cars, to light commercial vehicles, bike etc. started to fill many minds. A lot of patents and R&D effort has been made from that day setting up a huge number of joint ventures and start-ups to start the so-called commercialization period.

As I already mentioned an important driver fostering the transport electrification process is the investment and funding coming from governments' efforts. The policy support should be addressed both to the development of vehicle models by car makers and to the infrastructure deployment, reinforcing one another and proceeding in parallel. Here below is reported a bar chart dating back to 2014 useful to highlight which countries already provided the highest national purchasing subsidies.

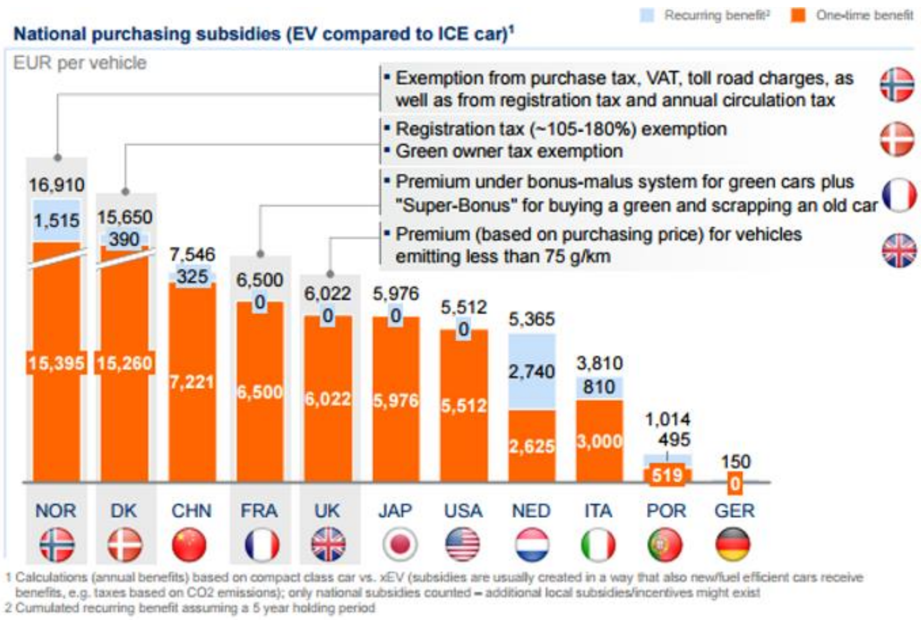



**Figure 17.** National purchasing subsidies for EV (€/vehicle), 2014. Source: [5]

Coming back to more recent years, in order to limit global heating and pollution effects, the revolution in transport sector should come as soon as possible and the key issue is to forecast in the long term the growth of electric transport in order to compare it with the imposed targets and develop an efficient innovation strategy for car makers and other stakeholders involved, both in terms of time of entry and pricing.

According to Bloomberg new energy finance (NEF) "EV sales Passenger EV sales jumped from 450,000 in 2015 to 2.1 million in 2019. They will drop in 2020 before continuing to rise as battery prices fall, energy density improves, more charging infrastructure is built, and sales spread to new markets."

The forecasts about EVs global sales speak about 1.7 M vehicles in 2020, growing to 8.5 M in 2022, 26 M in 2030 and 54 in 2040. By 2022 there will be around 500 electric models globally although Covid-19 is going to slow down this process. Market shares are small but are growing fast driven by Europe and Chine. Clearly there are many countries in the world which are making the global numbers still low. In 2020 the global market share of new cars registered is going to reach 2.7%, increasing to 10%, 28% and 58% respectively in 2025, 2030 and 2040. [8]

Looking at cumulative data, Bloomberg tells us that in 2020 the total global EV fleet amounts to 8.5 M vehicles growing to 116 M in 2030. However, the total global vehicle fleet is currently around 1.2 B and will be around 1.4 B in 2030 leading to "just" an 8% share of EVs, moving to 31% by 2040. China is identified by Bloomberg to be the leading country in electric mobility revolution, with the largest share of global EVs sales. [8]

Another interesting view about this phenomenon is given by McKinsey, even if this report is from 2014, it is really insightful and can give some long term (2050) perceptions. In this case the stress is put on how much government intervention with policies etc. may influence the future of mobility. McKinsey provides three scenarios according to strictness of regulations. ICEs are expected to fall down in any case, instead, FCEV, BEV and HEV seems to be really sensitive to this kind of variation. In particular, with very strict regulations BEV seems to become the dominant solution.

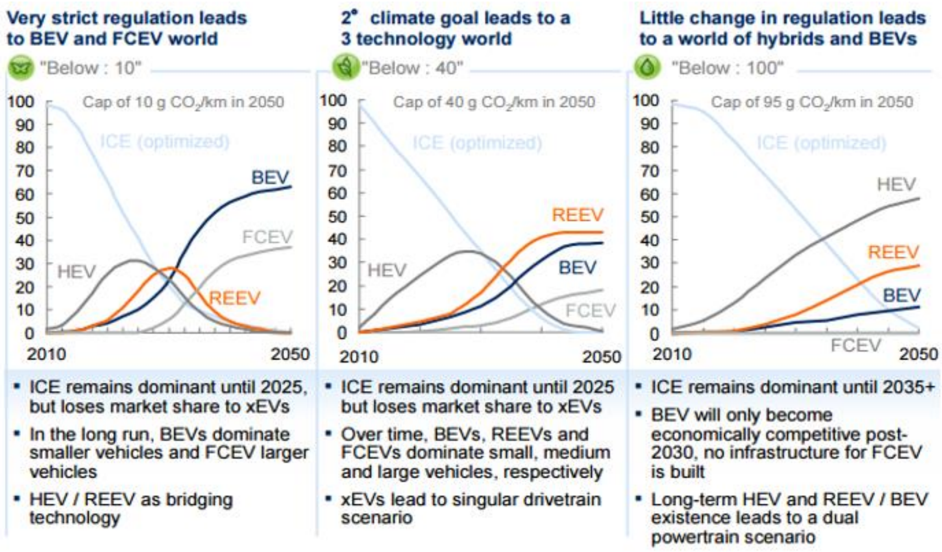



Figure 18. Market share of units produced globally, % (uncertainty of powertrain future market). Source: [5]

## EV Demand diffusion (variables under Roger's model)

The innovation strategy of each player is strongly influenced by the forecasted vision of the future because it is like betting on one technology or another in order to build an optimized portfolio to maximize profits. Timing of entry and pricing may be two key decisions in order to gain a market share without being trapped into competition or into a low demand due to unreadiness of customers and potential buyers. [7] The so called diffusion curve is an s-shaped curve which is usually plotting a relevant parameter versus time. An example of common parameter for this sector may be the cumulative electric vehicles sold from the beginning or the cumulative investment. By plotting and forecasting these curves it is possible to analyse out actual situation and understand at which point of the curve are we and how are we going to proceed. In the first section of the curve it struggles to ramp up due to uncertainties about the future dominant design. When a dominant design emerges the curves starts to grow almost linearly until the technology reaches a certain maturity and despite time is running no more large improvements can be performed and the technical parameter evaluated struggles to grow again. In case of movements along the curve we speak about incremental innovation while, when saturation is reached, there is a gap period of trials to leap to another technological paradigm. Shifting to another curve implies a radical innovation. From diffusion curves we understand that adoption has not the same timing for everyone so it is logic to think that not all the customers are the same. The most popular segmentation has been proposed in 1962 by rogers and, by analysing the sales curve (not cumulative) over time he segmented the customers into 5 categories according to standard deviation multiples. From this theory, Moore in 1991 proposed the existence of a gap (chasm) between early adopters and early majority segments. This gab marks some differences in the adoption reason and the fact that a product is adopted by early adopters “looking into the future” doesn’t automatically mean it will be successful among early majority who like a mature product. So, leader companies in the early majority segment may fail to understand the majority market needs and can lose market share and attractiveness when “crossing this chasm”. This leads to the disruption phenomena. The strategy of a company, from a managerial point of view, depends on the segments reached and the timing in the product lifecycle. [9]

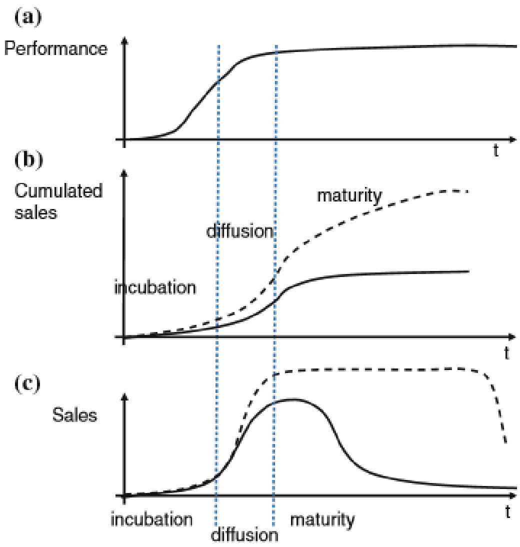
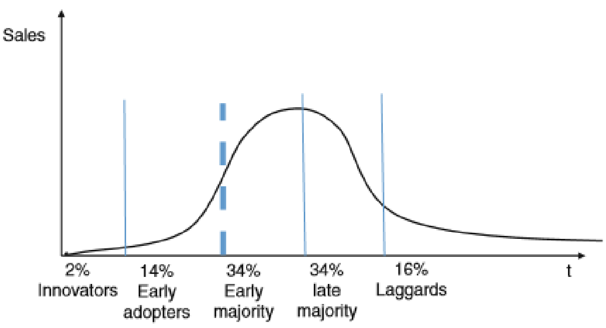



Figure 19. Performance and diffusion S-curves. Source: [9]




Market segments along the technological lifecycle

Figure 20. Market segments along the technical lifecycle. Source: [9]

It is important to understand which are the main variables affecting technological diffusion and their evolution over time. In the attempt to apply these concepts to our industry it comes out that the main variables in electric mobility may be:

- The charging infrastructure

- Battery range autonomy and battery cost
- Up front investment for driver (i.e. price tag)
- Cost of fuel
- Durability
- Model variety
- Compatibility
- Triability and observability

Traditional car makers behaved in different ways one from the other in the last years. Some of them immediately put a big effort in EVs design and production betting on that dominant design emergence, while others only made partial commitments and other seemed to ignore the revolution by waiting other players' moves. Clearly many start-ups a new companies were founded in the last ten years and some of them grew up really quickly since market is changing, new technologies appear and new investment possibilities are open. Traditional manufacturers clearly want to maintain their status quo and while at the beginning many of them tried to postpone the EV diffusion to take time to analyse the phenomenon and re-organize with a new strategy, now almost all are fully involved in electric mobility and their portfolio management strategy has changed a lot. [7]

To my opinion, car makers and governments in many countries are struggling right now to cross this chasm in order to move to an early majority of adoption. Some countries are ahead in this process while others find more obstacles or started far later. This passage is crucial, since the BEV dominant design has just emerged and the biggest jumps now has to be done. In order to do this there are many possible actions to take, starting from increasing the demand of EVs by majority of population by spreading correct information and improve the perception. Then price tag for electric cars, which is still the highest obstacle, need to go down in order to lower the TCO and making it comparable to an ICE powered car as soon as possible for any vehicle class. To di this the help of governments is crucial as well as the learning curve effect for components' prices reduction and the research of innovative pricing and business models.

Managers are trying to concentrate their attention and effort on the first segments since they are crucial to mass diffusion of EVs. We are living a highly innovative, competitive and uncertain time frame.

As I previously said, each company needs to elaborate a robust strategy with an extremely high degree of flexibility in order to manage optimally the timing to enter the market with each model and at the same time to adapt to continuous changes due to uncertain times, from design to production passing through business models. Choosing a fixed strategy based on a single bet on the future of this technology would be risky and counterproductive in manty cases. Many researches point out that the chasm may be crossed between 2020 and 2025 while the higher sales growth is forecasted for 2025-2035. [7]

### Key variables

The charging infrastructure deployment represents a relevant network externality for car makers and being ready and in perfect time to invest in a new technology may lead to important learning curve effects as well as economies of scale in production processes. Connected to the network externality problem is the automaker's dilemma in which an increased availability of EVs "provides a dilemma for automakers as they sacrifice traditional cash-cow internal combustion engine sales for expensive and lower-margin electric cars, necessary to meet onerous new emissions legislation" and this increases the pressure about what to do and when to do it. [7]

Among various possible reasons like high prices, few models available, low range autonomy, charging times there is one which is less considered and worse addressed and this is the dealer problem. The dealers and car repairers are part of the supply chain and they proved to be reluctant to this radical change and tried to postpone it for many reasons. Some of them are reported here:

- Little knowledge
- Business conflict of interest
- Little to no sales organization standards
- Poor model selection and sales effort

Going on, batteries play a key role in the development of electric mobility paradigm and their cost and performances are determinant in a TCO analysis (I already introduced it). Degradation cost over the battery lifetime and initial investment cost should be considered

This scenario is going to improve as economies of scale build up, technology advances, supply chain matures and production costs fall down. This will also bring to battery improvements much needed right now to improve autonomy range and charging time. It is clear that form automakers' perspective, being able to acquire batteries at the lower costs with a strong and efficient supply chain will allow them to overcome the competition and earn higher margins. Many forecasts have been made about the decrease of batteries costs over the next 30 years and automakers should shape their strategies on these forecasts even if uncertainty is very high. It is linked to material scarcity or technological limitations creating uncertain perspectives about battery density growth and production costs. For sure they will need to address investments according to different scenarios, keeping in mind that TCO is strictly dependent on market size and classes. In this way a differentiated portfolio strategy is advised to penetrate the market. Competition in battery supply market may enhance the price decrease leading to a less concentrated market.

Battery prices are a key issue but investments and long-term strategies strictly depend on regulations and oil prices too. [7]

According to Bloomberg NEF, "Battery prices, which were above $1,100 per kilowatt-hour in 2010, have fallen 87% in real terms to $156/kWh in 2019. By 2023, average prices will be close to $100/kWh". [10] This happened thanks to an increase of electric vehicle sales, high density cathodes, new pack designs and manufacturing practices. The cumulative demand is forecasted to reach 24TWh in 2024, with prices below \$100/kWh (these data are always dependent on region and vehicle segment). According to the research, by 2030 the battery market may be worth \$116 billion annually.

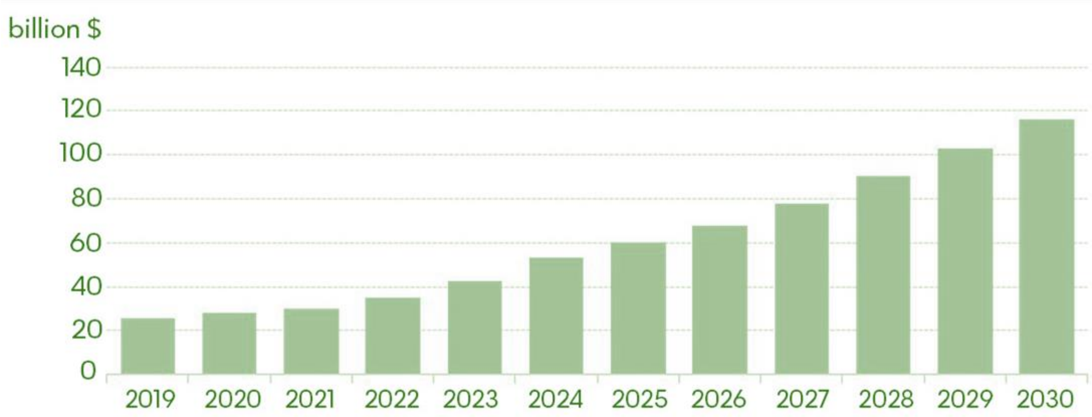



**Figure 21.** Annual lithium-ion battery market size. Source: [10]

BNEF's analysis finds that "as batteries become cheaper, more sectors are electrifying. For example, the electrification of commercial vehicles, like delivery vans, is becoming increasingly attractive. This will lead to further differentiation in cell specifications." [10]

### EV market strategies for innovation

#### Type of EV investments for 2017-2021 period

In this time frame car manufacturers decided to adopt and are still adopting different strategies for market penetration. It is possible to divide them into four categories in a 2x2 matrix defining their future portfolio. On the x-axis there is the number of segments covered while on the y-axis the number of models per sector. The four categories are: specialists, qualifying, trials and complete athletes.

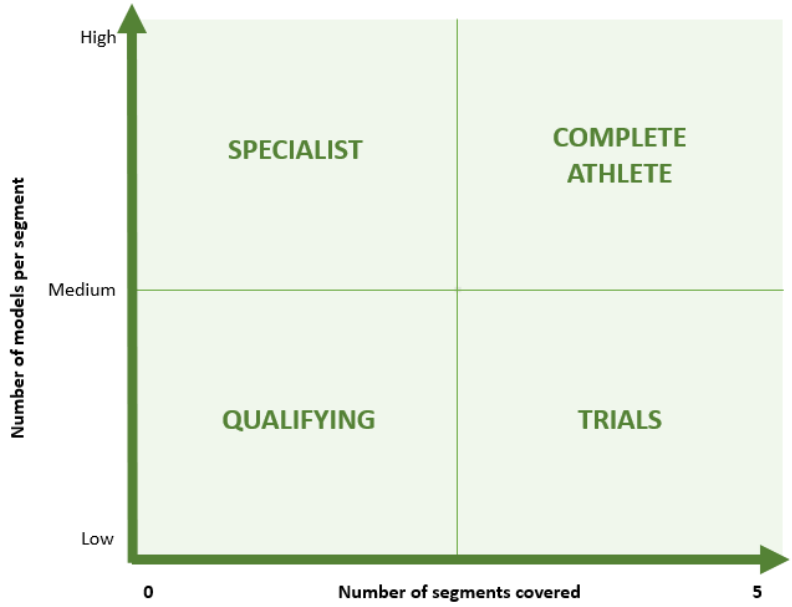



Figure 22. EV investment strategies. Source: [7]

Specialists are probably going to specialize on few sectors in which they believe the most in terms of future diffusion and market shares. In this focused sector they will commercialize a lot of vehicles' models. This strategy is useful to monopolize a segment and reveals particularly successful only in case the initial bet reveals correct. Qualifying, like the case of FCA in Italy, are waiting for other automakers to experiment and make errors. They are not sure about future and cannot make huge investments right now, they are going to be postponed. Trials are, instead, investing in many segments by introducing just few models in order to diversify as much as possible their portfolio avoiding a single risky bet in one segment. This strategy reduces the market penetration potential but allows to "stay in the game" on multiple sides. Finally, complete athletes offer a portfolio covering many segments with a lot of models per segment. Their commitment to this electric mobility paradigm in full and are trying to offer a real concrete alternative to traditional mobility. This strategy is obviously really difficult to implement at the moment since smaller start-ups do not have enough capital, while big incumbents cannot commit so much with all these uncertainties.  In the last 2 years the situation is changing since almost all big incumbents are almost forced to invest a lot in a renewed portfolio to keep up with competition and avoid new entrants' threats.

Regulations as well are imposing these kinds of investments to big players, even if for a traditional manufacturer is quite scary and counter productive to invest on EVs and sell it at price-comparable with respect to ICE vehicles, affecting profits and sales.

In this situation, different strategies for entry time can be followed by players. An insightful elaboration is offered by [7], using a 2x2 matrix to position four categories of players according to time entry strategies defined on the base of the mean asset position prior to commercialization period (x-axis) and mean annual income during commercialization period (y-axis). The first indicator defines the market penetration opportunity and the second one represents the incentive to innovate due to below average net income. Possessing high asset position means having a competitive advantage and having the possibility to diversify the portfolio as well as selling the protected intellectual property.

In this matrix the four identified categories are: First movers, early followers, late followers and laggards. The possibility to institute partnerships, JVs and alliances can clearly modify this classification and their competitive position.

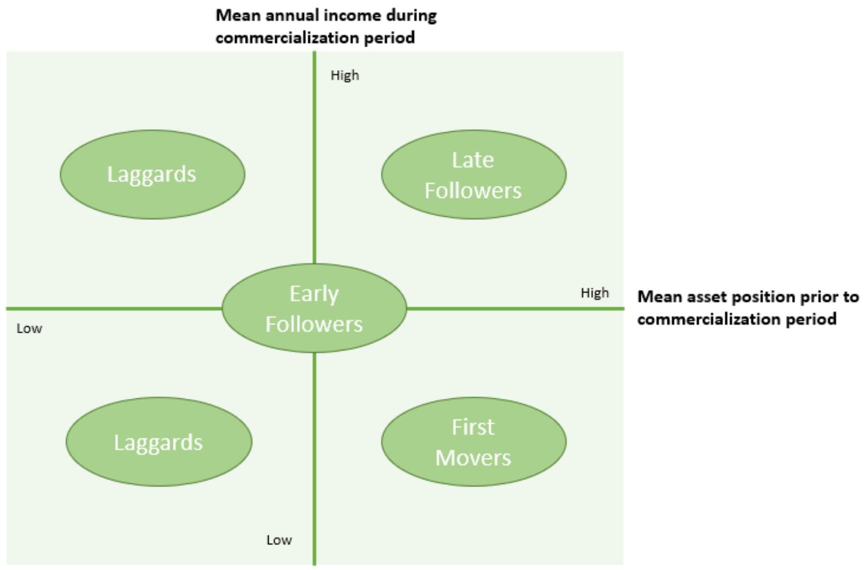



Figure 23. Timing of entry for competitors. Source: [7]

Timing of entry of established competitors based upon EV asset and annual income position prior to commercialization period.

An enviable example of market penetration is Tesla's one. They designed and commercialized some low volume highly expensive cars in order to get revenues to finance a broader project of commercializing higher volume less expensive cars in the following years. This allowed them to target a less price sensitive customers' category, increasing revenues without having to show mass production efficiency from the beginning. In the meantime they waited that the economies of scale and learning curve of their vertically integrated batteries production and infrastructure deployment could give satisfying results.

Again, as far as paper [7] reports, many studies have been conducted on the innovation strategy adopted by companies depending on their resources, capabilities, knowledge and future vision. Among these I found particularly interesting another 2x2 matrix describing the strategy as linked on the y-axis to manufacturing capability and on the x-axis to R&D investment. In this framework four main strategies can be identified:

- Leader or offensive strategy: This strategy implies huge R&D investments and marketing costs, this belongs to companies voted to strong innovation desire and risk lovers.

- Fast followers or defensive strategy: This strategy implies a quick response to leaders moves and investments in order to try not to commit their errors and steal possibly some market share. This implies being very flexible, adaptive and absorptive.
- Cost minimizers: This strategy implies focusing just on producing a given technology at the lowest price possible. Usually these companies do not invest much in R&D and outsource it in order focus on improvement of exceptional production and engineering skills.
- Market segmentation: This strategy implies focusing on a particular market segment or niche in order to elude big mass producers competitors. These customers are less price sensitive and mass production efficiency is not so relevant. [7]

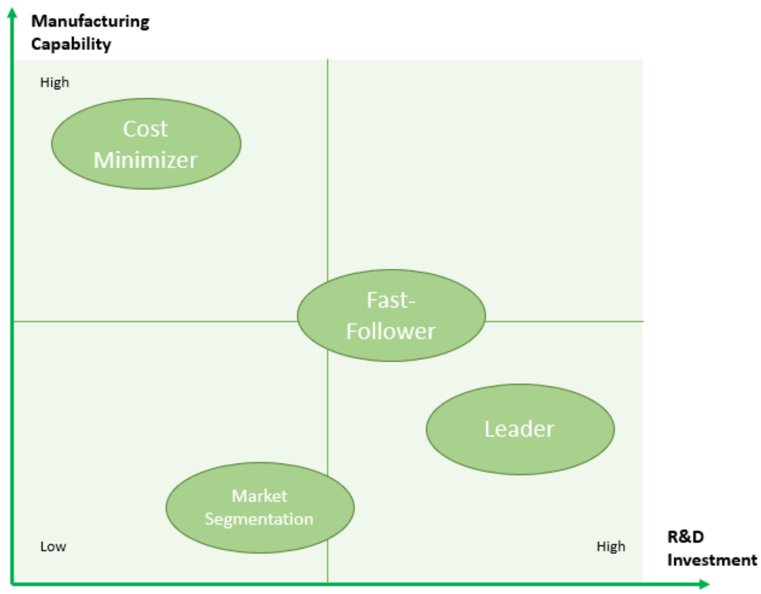



Figure 24. Strategic decision of innovation strategies. Source: [7]

Clearly a mixed strategy is often advisable and flexibility in the strategy is crucial in such a dynamic environment.

A final remark can be done by reporting the most recent challenges and evolutions demanded by buyers and markets. Buyers today are pretending more and more, they are innovation-oriented and want to see beautiful and creative designs focused on ergonomics, smart usage, variety and safety.

The main anxiety for electric vehicles' potential buyers remains the range autonomy. Until the supply network will be capillary and efficient then the lower operating costs and green impact will not be enough. Vehicles are evolving and completely new markets are going to be open thanks to autonomous intelligent drive.

Demand for electric vehicles must be increased from car makers by leveraging on architectural modularity of EVS, simplicity and variety of possible models.

### Risk analysis

As we can understand, this technological shift paradigm from ICE to Electric (future dominant design) has still a certain risk level and uncertainty today. The main risk is related to the huge amounts of money and time that should be invested and, so, it is strictly dependent on the reaching of a certain level of electrification and integration in the next years. This is a simple general risk analysis that can be taken into consideration and further deepened:

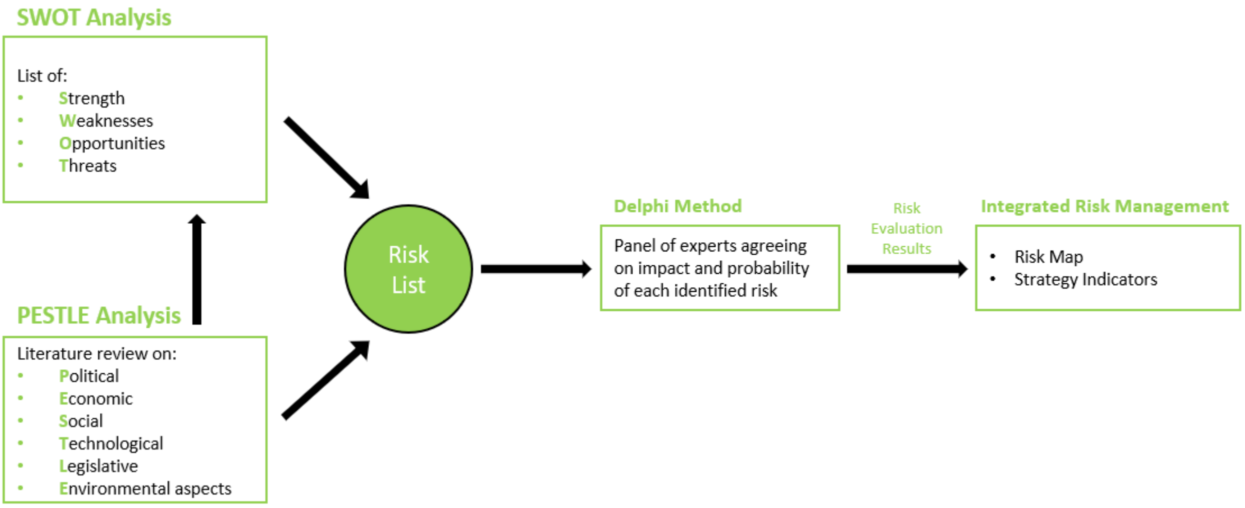



Figure 25. Risk analysis scheme. Source: personal re-elaboration

SWOT Analysis

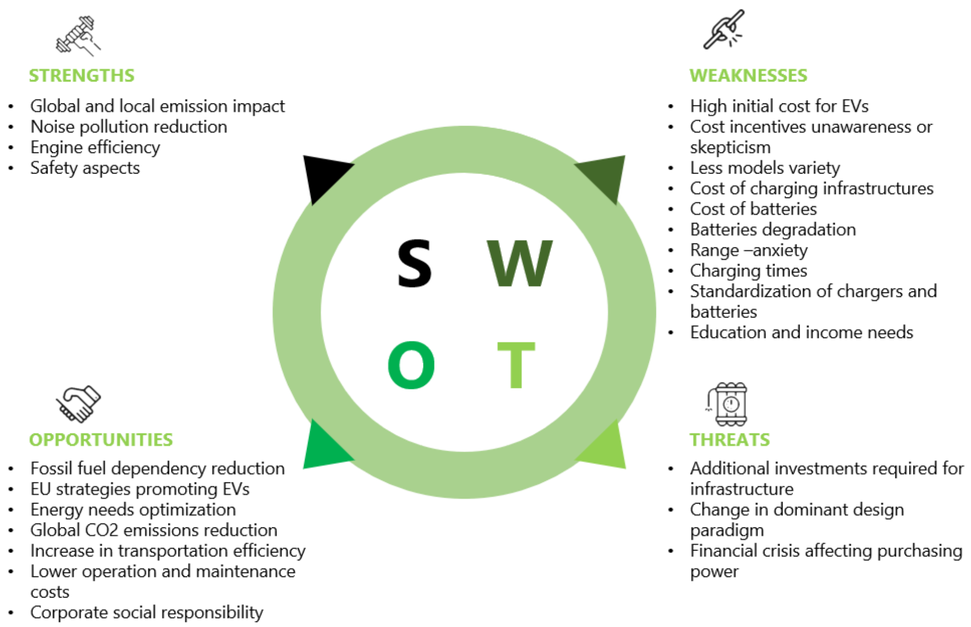



Figure 26. SWOT analysis about EVs. Source: Personal elaboration

Risk map

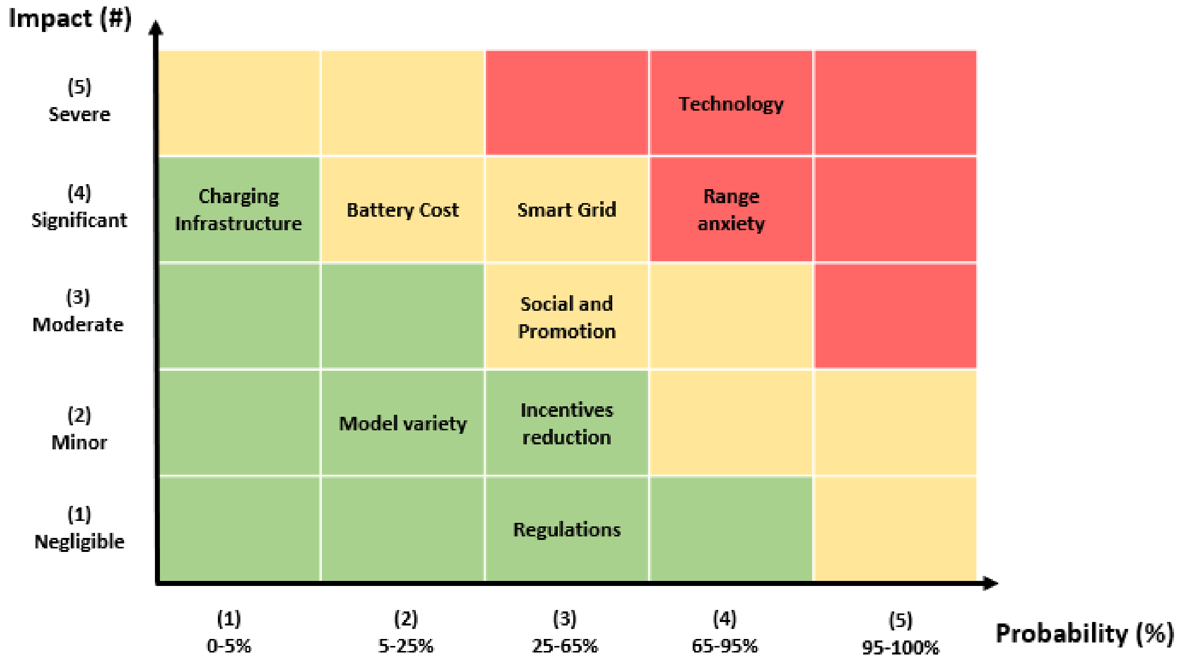



**Figure 27.** EVs risk map. Source: Personal re-elaboration

# 2.3 Industry evolution – Impact on players, value chain, business models

The EVs market can be analysed by exploiting value chain analysis and porter's five-forces analysis as well. We will take a brief look at the incumbents, new entrants, competition, suppliers and, most of all we will focus on the complementary assets' crucial role required by this technology as well as evolution in value chain and related business models.

Today many EVs are designed and produced by conventional vehicles' manufacturers, eve if some exceptions like Tesla are present. The production of electric vehicles is completely different from ICEs powered ones and this has a major impact on practices and business models, completely changing the game. A lot of new actors will play important roles with the risk for current actors to lose relevance. The large usage if IT is introducing actors like mobile phone companies, electronic companies or IT firms, affecting the value chain. Production processes are going to become more and more automated thanks to advanced industrial robotics (AIR) and industrial internet of things (IIOT).

As I said, electric vehicles are very different from traditional ones both in terms of complexity and components. Assembly is less sophisticated and components' number is lower but they require much more IT and electronics competences. That's why many new jobs can be created by new players penetrating the automotive value chain as well as new a contamination of managerial practises from these different industries.

The key players will be the battery producers. Car manufacturers have two possibilities about that. vertically integrate the battery production or outsourcing it. Governments, in the attempt to stimulate this market are trying to push for as much as possible inhouse production, since outsourcing would mean in many cases produce the batteries in countries far away like China, Korea or japan, being these really price competitive solutions. Traditional players like Toyota and Honda can exploit stronger and more direct alliances in this sense. A counterexample comes from Tesla, which decided to fully internalize battery production in order to reduce costs, creating their "Gigafactory". [11]

Electric vehicles today are seen more like Computers and that's the reason why the expertise in smartphones' industry is acquiring a lot of importance. Google and amazon entered the EVs market by developing futuristic autonomous vehicles.

A lot of players are part of the e-mobility environment, being essential for success even if not directly part of the industry chain. Among them charging infrastructure operators, IT services' providers, users, leasing companies and utilities companies. New and old actor can perfectly mix in the final resulting value chain.

Car sharing, car rental and leasing are other trends impacting a lot the value chain becoming powerful actors in the game because their business models are going to influence also the EVS manufacturers. [11]

This electric mobility revolution is challenging the old business models and the new business models are affecting the whole value chain end-to-end. [5]

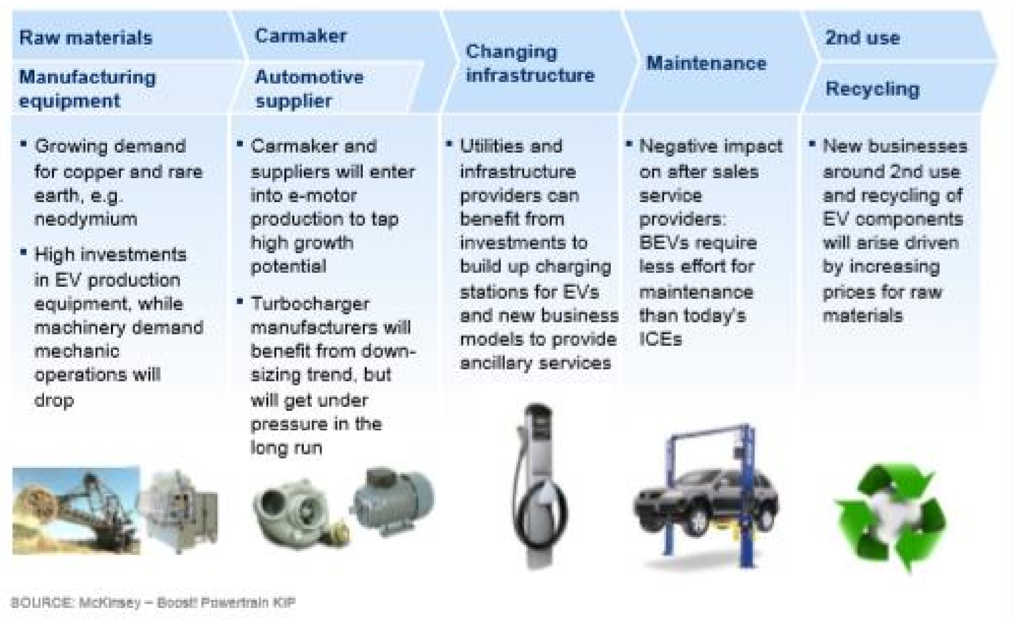



**Figure 28.** New value chain after electrification. Source: [5]

At each step of the value chain there is a huge opportunity for new players and new business models. Here below it is possible to observe how both incumbents and new entrants may get benefits from the evolution of the chain, by extending their competences, integrating, catch whitespaces in the market, increasing market share and scaling up and down the value chain. [5]


Figure 29. Incumbents and new entrants positioning in the value chain. [5]

The possibilities to innovate are multiple and here, according to McKinsey, a list of possible trends, evolutions and business models affecting different players.

- Battery leasing
- Navigation software and apps linked to charging infrastructure locations and information
- Battery swapping
- Smart grid applications (from electricity providers and distributors perspective)
- Aggregate demand-side response and flexibility in monetizing
- Stationary storage using EV batteries
- Mobility as a service
- Vertical integration of battery production

These solutions are helping to find profitable business models and increase maturity and adoption of the technology. [5]

Companies with bigger opportunities are represented by utilities, hardware and software providers (energy delivery sector), EV-based suppliers, battery suppliers, OEMs (conversion and propulsion systems sector) and, finally, telecommunications, e-mobility service providers and municipalities (services sector).

Companies at higher risk are represented instead by oil, fuel distribution (energy delivery sector), ICE-based suppliers, traditional OEMs (conversion and propulsion systems sector) and ICE-based services (services sector).

Demand for materials and intermediate products as well is going to change in the transition to electric mobility. Clearly electricity demand will increase and the grid system must be monitored and improved in order to bear demand peaks. Energy needs to be produced, stored and distributed in a much more efficient way. Production of batteries once again has a central role in the process and it requires new raw materials and natural resources extraction, first of all the lithium. Lithium-ion batteries are considered as the best solution right now and big players are trying to secure Lithium in huge quantities in order to avoid incurring in future scarcity problems. Many other material for battery production as well as car body etc. are being tested and used. Lightweight materials are more and more required by this market. In general, the demand for chemical products is going to increase.

Electronic components and, in general software, are so important not just for the vehicle itself but also to interact with the infrastructure and the complementary assets around in a more and more connected smart world. [11]

Work processes instead, as I previously mentioned, will feel an impact from this transition since less components will be part of electric vehicles compared to traditional ones but these components are going to be much complex. This means that the assembly phase will be easier (EVs are really modular) but manufacturing of individual components will require complex processes and specific skills.

A new balance between mechanical and electronic/IT operations and processes must be reached without having to change so much the managerial side. The advent of EVs may also stimulate a massive change in factories' modernisation process, by highly increase the automation level.

The rate of change and the amount of impact perceived by automotive production industry is strictly linked to the growth in EVs diffusion in the next years. [11]

According to Technopolis Group's research, to sum up, the electric vehicles' production processes, due to automation and less components will be less labour intensive. To some degree, many workers from mechanical background will be replaced by workers with skills and competences in electronics, IT, chemistry and physics and data analysis. Related to this last category, they will be highly required not just for vehicles' improvements but also to monitor and improve processes and connections with the grid. Many workers in the gasoline stations will probably lose the job but, on the other side, the new charging stations will create new opportunities. [11]

## 2.4 Infrastructure and charging issues

The EV-charging infrastructure relationship represents a clear example of a network externality problem in which two systems depend on each other to grow and generate a market value. This is due to the fact that infrastructure building and operating means huge investments that needs to be repaid by reaching target numbers of electric vehicles circulating and exploiting this infrastructure system. To allow this to happen the contribution of many different players and shareholders is required. It is a matter of role of complementary asset. Looking at the problem from another perspective it is clear that electric vehicles to reach an organic diffusion need an efficient and capillary infrastructure to be built, since without clear assurances of refuelling it is impossible to stimulate demand. This issue is called "chicken and egg dilemma". This turns out to be a timing strategy problem, investing too early or too late. To avoid remaining stuck into this situation, one of the two needs to make a big commitment first, incentives from government can help the parallel complementary development.

Both private and public investors are showing interest in the project, with different strategies. Inside the private investors' category figure both OEMs, suppliers, utility companies and external investors. Carmakers have strong incentives in entering the market as soon as possible and need to contribute quickly to infrastructure investments even if the biggest hurdle which is harming the whole market is the fact that the benefits of their investment will be earned by other car makers as well. This is the reason why a strong collaborative program must be developed, in order to reduce the risk of investment and to make it financially acceptable. Creating partnerships is a valid solution in order to increase investment capital, volumes, benefit from economies of scale and scope and avoid market wars. The partnerships between giants may be useful also to create a standard in charging technology

According to McKinsey [5], the availability of charging infrastructure has strongly increased in recent years. There are a few forms of charging that have penetrated the market to varying degrees:

- Battery swapping
- Induction (or "wireless")
- Wired charging (regular or fast)

Referring to TransportEnvironment report, in order to analyse the European charging infrastructure situation, it is necessary to categorize the member states into three clusters according to the successive "waves" in which electrification of mobility is going to happen. [12]

- Front-runners are most Western and Nordic countries: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Luxembourg, Netherlands, Sweden and the U
- Followers: Italy, Portugal and Spain
- Slow starters composed of EU13 and Greece: Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, and Slovenia.

Figure 30. illustrates the differences in annual investment in public charging infrastructure for the three macro-regions that we identified. As we can see the great majority of annual investment id made by front-runners every year. All the three regions' investment is growing year on year even if slow starters' numbers are growing at a lower rate, increasing the gap as we go on to 2030. [12]

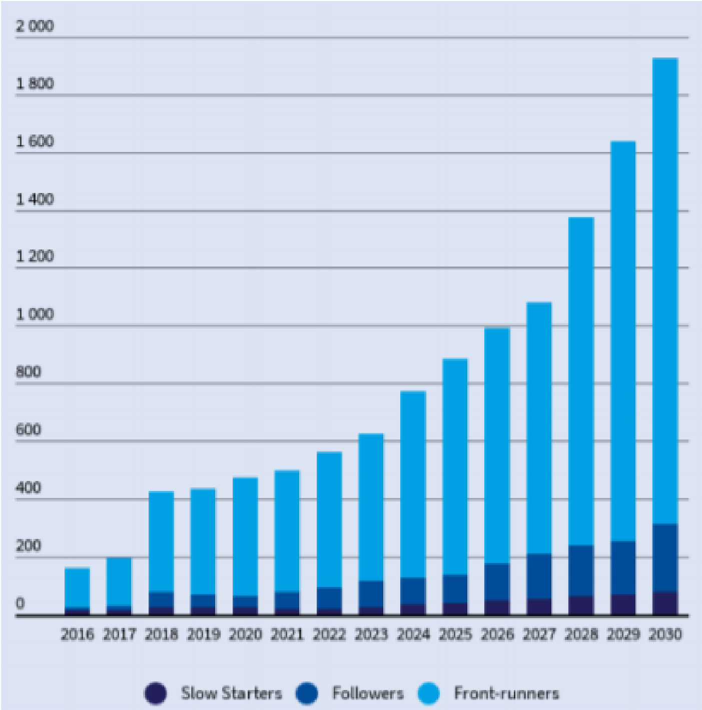



**Figure 30**. Annual investment in public charging infrastructure, 2016-2030 (Mln €). Source: [12]

Figure 31. is useful to analyse the actual situation of slow and fast charging supply in Europe. Overall in Northern and Western states the situation is favourable since a basic infrastructure of slow chargers is available for everyday life and many motorways are well covered by a fast charging infrastructure allowing almost any kind of journey. It seems that in these states the dilemma is solved since infrastructure is ready and now a steep growth in EVs sales and market shares is expected in order to return on the investment performed. The problem remains for those who cannot recharge at home their car, these individuals still need more incentives to switch to an EV. By mid 2020 the business is expected to be self-sustaining according to TransportEnvironment. [12]

Now it's time to push the EVs supply, reduce the dealer problem and increasing marketing and customer awareness.

Infrastructure deployment in Southern, Central and Eastern Europe is much more limited but it is proportioned to the number of circulating EVs. So, this is not a real issue in electrification of transport sector because the two processes are proceeding in parallel with 5 to 10 years gap compared to front-runners. Time is enough and the direction taken is good but it is clear that more conspicuous investments and financial incentives are required

According to the report, "Beyond 2020 the European Commission has announced a commitment to spending at least 60% of the EU's cross-border infrastructure fund on schemes that help the fight against climate change. Under the proposed budget, the Connecting Europe Facility (CEF) will have €42.3 billion, of which €30bn will go to transport. The proposal also says 60% of the overall €42.3bn must be used for 'climate spending' to assist in tackling climate change." These funds represent a great opportunity to definitely move to electric mobility and deploy an adequate infrastructure. [12]

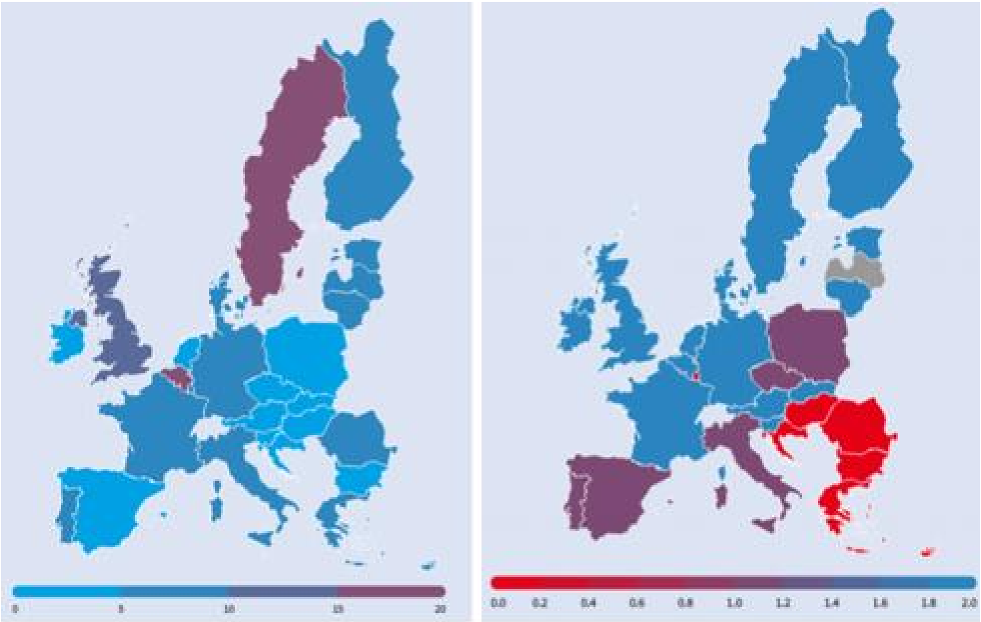



**Figure 31.** #EVs per public slow charging point (left), Fast charging sites per 60 km motorways (right). Source: [12]

Moreover, in this scenario, according to Deloitte, the concerns about infrastructure lack infrastructure will reduce thanks to improvements in autonomy range of future batteries and to the reduction of charging times allowed by ultra-fast charging stations. Anyway, even these good news cannot completely eliminate the problem. This because, apart from the problem of vehicle owners without private access to home charging, continued ultra-fast charging is proved to reduce the battery capacity, affecting the range of the vehicle as a consequence. [13]

# 2.5 The Italian market

Currently, compared to other European countries, the spread of electric vehicles in Italy is modest. In 2018, 9,579 electric cars were registered (5,010 pure and 4,569 hybrids), just 0.5% of the total (2 million) and yet enough to raise the circulating fleet to 22,000 units. We can’t forget the relative growth: the BEVs (Battery Electric Vehicles) increased by one and a half times compared to the previous year (and by 113% if we consider the first 7 months of 2019). PHEVs, or plug-in hybrids, grew by 60% instead. [14]

Worldwide, 2.1 million electric vehicles were registered in 2018, both "full electric" (70% of the total) and plug-in hybrids. This segment of alternative fuels recorded a growth trend of 78% on 2017 and in 2019, it exceeded 3 millions. China stands out with 1.2 million new electric vehicles (+ 78%), the triple of Europe. The Old Continent, however, is confirmed as the second market with over 400,000 registrations (+ 34%). Followed by the United States (350,000, + 79%) and Japan (53,000, -6%). In Europe, Norway is still at the top of the list of countries that adopt electric cars, which has over 72 thousand registered vehicles. Germany ranks second (67,000, + 24%), then Great Britain and France (respectively 60,000 and 45,000, + 26% and + 24%). Italy instead ranks in the rear, despite the fact that in 2018 there was an increase in registrations of 100% compared to the previous year (10,000 vehicles). [14]

For the first time in Italy, in April 2019, the threshold of 1,000 pure electric cars registered in a month was exceeded. A result that was repeated in May and June and which is also due to the incentives to purchase

("Ecobonus") introduced by the Budget Law 2019. This initiative has scratched the most significant barrier to the spread of electric mobility, namely the high initial cost of the vehicle. 6,0000 fully electric vehicles were sold from January to July in 2019 against the 5,000 of the same period in 2018. [14]

According to a survey elaborated for the Smart Mobility Report 2019 (MIP Politecnico di Milano), the main barrier holding back Italian customers (72%) when purchasing an electric car, confirming the fundamental role played by the Ecobonus, turns out to be the price.
The inadequacy of the recharging network follows (39%, significantly down compared to 2017). Finally, limited autonomy appears (28%). Almost everyone uses its electric vehicle for "short" journeys (no more than 100 km), a little more than 40% for longer journeys (32.5% weekly and 10% daily). Over 2/3 of the sample of Italian EV owners has the possibility to recharge the vehicle at home. The remaining 30% is divided between those who can do it at work (29%) and those who have to rely on public top-up (10%). However, over 80% use public infrastructure, albeit perhaps in a non-assiduous way, and only 14% think that the network is not adequate, compared to over 60% a year ago. Furthermore, more than 50% believe that the public network will be fundamental for the spread of electric mobility. [14]

The mapping of plug-in electric vehicles available in Italy has made it possible to identify a total of 62 models, with a slight prevalence of PHEVs (34, 55% of the total) compared to BEVs (28, 45%). The production of these vehicles will grow to quadruple the offer by 2025. [14]

According to this research, which outlines three possible scenarios, from 2.5 to 7 million EVs will circulate in 2030. In the "basic" scenario, electric cars will cover 30% of total new registrations only in 2030 (they are 1,5% in 2020). In the "moderate" scenario, however, already in 2025 they will arrive to 23% and 55% in 2030, with 5,4 million EVs that will represent 13% per fleet. In the "accelerated" one, 7 million EVs will be circulating in 2030. 85% of the total will be represented by full electric vehicles. In all three scenarios related to alternative energy supplies, the "real" impact is forecasted to happen around 2025, in line with the provisions of the draft PNIEC (Integrated National Plan for Energy and Climate), which is followed by a very sustained growth between 2025 and 2030. As regards the forecasts for the development of the charging infrastructure, public or for public use, the difference between the projections is significant, but less pronounced: by 2030, it ranges from a minimum of 34,000 to a maximum of 73,000 charging points. The number of private “columns” expected by 2030 instead varies from 1.7-2.2 million in the base scenario up to 6.3 million in the accelerated scenario. The study tried to estimate the market volume that can be generated by electric mobility. The researchers took into account two components, the investment (per vehicle and charging points) and management (cost of the public charging service and vehicle maintenance). The large differences in terms of registrations of electric vehicles in the three hypotheses lead to very different ranges. By 2025, it ranges from the “only” 17.5 billion euro in the base scenario to 52 in the accelerated one. Difference that becomes even more pronounced by 2030: from 76.4 billion to 214, the triple. Similarly, management costs, calculated on the basis of working capital in 2030, also change a lot: from € 893 million per year in the base scenario to € 2.5 billion in the accelerated development scenario. [14]

What comes out from this report is an encouraging scenario despite the numbers of electric cars in Italy are still small when compared to the total internal market for vehicles or the trend of electric mobility in the main European countries, where Italy represents 2.5%. However, it is now clear to everyone that we are no longer talking about a 'niche', but about a fundamental component of the transport of the future. Excellent signs are the expansion of the offer of car models, today more than 60 (+ 260% compared to 2015) between 'pure' and plug-in hybrids as well as the effort of the refill operators, which has allowed to reach the 8,200 public access charging points installed today in Italy, increasing users' perception of adequacy of the infrastructure. [14]

On the subject of alternative power car supplies, the evolution of the network of charging points is one of the most debated issues. At the end of 2018, there were 540,000 public points in the world (+ 25% on 2017). Of these 140,000 were "fast charges" (i.e. with power exceeding 22 kW). China still dominates the scene, both for the "normal charge" infrastructure (41% of market share) and "fast charge" (77%). Europe had 160,000 public top-up points (+ 14%), of which 15% "fast charge", which grew much more than the "normal charge" (+ 30% and + 12% respectively). In the first 7 months of 2019 there were 15,000 new installations. The diffusion is very uneven: it ranges from Holland, which has a recharge points/circulating electric vehicles ratio of less than 1: 5 (Italy's ratio is 1: 7) up to Norway, with 1:20. Today, in our country there are almost 8,200 charging points between public (3,500, + 23% on 2017) and private ones with public access, around 20% of the "fast charge" type. It is a figure in line with the European average and growing by 52%. Lombardy is the only region with over 1,000 charging points, followed by Lazio, Piedmont, Emilia Romagna, Tuscany and Sicily (over 500). The North holds 51% of the installations and 53% of the "fast charge" ones. About 70% are urban, on the road or in public car parks, almost 30% in "points of interest" such as shopping centres and car dealerships, less than 5% are extra-urban. At the end of 2018, private charging points in the world were over 4.6 million, that is 8.5 times the public ones and about 0.85 times the number of electric vehicles in circulation, with a growth rate of 50%. In Italy numbers point out about 4,000 private charging points installed in the year (+ 60%) and 11-13,000 in total. [14]

## 2.6 Latest key updates

The aim of this section is to provide a global final snapshot of EVs sales during these uncertain times. Due to uncertainty, many players involved may need to re-think some goals for the next years.

According to AutomotiveWorld, the last year has not been good for electric transport sector. Afrer 7 years of outstanding growing sales in percentage year on year, in 2019 there has been just a 5% growth. Clearly this is influenced by a reduction in global vehicle sales but it hides some troubles with xEVs' demand (Both EVs and PHEVs).

This change may be due to many factors and a deeper look into the single markets may be useful.

In both the US and China after impressive years, then in 2019 there has been even a decline in percentage registrations. (-4% in China and – 9% in U.S.). [15]

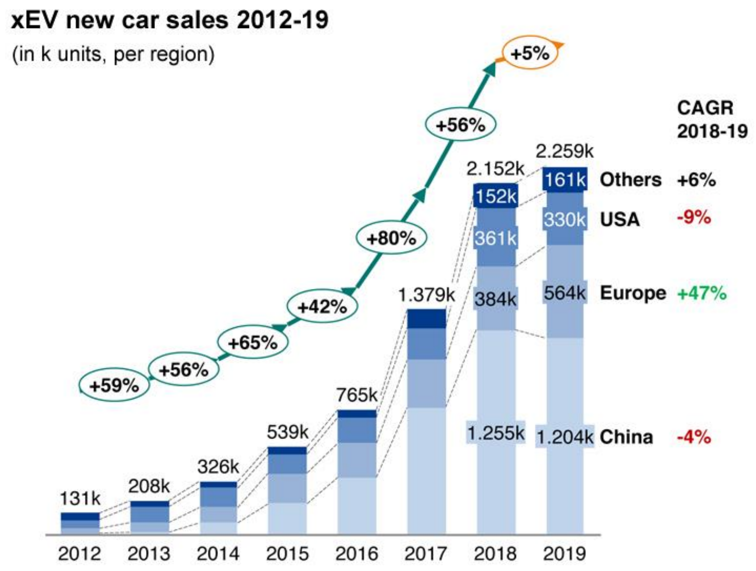



**Figure 32.** New car sales 2012-2019 per region. Source: [15]

Europe, instead, seems to follow the opposite direction, its market grew in the last years and was the fastest growing in 2019 as well, even if there is a lot heterogeneity among countries.

Three countries are mainly driving its growth, Germany first and then Norway and Netherlands with an annual growth of around 150%. [15]

### Key countries from now on

<u>USA</u>

As we said the number of EVs sold went down the last year passing from 361k in 2018 to 330k in 2019. The problem is probably to be found in too little subsidies and incentives from government and a poor charging infrastructure.

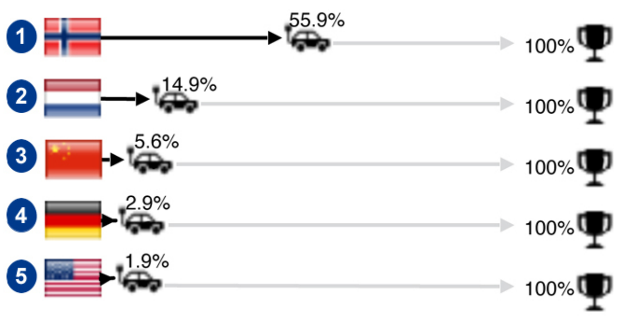



**Figure 33.** BEV and PHEV share (%) of total new sales per country, 2019. Source: [15]

According to AutomotiveWorld, there is very little chance of things changing in 2020 since oil prices are falling down too. In 2021 probably the strong Covid-19 impact will stop the growth again. [15]

## China

In China the new car registrations decreased 4% each year mainly due to a strong cut (halved to 3,3k €) to government subsidies in 2019. Being China such an important market it will be closely monitored in order to understand if incentives and funding will rise again to push for BEVs market to grow or the government is planning to switch to other technologies (i.e. fuel cells). [15]

## Germany

Germany's situation, on the contrary, is completely moving in the opposite directions with 59% increase in xEVs registrations in 2019 and £% of total car registrations in that year. The three models leading the sales in this country are Renault Zoe, BMW i3 and Tesla Model 3.


**Figure 34.** Dashboard to sum up Germany xEVs key numbers. Source: [15]

However, Germany is not intentioned to slow down, new clearer regulations have been introduced and the charging infrastructure has been enlarged thanks to huge national investments (from 4 k € to 6 k€). Going on, cars with prices higher than 40k € had tax cut from 0,5% to 0,25%. Company fleets are another enormous driver to promote electrification. Clearly on late 2020 and on 2021 the impact of Covid-19 must be considered right now. [15]

## Norway

Norway is probably the best example in the world in terms of electric vehicles. According to AutomotiveWorld, "In 2019, the number of electric car registrations exceeded combustion engines for the first time, with almost 80,000 xEVs—or 56% of the total—sold." [15]

The reasons for this are again the same, Norway has a well developed and capillary infrastructure counting almost as many charging points as fuel stations (14k) and national incentives are really generous in terms of car prices, reduced toll and parking prices. [15]

The Netherlands

The Netherlands is strengthening yoer by year its respectful position in terms of electric cars' registrations, infrastructure deployment and range of models offered.

AutomotiveWorls reports that "from 2012 to 2018, electric car sales around the world saw global annual increases typically well in excess of 50%. And then, in 2019, 2.259 million new electric cars were registered up just 5% on the year before"

However, incentives and tax breaks are not forever and from 2021 to 2026 the plan is to reduce tax benefits in order to reach standard values at that time. [15]

### Looking to the future: The global outlook

From now on it is likely to face a really turbulent year (2020) due to pandemic unpredictable consequences. Among these there will be some planned relaxations in CO2 emissions standards and targets around the globe as well as the high probability to postpone investments in the automotive sector or plants shut down. This is implying that a lot of new models for 2020 and 2021 will not be presented to the public, impacting negatively on the electric vehicles market.

However, many car makers and suppliers have invested huge amounts of money during these years in cars and infrastructures and need to go on with this project so they will find a way to sell EVs at competitive prices helped by the reductions in battery costs.

Looking at the first months of 2020, China's market went down due to Covid-19 while Europe was growing again, any from the third month the pandemic impact started to affect also European countries. Anyway, many new interesting models have yet to come, Tesla itself is launching a compact car in 2021 with promised competitive prices. [15]

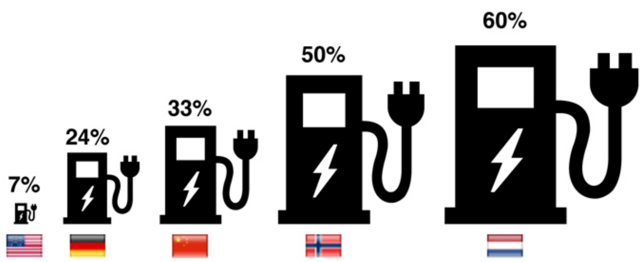



**Figure 35.** Share of charging out of total refilling network (% per country), 2019. Source: [15]

How, exactly, the corona crisis will affect xEV sales in the short term is impossible to predict. In the longer term, it could well have a positive impact, as our glimpse of a cleaner world might well change consumer mindsets to focus less on sales discounts and more on sustainability issues. What is needed now is a sustainable approach to combine economic restart with intelligent support for environmentally friendly mobility. That approach could include purchase incentives by governments for EVs but also in the short term for environmentally friendly ICEs.

AutomotiveWorld again suggests that "Reaching even 70% or 80% of the ambitious targets that many countries declared would be a success story" and this is due to the incredible uncertainty around this year and the following. Incentives and helps are not enough, a big job must be done to change public perception in many countries, trying to see the post-Covid scenario as a significant opportunity for global changes' actuation. [15]

Talking about goals and post-pandemic actions to foster economic restart, UK's is going to give drivers up to £6,000, or about $7,627, if they switch their combustion engine car with an EV. The idea is to help a quick recover of the economy post-Covid and to exploit this opportunity to fill the gap with other countries.

This initiative aims at reducing the up-front investment problem by highlighting the lower operating costs of an EV. Since by 2035 Johnson wants to ban the ICE powered cars then a strong electric market must be ready to take the lead.

Main challenges refer to the infrastructure availability and the peak management in energy demand. Johnson hopes buyer will not be too conditioned mentally by coronavirus and its strategy may be taken as example for other countries who want to bounce back. [16]

# 3. Complementary technologies for Electric vehicles

## 3.1 Alternative solutions on the market

The most renewed charging technologies nowadays include fast charging, inductive/capacitive charging, mobile charging, robotic and autonomous charging, battery swapping as well as particular charging for fleet EVs. Now the most important ones will be discussed here below.

### 3.1.1 Plug-in charging stations

Wired charging is actually the most widespread solution without real competition right now. It simply consists in pugging in the car to a charging station through a cable. [17]

**Regular Charging**

Usually chargers are of onboard type or can be connected to an external infrastructure. The current for normal charging is most of the times low and multistage charging is the common solution, in which voltage and current are constant. Charging times largely depends on the battery size and a full charge may take from five to twenty hours. This kind of charging is also known as AC charging. In case of onboard charging the car maker provides the AC/DC converter and charging power is usually small (3-5 kWh) and useful for small electric vehicles. In case of off-board charging (called also DC charging), charging powers are larger and it is for larger vehicles. Converter is provided at the station. Normal charging, having low power and current, doesn't stress too much the grid and preserves the battery life. It can also be economically convenient if well planned. The odds of this solution is the time required (it is not indicated when we are in emergency or scarcity of time). [17]

**Rapid Charging**

Rapid charging has been thought as a solution to time problem coming from regular charging which has limited the spread of EVs. This charging mode implies higher currents (150-400 A) and powers and is performed off-board at charging stations, allowing to recharge the battery at 60%-80% SoC in just 20-120 minutes. This solution has some disadvantages too, usually a pulse-type charging is commonly adopted and being it difficult to control charging current pulse then damages to battery lifecycles may happen. Going on, we should consider also that a little level of standardization is present today and installation/operating/maintenance costs are higher than normal charging. Finally, this kind of solution is not optimal in managing energy consumption with its daily peaks and valleys, being not able to guarantee flat loading and unloading the whole day (through B2G systems as well), making it difficult to implement a modern holistic vision of a 360 degrees system of grid, vehicles, batteries and electronic devices fully connected. The power grid is stressed reducing its stability and challenging its capacity due to output current peaks (mostly when many vehicles are being charged together). For these reasons, rapid charging is useful for emergencies and to help EVs diffusion, however it cannot regularly substitute normal charging. [17]

Looking at charging costs in Italy, to have an idea, recharging the electric car using our own home network, in fact, has a cost of 0.20 euros per kWh, while this increase to 0.45 euros per kWh in the event of the operation taking place at the 11 or 22 kW alternating current columns. If, on the other hand, electric car charging is provided at the 50 kW fast charging columns, the cost for the supply of electricity is 0.55 euros per kWh.

### 3.1.2 Wireless induction charging

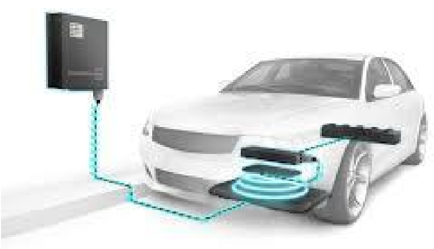


**Figure 36.** Wireless induction charging example on a car. Source: [18]

Inductive charging (also known as wireless charging or cordless charging) "is a type of wireless power transfer. It uses electromagnetic induction to provide electricity to portable devices."

It is mostly applied to smartphones, smartwatches, tablets, toothbrushes and medical devices, However, it can be used also for electric vehicles. Energy is transferred from an inductive pad (no perfect alignment is required) through inductive coupling, with no need of wire connection.

AC runs through the induction coil in the pad (primary coil) and, thanks to electromagnetic laws, an alternating electric current is transmitted to a second induction coil (receiving) in the car. This AC current is converted in DC current through a rectifier and utilized to charge the battery of the vehicle. [18]

Compared to plug-in charging wireless charging offers benefits in terms of simplicity, user friendliness and sometimes better efficiency. Main issues are instead coming from compatibility, limited power and the fact that today their usage is limited to stationary charging which means when the car is parked with engine off. The real innovation would be the dynamic charging mode which would solve most of the problems linked to short ranges. This solution is currently under research but has two major obstacles which are large air gap and coil alignment, affecting the efficiency of power transfer. Also possible impacts on human health are under research. [19]

Induction wireless charging is operating under some pilot projects in particular locations but is not actually commercially viable. In 2018, BMW revealed that: "We would offer wireless chargers with the 530e plug-in hybrid in select markets worldwide." In reality, until now, no more news has been released by the German car manufacturer neither about details of the project nor about a project extension. If the previously reported problems could be solved, wireless charging would have an enormous potential to change EVs usage scenarios. In particular, it would be beneficial to autonomous driving development and advance since cars could easily charge without human intervention both statically and dynamically. The advantages of such a technology may impact also rideshare, taxi and public transport applications. [20]

US-based WiTricity, a leading developer of wireless charging tech, has stated that "their systems are capable of bi-directional power transfer, chargers with this capacity could allow EVs to resell energy to the grid during peak periods, potentially combating storage and overload issues that could otherwise be a major obstacle to widespread EV adoption." [20]

Anyway, the odds about this technology are still limiting its commercialization and companies holding patents are waiting for the right moment to invest on its penetration on the market. Until that day, plug-in charging technologies will be a good solution to let the EVs sales ramp up since charging times are improving constantly. [20]

## 3.1.3 Superchargers

I fell that a particular mention should be reserved to Tesla's superchargers project which revolutionized the fast charging business.

Tesla's supercharger is a 480-volt DC fast charging technology as a proprietary complementary good for its electric vehicles. The superchargers' network has been introduced in 2012 and in March 2020 there were 16,103 Superchargers in 1,826 stations worldwide (an average of 8.8 chargers per station) in U.S., Europe and Asia. Electrical power is supplied at maximum 250 kW with the off-board connector. [21]

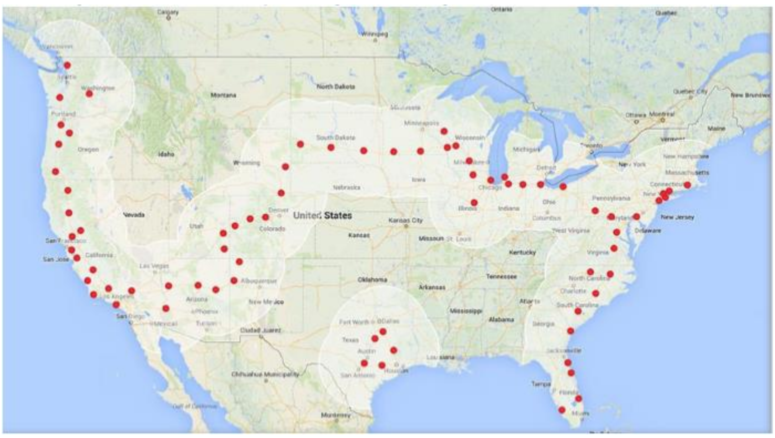


**Figure 37.** Tesla's network of superchargers in the U.S. in 2014. [21]

Tesla Model S has been the first car to be able to exploit such a network followed by all the others. The business model implies free charging for life in some case and a maximum kilowatt-hour per year in others. The payment occurs by credit card and is based on energy used or time spent.

Tesla decided to focus their usage on longer journeys. Apart from this network of superchargers, the American company owns a proprietary network of 23,963 destination chargers in places like hotels, malls or restaurants. These chargers provide less power (22 kW) and are used to charge cars slowly for free (for Tesla's customers). [21]


**Figure 38.** Tesla's supercharger station. [21]

In September 2017, Tesla launched the urban superchargers which are more compact and power-limited versions of the common supercharger, deployed in urban areas like parking, malls of garages. Tesla is planning to increase the percentage of superchargers' stations using solar panels.

All Tesla's models apart from the Roadster are able to exploit supercharging technology and the future planned models as well.

In 2019, Tesla opened the "V3" stations which provide up to 15 miles per minute (depending on circumstances).

In the European market, Tesla has been required to adapt to standard for European public charging (i.e. CCS/Combo2), providing existing models with adapters. The incompatibility with models imported from U.S. still remains.

Currently Tesla is also working on possible agreements with other car manufacturers for superchargers network sharing and on the deployment of mobile superchargers. [21]

### 3.1.4 Battery swap

An entire section (i.e. Chapter 4) is dedicated to a deeper analysis of this technological solution, however the intention here is to introduce battery swapping and highlight some key points.

Although developments in technology and battery improvements are expected in terms of the ability to store energy and to recharge faster, replacing batteries today seems to be the fastest and safest system by now to restore the autonomy of an electric vehicle, since a lot of issues can be found concerning the two other most known emerging solutions.

Fast charging technologies, such as Tesla superchargers, are not currently considered the best choice by many experts, as in the long term they could significantly shorten the useful life of the batteries and their ability to maintain charge. Wireless charging if not provided in a dynamic form are useless in solving the charging duration issue (waiting time for customers) since charging is slow and this slow charging problem must be added to concerns related to safety and technical efficiency.

What is sure right now is that even if fast charging is growing year by year it still poses a lot of critical challenges and, even if it allows to fully charge many cars in less than one hours, the actual technology cannot be in any case competitive in terms of convenience with a traditional vehicle which takes 5 minutes to fill the tank. From this basic consideration started my work.

A battery swap solution, instead, based on a subscription model guaranteeing access to the infrastructure in exchange of a subscription fee, may be useful to reduce upfront investment and can easily expand the range. From the driver's point of view a BSS works much like a gas petroleum-based station today. [22]

But let's take a step back and describe what battery swap actually is. The concept of Battery Swapping as an energy refuelling station for electric vehicles was already introduced in 1896 to solve exactly the same problems that still afflict this type of vehicle, autonomy and long charging times. It was then put into practice by the Hartford Electric Light Company which created a battery supply and maintenance service for vehicles of the General Vehicle Company (a subsidiary of the General Electric Company). The vehicle buyer could buy the car without the batteries and then pay a monthly fee plus a variable for miles travelled for the replacement service. Both the vehicles and the batteries were modified to adapt to a quick replacement and the service was active from 1910 until 1924 allowing coverage of over 6 million miles. In modern times the solution is quite common for work lift trucks for example. The first company that tried to spread a Battery Swapping system was Better Place. [24]

The process flow is simple, he just needs to stop and let the mechanism swap his exhausted battery with a fully (or almost) charged one thanks to its subscription fee. In this way the customer is able to go on to his final destination and the concern is about the diffusion of these stations rather that the capacity of the battery itself. The depleted exhausted battery is then charged. [22]

Grid reliability may take some benefits form a battery swap solution since today it is not designed to support the load profile of the estimated growth of circulating EVs. For sure an improvement in the grid structure as well as an optimization in the management of charging strategy will be required but they might not be sufficient and here comes out the BS technology. Some studies have also confirmed that the degradation rate of the battery in case of fast DC charging is much faster that slow charging which may be adopted in battery swapping stations. [23]

It seems legit to think about battery swapping as the solution to all problems but things are quite different since there are many odds and obstacles and, most of all, many doubts arise about the customer acceptance of such electrification strategy. [22]

Battery swapping projects are supposed to be very expensive and a big problem of compatibility is present as to participate in the battery exchange you need an EV compatible with a battery architecture designed for the BSS (i.e. standardized).

Moreover, BSSs offer a quick and reliable alternative to recharging batteries only on the assumption that consumers are willing to lease their battery as opposed to owning the battery.

Figure 39. shows an example of the simplified operating process of a Tesla during the swapping of its battery. This Tesla BSS includes a vehicle platform, a vehicle lift, battery lifts, vehicle alignment rollers, electrical connection alignments, battery and rack transport shuttles and battery storage rails. [23]

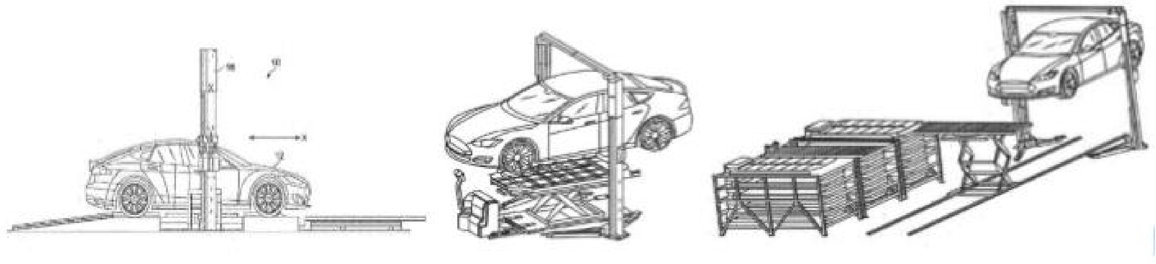


**Figure 39.** Example of battery swapping operation on a Tesla. Source: [23]

To take the most out of such an operating model, batteries should be easily identifiable and replaceable.

A strategically exploited BSS can act also as stationary energy aggregator and can participate in markets for electrical energy and reserve. In this way profits can be optimized, thanks to voltage support, regulation of reserves and energy arbitrage (as shown in Figure 40.). [25]

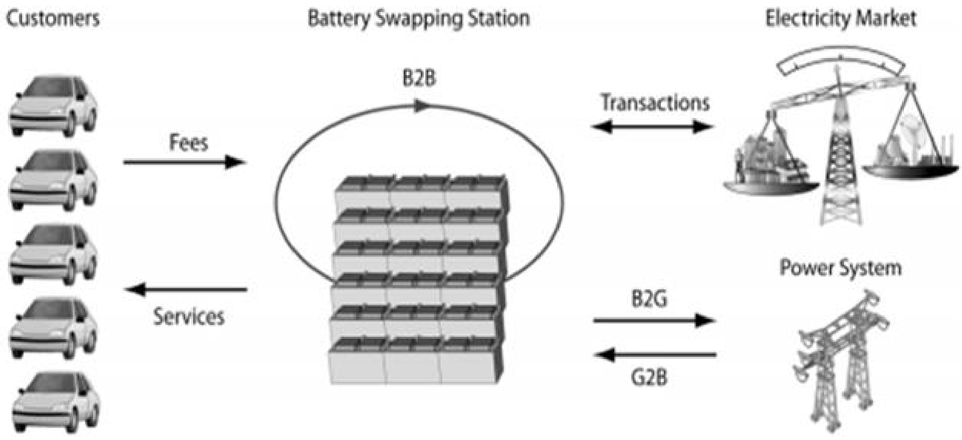



Figure 40. Interactions of a BSS with customers, market and power system. Source: [25]

The greatest advantage of BSS is probably the load shifting which means to shift the energy demand from peak moments to lower periods reducing the impact on the grid which would not be able to bear such an electrification process. One step further is represented by the V2G concept of providing electricity to the grid for balancing purposes with a bidirectional flow of energy. The BSS can be the V2G enabler. In a smart scenario the charged battery of an electric vehicle may also be seen as an energy storage for other purposes such as vehicle to building energy flow. [5]

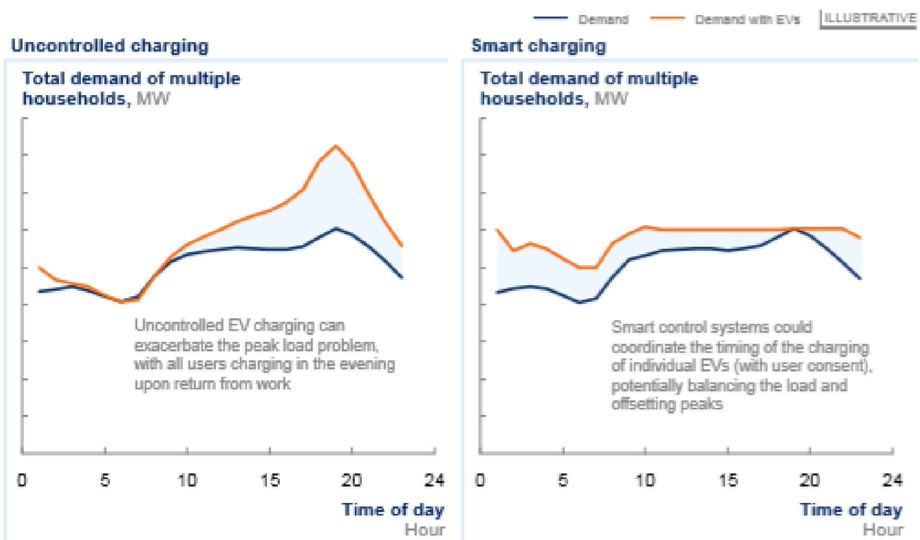



Figure 41. Uncontrolled charging vs. smart charging curves example. Source: [5]

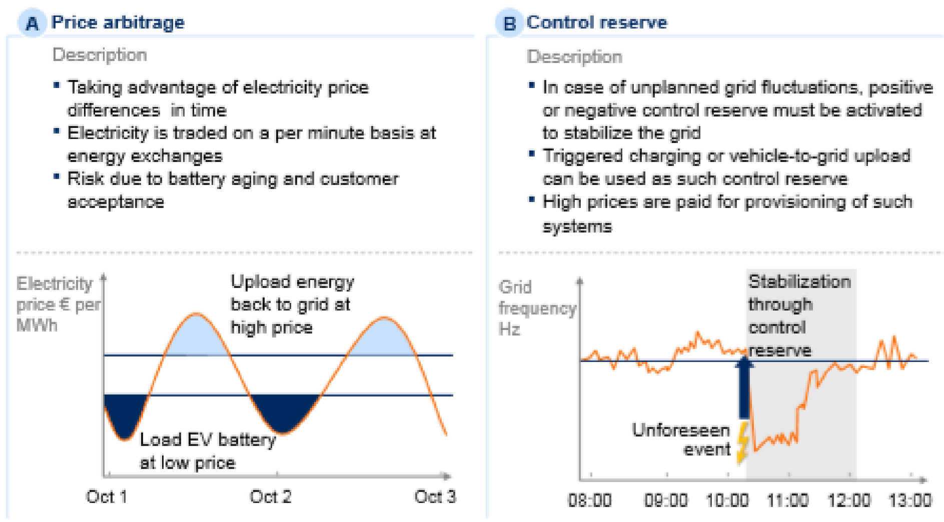



**Figure 42.** Examples of price arbitrage and control reserves' mechanisms. Source: [5]

A BSS so is considered a new energy load for the distribution system. Its main electrical components are the ones represented in Figure 43., a distribution transformer, AC / DC charger, battery packs and a battery energy control module (BECM). [23]

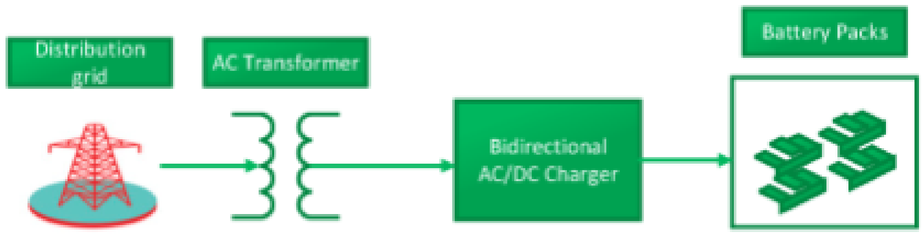



**Figure 43.** Electrical components' scheme of a BSS. Source: [23]

According to [23],"almost 40 million vehicles in circulation today in Italy travel on average about 30 km per day. In the Italian scenario (6.6 km per kilowatt hour), if the cars were all electric (futuristic hypothesis) their recharge would require 181 gigawatt hours per day, that is about 23% more than our total daily consumption".

The Figure 44. shows an example of EV swapping demand from which to start planning an optimal operating model in which the recharging of the batteries should be mainly concentrated on the off-peak periods, while the injections of B2G mainly in the peak periods. The charging process has to ensure that the BSS can bear the energy requirement of exchanging batteries during the peak periods.

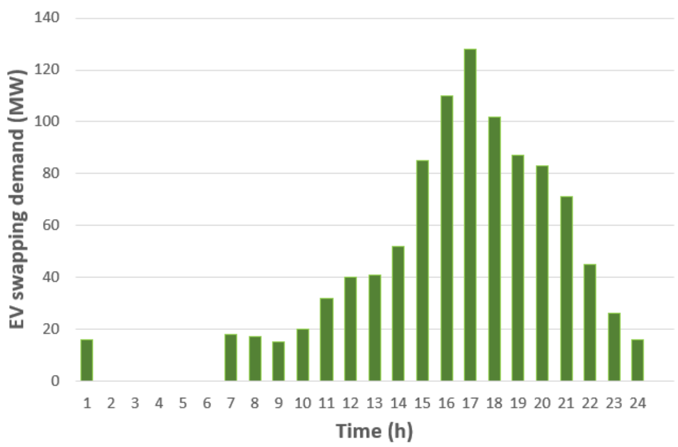



**Figure 44.** EV swapping demand example. Source: [26]

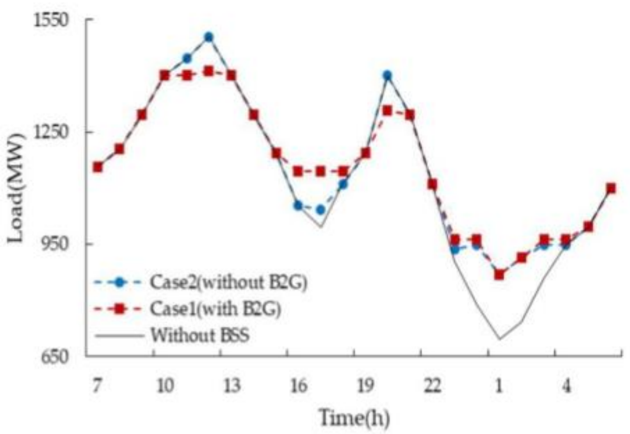



**Figure 45.** Example of load flattening beneficial effect. Source: [26]

The scenario that emerges is therefore a Battery Swap Service in which the customer no longer has the ownership of the car but accesses a service with a view to sharing economy and sharing mobility.

# 3.2 Comparison applied to different scenarios

We know that EVs are going to lead market sales (today only around 2% globally) in road transportation sector. According to IDTechEx, "by 2030 there will be over 100 million plug-in EVs on road globally including passenger cars, buses, trucks and vans which are the most relevant sectors to consider for EV charging infrastructure." [27] Clearly electric passenger cars will represent the largest volumes but electric fleets (buses, trucks and vans) are going to grow fast until 2030 and they will strongly affect the infrastructure. Again, according to IDTechEx: "by 2030 global EV charging infrastructure market will be worth estimated $40 billion per year, which could provide huge value opportunities for companies along the EV charging value chain. The global EV charging infrastructure market expected value, instead, will grow at 24% CAGR in the forecast period and reach $40 billion per year by 2030." [27]

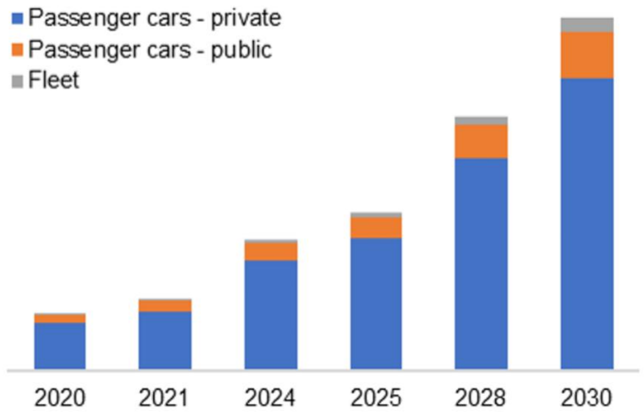



**Figure 46.** Global annually new-installed EV chargers by sector (k units). Source: [27]

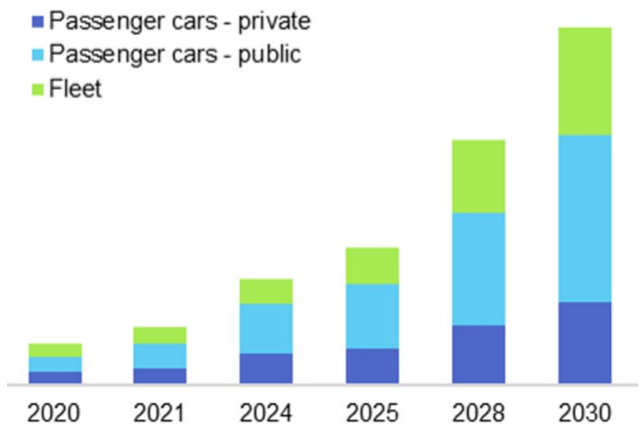



**Figure 47.** Global EV charging infrastructure market forecast by sector ($ Bln.). Source: [27]

With the term “scenarios” we mean in terms of mobility choices and needs. A few parameters need to be considered in order to differentiate the application of a technology to a certain means of transport, determining its suitability and best fit. Among them, most relevant:

- Dimensions of the vehicle
- Routes travelled on average
- Usage modes
- Timings
- Typical operating environment

## 3.2.1 Private transportation

In this category fall the private passenger cars, the vehicles we are using everyday for any kind of movement. This is probably the wider and most complex category since vehicles belonging to it represent the large majority of totality and are really different one from another. Users of private vehicles have so different needs one with respect to another and finding the best solution for everyone is impossible, it is a matter of finding the best trade-off. Large vehicles’ users who are often taking long journeys by car need first of all very high autonomy levels and fast charge, as well as powerful batteries ensuring high performances and requiring much more space in the car (working on battery cell density is so important). On the other side, city cars' owners are usually using their vehicle for short mileages and, so, they priorities are completely different. They primarily need a capillary infrastructure network covering the city to partially charge their vehicles and they also need their vehicles to be light weighted and small sized, preventing the use of big heavy batteries to improve performance and requiring space optimization to ensure compactness and agility.

As we already know, all the previously mentioned technologies have found applications on private vehicles. Some of them actually have commercial potential and are already quite diffused while others remained a bit more than prototypes.

Plug-in charging has been from the "day one" the chosen technology to invest in and it is actually the most diffused. All other technologies developed in the last years tried to impose as standards, often failing in their technical project or, more often, struggling spread across different car models and brands, remaining in this way niche application. To develop a strong national infrastructure a real definitive standard must emerge, overcoming the standardization problems of any kind.

Battery swapping has been quite a common solution in the last years, even if failures, due to commercial and strategic issues most of all, prevented it from becoming a reliable and diffused standard. Many examples are provided in the next chapter. While in Europe standardization is still a far away concept seen as a limitation to car makers design differentiation and fostering monopolies, in China the situation is quite different. Battery swapping, after a break, is coming back as a trending technology to be developed and Chinese government in 2020 has increased its efforts to introduce common standards in the sector. According to the agency's report, the goal is to standardize the process on any car, battery and system, allowing for replacement in just three minutes. Among the first supporters of the battery replacement project is the Chinese car manufacturer Nio which already in 2018 promised to build a thousand exchange stations to serve its fleet. It currently has 125 stations for quick battery replacement. But Bloomberg indicates that BAIC BluePark New Energy Technology also offers the service today. The state-owned BAIC group and its various entities, including BAIC JEV, are the second largest electric vehicle manufacturer in China. Its numerous partnerships connected Daimler and Magna. And last, it announced plans for 3,000 exchange stations, supplied to half a million electric vehicles by the end of 2022. Most of the BAIC models are small and affordable, with prices offered on the Chinese market. BJEV, in 2018, sold its EV300 compact car for around $ 12,000, with a battery rental agreement for around $ 60 a month.

Tesla tried both the battery swapping technology and the superchargers, in both cases tried to adopt, as usual, innovative business models to gain market share and lock-in customers. Superchargers had a much bigger success rate compared to BSS since they were less disruptive, less standardization and upfront capital was required. It happened also that supercharger technology prevented Tesla's users from adopting BS solutions. According to Musk, "It is unlikely to be worthy until and unless something changes or proper awareness is being provided among people", as a proof of how difficult it is to impose a common standard at this point of the diffusion curve.

In reality, if pure charging speed is what we are looking for, there is already an alternative storage technology to the electrochemical one of batteries: supercapacitors or supercapacitors. A supercapacitor (SC), also called an ultracapacitor, is a "high-capacity capacitor with a capacitance value much higher than other capacitors, but with lower voltage limits, that bridges the gap between electrolytic capacitors and rechargeable batteries." [28]

Their main benefits are the ability to store 10 to 100 times more energy per unit volume that electrolytic capacitors, can charge and discharge much faster than normal batteries and bears much more charge-discharge cycles than batteries. So, they can be charged and discharged almost instantly (high specific power) and have a much longer life than electrochemical devices, easily exceeding 10 thousand charge and discharge cycles. On the other hand, they can store much less energy. An element that precluded any application in the field of e-mobility. “A capacitor vehicle or capa-vehicle is a traction vehicle that uses supercapacitors (also called ultracapacitors) to store electricity.” [28]

A team, made up of researchers from Bristol University and Surrey University, hopes to have untied the latest technical knots that keep these devices away from electric cars. The highlight of the research - which the group has been working on since 2016 - is a new polymeric material capable of increasing the energy density of supercapacitors. The polymer has dielectric properties 1.000 to 10.000 times better than existing electrolytes. Scientists have reached practical capacity values between 11 and 20 F per cm 2, when on the market these devices do not usually exceed 0.3 F/cm 2. The technical details of the research are still kept in the most complete reserve, waiting to obtain the patent registration, but the results make the group jump for joy. If these capacity values were maintained during production, the supercapacitors could reach a gravimetric density of 180Wh/kg, a value higher than the lithium batteries on the market, whose density does not exceed 120 Wh/kg. And most importantly, they would allow to charge electric cars in about ten minutes. [29]

The hardest problem or limitation about wireless inductive charging systems, instead, is that they can only be utilised when the car is parked or in stationary modes, such as in car parks, garages, or at traffic signals and until the dynamic enabled version is patented and commercially released its benefits are not going to be sufficient to displace the traditional wired technology.

For sure, all these trials and business ideas were thought, funded and implemented by single car manufacturers, fostering a fragmented market environment and hindering the possibility of a common solution. In my opinion, maybe, national institutions should intervene by suggesting a clearer path through incentives and targeted actions so as to contribute to move in the same direction.

## 3.2.2 City transport service

In this section we will consider the public passenger cars (i.e. taxis) and the public transportation fleets (i.e. buses).

#### Bus

During 2019 the number of electric buses circulating set a new record in Europe reaching three times the values in the previous year. Around 12% of urban buses register in the last year were BEBs (battery electric buses). This trend is going to become stronger very soon, Interact Analysis forecasts that “approximately 40% of new city buses registered in Europe in 2025 will be battery-electric”. [30]

Still according to this analysis, “Zero-emission buses use large batteries or stored hydrogen which is converted to electrical energy using a fuel cell to power electric motors. In the short- to mid-term, the big majority of zero-emission buses will use large batteries due to the high-cost of manufacturing fuel cells and the under-developed infrastructure required for hydrogen re-filling.” [30]

In 2019 the top ten list was dominated by VLD with 386 e-buses registered and 22.5% of market share, while BYD is in second place with 236 buses.

The big difference from other means of transport is that this kind of vehicles is not owned directly by the driver, it is instead owned by public (Comune) and private companies.

The fixed route imposes to electric buses can make easier some of the biggest problems of electric mobility (costs, driving range and charging times). So, BEBs can really be a bridge toward popularization of EVs. The biggest obstacle is the energy replenishment required quite often due to little ranges and the quantity of kilometres to be driven every day. The main replenishment solutions today are battery charging and battery swapping. [31]

Battery Swapping systems

Traditional battery charging in case of buses is quite problematic cause it takes hours even in case of rapid charging and reduces batteries' lifecycles. This loss of time is a big problem for everyday tasks.

On the contrary the battery swap solution seems to fit better to this use case. The public transport systems have different charging demand compared to EVs and, so, new methods and designs are required. [31]

Battery swapping for public transportation may be particularly beneficial for low speed buses which needs to travel fixed short routes but many times in the day. Let's take a look at a couple of business examples. [25]

Next Gen Battery swapping system for E-Bus at Aleees is the first one. Ales provides swaps of 6 minutes to buses instead of hours of charging. According to their business model, each operator owns its swapping station and so the infrastructure is not financed by government. Battery leasing is managed by Alees. The major advantages are reduction of time, saving of spaces and easier battery management and maintenance system. [25]

Another example comes from XJ Group Corporation. During the 2008 Olympic and Paralympic Games in Beijing, 50 battery-powered electric buses were used to achieve the goal of having a zero-emission Olympic village. The project led by the BIT (Beijing Institute of Technology), together with over 20 other organizations, had the objective of developing technologies related to green mobility and speeding up the transition to electric public transport of the Chinese population (BIT 2008). One of the companies involved in this project was the XJ Group Corporation, founded in 1947 and part of the aforementioned SGCC (State Grid Corporation of China). XJ Group operates as a public transport operator in Qingdao, a city with 8 million inhabitants and for its own electric vehicles has opted for the development of a Battery Swapping system as it is considered ideal to overcome the problems of limited range and long waiting time during charging. The system designed in collaboration with Phoenix Contact provides that robots positioned on the sides of the bus replace the discharged batteries of the vehicle with units previously charged in dedicated stations. The exchange operation lasts for seven weeks, after which the bus can go directly back to service and resume its journey. [32]

**Figure 48.** XJ Group Corporation's battery swapping station. Source: [32]

The buses have been in circulation since June 2011 and since then over 800,000 battery replacements have taken place, supplying power for more than 18 million kilometres travelled without ever having failed the exchange system. In May 2013, the XJ Group planned to reach 1,500 units for its bus fleet by the end of 2013 and to open Battery Swapping centres in new cities. Obviously, users do not pay for Battery Swapping, but it is the company that bears the overhead costs and will recover them through lower operating costs. Interest in commercial battery swapping is also growing in Europe. [32]

The case of XJ Group and its buses has shown that Battery Swapping can also be applied in public transport. Urban transport buses are in fact heavy-duty vehicles which if powered by batteries could quickly recover the initial investment thanks to savings on fuel. Battery Swapping stations could be positioned using the pre-established routes in places shared by several routes, at the terminuses, depots or other areas with common access to multiple vehicles. [32]

<u>Capacitors</u>

All around the world, according to country specificities and local customers' needs, many other technologies have been developed in order to optimally satisfy them. For example China is experimenting with a new form of electric bus, known as "Capabus", which is an autonomous vehicle that works with no continuous overhead line. It uses power stored on big onboard electric double-layer capacitors (EDLCs), which can be recharged quickly partially at every bus stop (under the so-called electric umbrellas) and then charged fully at the depot. After some prototypes released in Shanghai, they are now quite used in China. Obviously can run only on very predictable predefined routes and need to stop always regularly and often. The partial recharging at bus stops lasts around a couple of minutes and the bus is able to collect energy also from braking and solar panels are under installation in the recharging stations. [33]

The Chinese company Sunwin, a joint venture between Volvo and China's largest automaker SAIC provided, for example, the city of Shanghai with 61 electric buses using supercapacitors for the Expo 2010 and is releasing new-energy city buses with battery plus capacitors every year in China. [34]


**Figure 49.** Sunwin electric bus in Shanghai. Source: [34]

<u>Wireless charging</u>

Wireless charging with inductive technologies for electric buses can be used as a complementary daily recharge to the overnight depot plug-in charging. In just 5-10 minutes of charging through a wireless pad a small bus with 60 kWh battery capacity can operate the whole day. In Europe there are 17 countries who are preparing to use wireless charging for buses. For example, in Madrid a recent study by IPT Technology has proved the feasibility and benefits of this solution, in which Electric buses can charge in three different scenarios: Overnight charging, Opportunity charging and In-Motion (dynamic) charging. [35]

In U.S. as well this charging mode is present, in particular, in Long Beach, California, some buses can stop over a charging pad which transfers energy to a receiver on the bottom of the bus. In this way the range of the bus can be doubled, they don't need to come back frequently to the depot and one bus can do alone what two electric buses should do without this solution. [36]

Another company investing in this sector, in Washington D.C. (US) is called Momentum. They announced the readiness of an operational system developed for BYD K9S bus in Washington. The major problems of wireless charging, as I already explained before, are the charging efficiency and charge rate and Momentum didn't release many details about these issues, only declaring that "their system is more efficient than plug-in chargers of the same power rating." [37]

Of course, charging efficiency and charge rate have always been the main problems with wireless charging technologies. Momentum Dynamics clearly got the charge rate part figured out and when it comes to efficiency, they, unfortunately, didn't release any specifics data, but they claim that "the system is more energy efficient than plug-in chargers of the same power rating."

The company insisted that this solution is the best for electric buses on-route opportunity charging in terms of time (only 5 minutes required on the pad to offer enough energy to reach the next bus stop). The company is planning an expansion in other U.S. cities and Europe. [37]


**Figure 50.** Momentum Dynamics wireless charging bus. Source: [37]

### Taxi

A good number of issues and features related to public transportation through buses can be applied to taxis fleets as well. The quantity of taxies is, for sure, less than private cars, but fuel consumption and emissions ratio are larger than the private cars, government subsidies helped to promote electric taxies and maximize the effort in reducing CO2 emissions. Now, again, is the time to solve the problems linked to electrification and invest in parallel on a strong, reliable, optimal infrastructure and charging technology.

Taxi fleets are made up of cars required to travel a large number of kilometres every day usually always within the same city and a single daily full charging is not enough for the whole working day. However, stopping for a certain time to charge the car means stopping the work-shift and losing potential clients. For this reason a battery swap solution may be beneficial.


**Figure 51.** Taxi vs. private car comparison. Source: [38]

<u>Battery Swapping System</u>

The installation of battery replacement stations at their usual car parks such as near stations, airports or other points of interest, would allow these cars to solve the problem of the limited autonomy of electric vehicles, save on fuel costs and exploit the economies that would be created by the shared use of the same charging facility. Taxi companies have problems with long charging stops and this BS mechanism is very useful for this problem. Being installed also at petrol stations it will require less infrastructural investment. In case of public transportation or commercial transportation another major problem linked to this technology disappears, standardization of modular batteries. It is far easier for a mono-brand category of vehicles to fit and standardize batteries for a swapping station and this is what in many cases in the past prevented the mass diffusion (i.e. for private mobility as well) of battery swapping systems.

An example comes from KeyPower. This company is developing a Battery Swapping system similar to that of Tesla and Better Place designed to serve the taxi fleets that circulate for Beijing and other cities in China. Since a charged battery allows you to travel on average from 100 to 150 kilometres, but taxi drivers travel at least 300 a day, they need to recharge quickly and the system designed by KeyPower allows you to make the exchange in less than three minutes via a platform that extracts the exhausted battery from the car floor. The peculiarity of the KeyPower project is that they use batteries of 4 different sizes to adapt to the various sizes of vehicles, while using standardized communication connectors and protocols. [32]

**Figure 52.** KeyPower’s BS system. Source: [32]

Another company in China providing this kind of service is the state-owned BAIC Group and its legal entities, among them figures BAIC JEV. They are the second largest EV maker in China and its huge number of partnerships include Daimler and Magna. BAIC BluePark declared that have already installed 187 battery swap stations in 15 different Chinese cities for more than 16.000 electric taxis. [39]


**Figure 53.** BAIC electric taxi. Source: [39]

Looking at the future, the innovative Italian company Flymovedianchè is trying to revolutionize the entire green mobility system by dealing with the problem at 360 degrees. Among the others, they are planning the production of their own vehicles and their 5-seater city car is projected specifically for taxi fleets, allowing them to exploit the company's battery swap platform and a bundle of many other services. [40]

Wireless charging

Many European countries seem to be more likely to invest and adopt this kind of technology. Two examples are provided here below.

"Norway's capital city of Oslo will be the world's first metropolitan area to install wireless, induction-based charging stations for electric taxis, in a bid to make a zero-emission cab system by as early as 2023", according to *Reuters*. This effort copes with the plan according to which all the cars sold in the country will be fully electric by 2025. Norway is collaborating with Finland and with Momentum Dynamics (U.S.) to install the charging pads on the roads, to be connected to energy receivers in the taxis. The goal is to use induction, which is more efficient, to charge taxis while they are waiting for passengers in order to make the charging quicker, easier and more affordable. [41]

Another example comes from UK, seeing a revolution in electric vehicle charging after the Transport Secretary announced on January 2020 that "£3.4 million will be invested in trials for wireless charging of electric taxis in Nottingham." [42] The idea, again, is to reduce clutter on the streets and to allow multiple taxis to charge at once in an easier way. Obviously, the taxis are used as a test with the view to expand this solution to many more private EVs. Electric taxis and clutter reduction mean reduction of transport emissions in the air. This solution is ideal for small batteries' cars which needs shorter and more frequent charging, reducing the range anxiety for drivers. To conclude, it is true that this technology allows taxis to charge while waiting but, anyway, is still limiting the earning potential of a work-shift.

### Car sharing & autonomous driving

Autonomous driving and shared mobility are going to reshape the road transport in the next decades, impacting on electrification of vehicles and electricity system as well. EVs have higher upfront costs of purchase but lower fuel and maintenance costs. This is a huge advantage for autonomous and shared fleets because their usage is much heavier that private cars and switching to EVs may be convenient even if some doubts are still present.

Starting with shared mobility, there are two typologies: free-floating and hub/depot services. In the last years smartphones and connectivity made it easier the diffusion of the first category. Car sharing is a good fit with EVs because they need short distances to be driven with high frequencies, in fact some companies (Moov'in, Blue SG, Carma, Car2Go and DriveNow) are testing this solution. The big problem for free-floating is charging while using due to still low presence of capillary fast chargers infrastructure. So, hub/depot typology is less handy but has not this problem since slower and cheaper charging can be scheduled during vehicle downtimes.

Smartphones have introduced also the diffusion of another service, the app-based ride-sourcing offered by the so-called transportation network companies (TNCs) such as Uber, Lyft, Didi Chuxing and GrabTaxi. Despinte the convenience, the diffusion of EVs in this market is still very low. According to the article: "EV shares on the major ride-sourcing platforms remain below 1% with the exception of Didi at 1.3%, which already has over 400 000 EVs on its network. In California, EVs represented about 1% of vehicle share and trip miles in 2017." [43]

Probably this can be explained by some barriers to adoption like high prices and limited available chargers and others. FCEVs sometimes are able to address some of these challenges in this sector.

In the meantime, AVs are getting closer to the market thanks to sensing technologies, AI and connectivity. AVs are probably going to start spreading among electrified commercial fleets due to low operating and maintenance costs, creating synergies. Automated driving technologies could be easier to be implemented in EVs because there are a lot of drive-by-wire components.
AVs require significant power consumption to on-board electronic, although this parameter is rapidly improving. No one exactly knows when and how these autonomous vehicles will penetrate the market but, for sure, there are some favourable use cases to start from, like commercial applications. This happens because in these applications labour costs are high and automation could improve utilizations and efficiencies (e.g. trucks and buses) reducing costs.

Once again, fleets require greater and different charging infrastructure deployment and this may be a critical factor in electrification and evolution of shared/automated mobility's business models.

A transition to shared, automated, and electric vehicle (SAEV) fleets may also provide benefits to the grid and charging infrastructure. According to the article: "volumetric energy rates based on hourly wholesale pricing, for instance, may be a promising means of reducing peak loading and promoting charging at times when variable renewables are at their peak." [43]

About the criticality of infrastructure development, it is possible to state also that cities where taxi and bus fleets are participating in the electrification process may leverage the infrastructure built for these fleets to foster the transition to electric shared mobility.

In any case, these kind of share-autonomous robo taxi will be part of our urban life in the next decades and no one can plug them in, so, new solutions to charge them without extra labour costs are required. These cars will need to automatically recharge during downtimes, stressing the importance of future charging trends and technologies like robotic charging, wireless charging as well as electric road systems. [43]

### 3.2.3 Commercial road transport

This category includes fleets composed by light, medium and heavy (trucks) commercial vehicles. In the same way as for buses, also heavy commercial road transport vehicles are not owned directly by the driver, they instead belong to a logistic company. This kind of transport will be discussed deeper in the fifth chapter (i.e. the paper's case study).

According to IDtechEX, "Electric vehicle fleets such as trucks require very different charging infrastructure from the existing infrastructure built for passenger cars. The rising population of electric vehicle fleets represent huge opportunities for developing dedicated charging infrastructure for electric buses and trucks. It is worth noting that although electric fleet charging represents less than 5% of the total charging infrastructure in volume, it constitutes over 30% of the total market value of the charging industry." [27]

BSS

Commercial vehicles' traditional powertrains are well known for being among the most polluting and fuel consuming means of transport, so, moving to cleaner electric solutions would be extremely beneficial. However, these are usually massive vehicles travelling for long hours in most cases. Under these assumptions it is clear that these vehicles need big powerful batteries and time required to charge these ones is likely to be too much, so a battery swap solution seems to be optimal.

Most trucks stop at parking lots or restaurants (e.g. Autogrill) and some space can be bought or rent near these places where a BSS may be installed. Payment as-you-use by app or payment of a fixed (monthly or annual) fee are two possible viable pricing strategies to implement this business. No time lost in long lines, quick swapping a free time to rest and eat. Another possibility is to set up battery swapping stations at the toll plazas and swapping can be simultaneously performed. A dedicated lane can be used for electric trucks at toll plazas needing a battery swap. Existing infrastructure can be exploited in order to reduce upfront capital expenditure. Amount due to swapping can be directly added to toll bill, paying by cash, card, app or Telepass, while the battery is being swapped. Through "Autostrade per l'Italia" app the driver could also book and order a battery to be swapped, in order to maximize operation's efficiency.

Examples of business models and features of a BSS applied to commercial vehicles are provided in the next chapter (e.g. GreenWay).

Wireless charging

In common opinion, wireless charging is thought as inefficient, but in some cases it may be more efficient that wire charging because there isn't much energy lost to heat over the cable.

Wireless charging is commonly misunderstood as inefficient, but in some applications it could prove more efficient than cables because there isn't so much energy lost to heat over the length of the cable. Among these applications for sure figures the commercial transport sector. Wireless charging applied to passenger vehicles is striving to impose but recently some demonstrations showed the potential of this technology applied to commercial trucks. It is more efficient, faster and less space consuming that actual wired charging solutions.

The United States Department of Energy's Oak Ridge National Laboratory (ORNL) announced in a press release that it "had demonstrated a 20-kilowatt bi-directional wireless charging system on UPS hybrid delivery trucks and the system transferred power between a wireless charging pad and the truck with more than 92% efficiency". This result has been reached thanks to an 11-inch air gap between electromagnetic coupling coils in the truck and charging pad. At the 20-kw level, a 60 kWh battery pack of a truck would require about 3 hours to fully recharge, against the 5-6 hours of the conventional charging cables. [44]

Another example comes from the "Smartroad Gotland consortium" which now succeeded in the stationary wireless charging of a special prototype of a 40-ton fully electric truck in the view to prepare for dynamic wireless charging on the public Swedish roads. The vehicle is equipped with five 20 kW receivers (total 100 kW) and can recharge in stationary conditions with around 90% efficiency. A common passenger car would be equipped with only one receiver. By mid-2020 the prototype electric truck and the electric bus will be able to exploit dynamic charging while driving on the test section of 1,6 km. The energy surplus would be used to recharge the batteries. [45]

Now, let's focus our attention on the battery swapping technology, as core topic of the paper.

# 4. Battery swapping systems

Among all presented charging technologies and/or related infrastructures this paper focuses on battery swapping (BSS), which is considered the solution that best fits the modern market, society and stakeholders' requirements. The idea is to analyse it in depth in all its aspects, providing examples, deep dives on operations and a simulated case study as well.

## 4.1 Deeper analysis

**Stakeholders involved**

A BSS project would have a huge impact on many players in the business and society. The diagrams below depict the mutual interaction with some of the main stakeholders involved. These are the so called Venn diagrams, showing how important and relevant a stakeholder is for the business model and how strong are its interactions with the other players involved. Charging station owners can be government as well as private companies or, sometimes, even the car maker company.

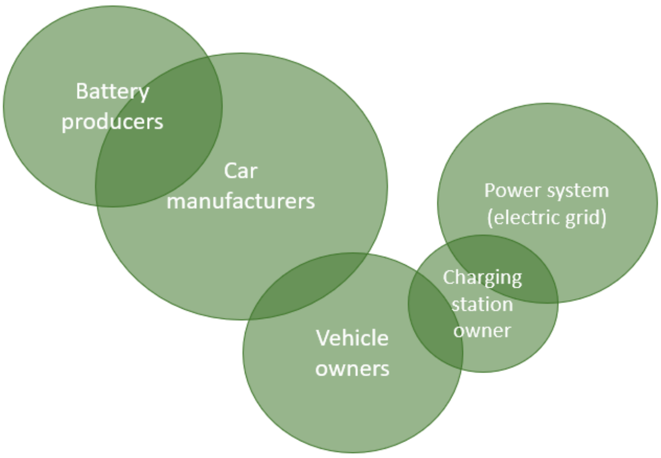



**Figure 54.** Venn diagram in traditional scenario. Source: Personal elaboration

The first diagram is related to a "traditional" wired charging station business while the second one is a snapshot of a battery swap business scenario. In the former the battery producers are not interacting with any player except for car manufacturers who outsource battery production. Instead, in the latter, batteries are directly sold and managed by charging stations' owners in an ideal scenario of battery standardization and compatibility, reason for which the interaction with car makers is still present (shared specifications). I decided to highlight the triple interaction among charging station owner, power system and vehicle owner as a reference to the smart and connected energy management system provided by this kind of solution as well as peak shaving and demand optimization.

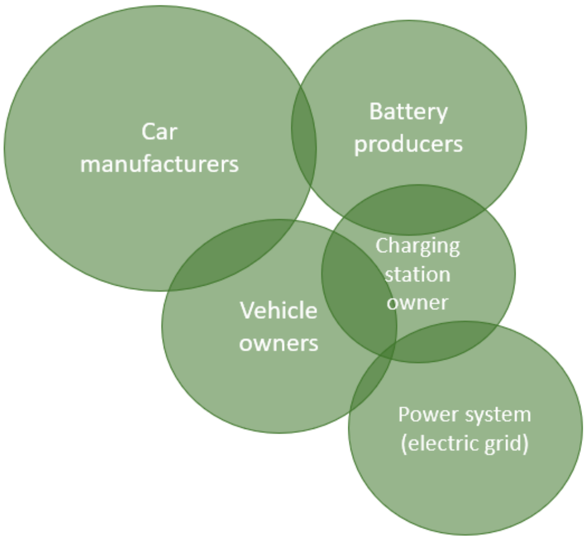



**Figure 55.** Venn diagram in battery swap scenario. Source: Personal elaboration

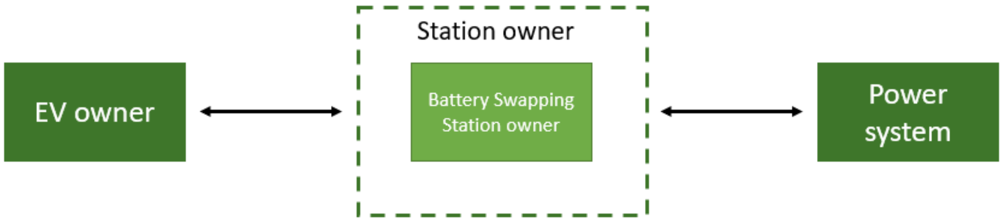



**Figure 56.** Interaction scheme in battery swap scenario. Source: Personal elaboration

## SWOT Analysis

**STRENGTHS**

- Lower service time for customers
- Energy demand optimization and planning (decoupled from the supply)
- Peak and valley flattening
- Preservation of battery lifetime
- Space requirements reduced
- Battery leased and not owned anymore

**WEAKNESSES**

- Huge upfront investment required
- High degree of compatibility and standardization required
- Complex structures and infrastructure as a whole
- Complex transport and logistic system required


**OPPORTUNITIES**

- No more long waiting times
- Reduction of range-anxiety for long-distance trips
- Minimization od energy cost by wise scheduling
- IoT technology promotion
- Development of a unique, integrated and connected system
- More free space to be re-utilized
- EVs price reduction since batteries are not sold together

**THREATS**

- Fast charging technologies rapidly growing
- Market penetration lower compared to expectations
- Impossibility to reduce battery diversification
- Unavailability of enough batteries
- Excessive difference in degradation from a battery to another in the warehouse

**Figure 57.** SWOT analysis of battery swap. Source: Personal elaboration

## Advantages

Following, benefits associated to a BSS are reported from three different stakeholders' perspectives:

<u>Power system Perspective</u>

1 Possibility to schedule battery charging time optimizing the charging strategy
2 Postpone the charging of batteries to the night time or off-peak hours in order to avoid increasing peak loads or network congestions
3 Peaks and overloading can be better controlled and flattened by distributing the charging and discharging times

<u>EV Owner Perspective</u>

1. EVs sold at lower prices
2. Quick battery replacement (autonomy regenerated in a short time, as fast as refuelling a gasoline-powered vehicle)
3. No more range anxiety, long trips are easy to deal with is an adequate swapping infrastructure is present

4. The owner of the vehicle does not own the batteries, thus transferring their cost and maintenance to the company managing the swapping stations
5. The owner of the vehicle no longer has to worry about the useful life of the batteries, being able to exchange them easily and continuously. This creates benefits for the resale of the vehicle in the used market
6. Improving household infrastructure to high power chargers is not required

<u>Station Owner Perspective</u>

1. Minimization of electricity cost by scheduling the battery charging process
2. Maximization of its profits by participating in electricity markets and also providing additional services
3. Reducing the cost of real estate, as there is no need to access large parking spaces
4. If a new and more efficient battery technology is made available, the new generation could be introduced through the swapping stations
5. Battery lifetime is preserved since rapid charging can wear the batteries reducing their useful life

Often in the last years the most common criticism made to this technological choice is that ultra-fast charging technologies are growing year by year, stealing market share to battery swap and making investments vain in the long term. However, very often, it is not considered the fact that advantages provided by this solution go far beyond the simple reduction of time and, among the others, energy demand optimization, space reductions and preservation of batteries useful life are just examples of benefits not provided by other fast charging solutions. Moreover, adopting a BS business model means changing deeply the mobility sector as a whole, introducing the concept of battery leasing, changing pricing policies and modifying the interactions among stakeholders involved. [25]

### Disadvantages

The process is very simple, but it has several disadvantages which are mainly the following:

1. Battery pack design: one of the first problems faced by BS is battery design. In battery swapping, the batteries must be easily accessible and located in a single pack. The goal is to be able to easily remove and re-attach the battery during a swap.

2. Compatibility: it is a fundamental feature for a technology to become successful and a dominant design paradigm. For BS to have a possibility to become a commonly used technology, interchangeable battery packs that are similar for different manufacturers must be designed. This could be a limitation to creativity and design specifications of single car makers, limiting their innovation propension. Battery manufacturers as well should then produce very similar battery packs.

3. Infrastructure: the infrastructure needed for the BS is enormous and much more complex and expensive than charging. Swapping stations must contain a sufficient number of batteries to be provided anytime to customers in need, and batteries are the most expensive component of the car. Mechanisms and structures are far more complex as well.

4. Battery Degradation: battery performance degrades over time, and as a consequence the autonomy related to each charge. Not all batteries will have the same degradation level in the station and so not all customers will receive the same battery. Newer batteries give greater ranges and less trips required to the station.

5. Battery Ownership: The EV owner is not owning the battery, since it is part of a continuous exchange. The battery is leased and new business models are elaborated. This means not caring about battery replacement in time and means paying less the vehicle, but on the other side the driver is going to bear higher cost of ownership, since he is going to pay the lease in addition to the energy.

6. Transportation of Batteries at charging stations: Total cost of ownership could increase also due to necessity to transport heavy batteries from a station to another station or to a centralized warehouse. [46]

### Operation of a BS station

A compatible electric vehicle with a battery architecture designed for the swap is required for participating in battery swapping. What's more, preceding showing up at the BSS, the electric vehicle can plan the BS early to affirm that a battery pack will be accessible for trade. At the point when the EV shows up at the BSS, it ascends a slight incline as appeared in Figure 58. and this establishes the starting of the process. Figure 58. shows the progression of activity of the BS. According to what the paper reports, "The vehicle is situated accurately in the X direction and the vehicle power is turned off for security. Next, the vehicle is raised with the vehicle lift as appeared in Figure 58., where the lift sheets, for this situation, draw in the jack pads on the vehicle to offer help. When the vehicle is lifted, even entryways underneath the vehicle are opened to permit access to the battery that sits underneath the vehicle. Next, the battery lift is raised until it contacts the underside of the battery pack so as to help it for evacuation. When the lift is accurately positioned underneath the battery safely, the fastener removal can start. Next, a battery transport is brought underneath the battery lift. The pre-owned battery, presently on the battery lift, is brought down onto the battery transport, the utilized/exhausted battery is supplanted by a new one from a battery rack. The new battery is then raised up underneath the vehicle. The battery is again positioned and secured by the battery lifts, the fasteners are locked in and entryways shut. Now, the vehicle is ready to be lowered and controlled back on down to get back out and about with a completely renewed battery pack." [23]

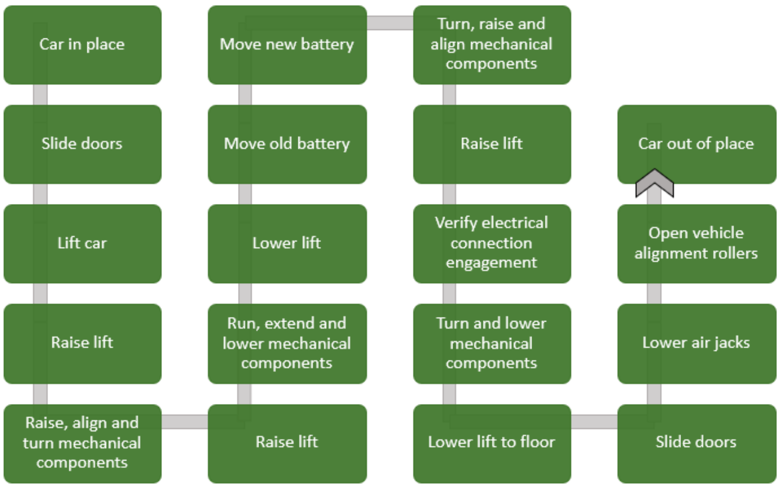



**Figure 58.** Battery swapping procedure flow chart, personal elaboration based on [23]

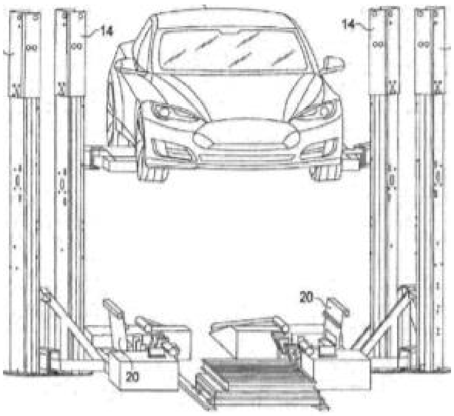



Figure 59. EV raised with the vehicle lift in preparation for a swap. Source: [23]

### Network of sharing stations concept

Battery swap technology provides a real interaction system, fostering the synergy creation between green mobility and green energy.

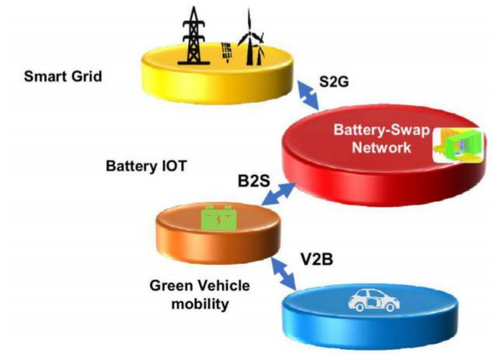



Figure 60. Scheme of the interactions system. Source: [38]

One of the most inventive prospects offered by this technological decision is that he BSS idea depicted in the previous chapter can be altered to incorporate a sustainable power source framework. A photovoltaic system can be incorporated with the BSS. Furthermore, a bidirectional AC/DC converter is executed permitting the battery packs in the BSS to give V2G services to the smart grid, utilizing the energy storage functions. In the Figure 61. is indicated a graph depicting the framework structure of the alleged BShS. The BShS is additionally a piece of a system of BShS, alluded to as a BShN, connected together using the IoT and media transmission interfaces, communicating to optimize the expense of charging, reduce the time to wait for swaps by swapping estimations and share the emptied battery packs among one another. This suggests the requirement for committed vehicles to transport electric vehicles' battery packs from station to station or to a centralized warehouse, to recharge them ideally. The Figure 62. is a conceptual delineation of the BShN. According to the paper, "the BShN comprises of a few useful subsystems; the correspondence between these systems is taken care of by the BShN Management System. This system facilitates the bidirectional flow of power between the BShS and the smart grid which is designed for distributed generation and bidirectional power flow. Furthermore, the BShN management System controls the planning of battery swaps just as anticipating of future swaps and grid loading." The BShN management system, so, turns into a grid utility, offering types of assistance to the network, for example, peak shaving and loads adjusting, and fills in as a save for the grid during potentially “dangerous” situations. What's more, the battery packs are likewise associated through IoT to continually deal with the battery state of health (SOH), condition of charge (SOC), and communicate its different information focuses with the BShS and the BShN. [23]

In this way the battery swap network is seen as the point of junction between mobility and the smart grid. It not only provides energy supply services to green mobility, but also provides peaks management and energy absorbing services to the power grid.

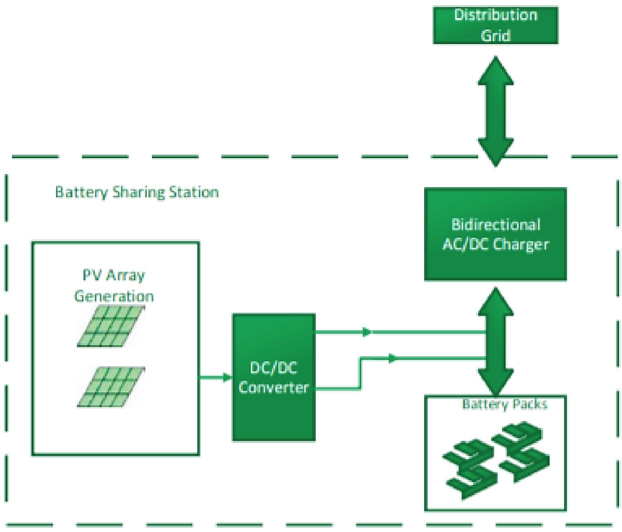



**Figure 61.** BShS with a local RES with a bidirectional connection to the grid. Source [23]

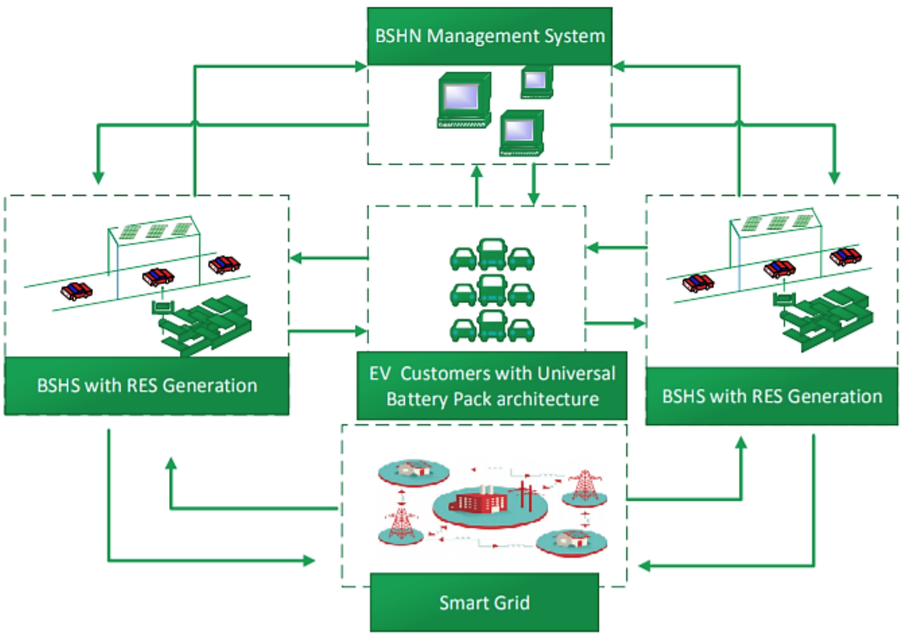



**Figure 62.** BShN communication Interface between components and the smart grid. Source: [23]

# 4.2 Business models and examples

A company's business model describes how it creates, distributes and captures the value. The business model description, generally, can be done exploiting the Osterwalder's theory about the nine key points, namely:

1 Value proposition
2 Objectives
3 Distribution channels
4 Relationships with customers
5 Revenues streams
6 Structure of costs
7 Key activities
8 Fey resources
9 Network of partnerships

Battery swapping model hasn't reached a complete success in the world until today mainly because of technical or commercial issues. The development of a diffused and reliable battery swapping network would be really beneficial to electrification and electric vehicles adoption, however many problems are still present.  As already mentioned, the main obstacles include standardization, compatibility, pricing strategy, commercial viability, partnerships exploitation huge upfront investments and reliability of leased batteries and some others.

Since every market and every player had to face different situations and problems. That's the reason why I decided to report some of the most important case studies of the last decade, as examples of successful or unsuccessful business models. Some of them, as in case of Flymovedianchè, are very recent and completely innovative still today, others are older examples of companies that sometimes today result failed or switched to other solutions in their investment portfolio. Anyway, it is important to analyse their old business models in order to understand the evolution of this technological solution.

### Flymovedianchè

I decided to mention this one as the first example being it not just Italian, but also representing the most innovative and well structured long term project on the market today, according to my opinion. Flymove Dianchè, acquiring the historical automotive design brand Bertone, developed a unique business model combining design and production of their own cars, solving standardization problems, with a smart mobility platform to recharge batteries and optimize energy flows.

**Figure 63.** Logo Flymove. Source: [40]

According to FlyMove Holding (UK), the Dianchè Smart Mobility Platform (SMP) is an innovative platform for sustainable mobility platform that today can be defined as unique in the world for the great advantages provided both in terms of optimization of energy consumption, environmental impact and user-friendliness. [40]

This platform is based on a battery swapping system which is advanced and reliable, with swapping time just around 30 seconds, eliminating the waiting times for the users. Space in streets and car parks are fully reinvented and optimized, a single station avoids the installation of thousands of charging points, in an aesthetic pleasant and non-invasive way. The stations is projected to automatically manage thousands of vehicles every day. The BSS system is unbeatable for structural, management, efficiency and speed, it is flexible and can be used in all areas of a Smart City as it is adaptable in different versions and sizes to specific positioning needs. Costs of construction and installation for stations of any dimension is extremely competitive if compared to the huge number of standard charging points required to build a capillary network. Energy required by the BSS is much lower with respect to energy required by fast charging and, what's more, we need to consider that timings provided by fast charging solutions are not as low as BSS and it is easier to use renewable energy source (e.g. solar panels) in case of BSS. [40]

A more general concept is the POE (point of energy), which is a station unique in design, functionality and technical characteristics, with a zero constructive and environmental impact. It is the operational center of vehicle charging activities, a multifunctional service station, where it will be possible to use the battery swap system for Dianchè-powered cars and to recharge electric or hybrid cars with a fast charging cable. It is also prepared to supply hydrogen for the mobility of the future.
This station is projected to self-generate its energy from renewable sources, perfectly in line with vehicles and mobility of the future. The POE exploits only bio-materials and recycle all your organic and inorganic waste. The POE station is also, to date, the only multifunctional road station in the world that also allows the operational management of e-VTOL aircraft for vertical mobility. [40]

These prototypes of stations will be available in different countries, from Europe to China and U.S., and will be fully configurable and adaptable for what concerns dimensions and location. The capillary network will eliminate range anxiety problem, optimize energy management and will give the possibility to users to make any long-range movement inside or outside the city. [40]

According to the company, these stations will be available in two main configurations, amall&medium for the cities and large for the main connecting roads and motorways. Flymove's CEO decalred that with only 16 stations positioned "star" on an urban surface equal to that of a city like Milan, it would be possible to guarantee energy coverage to more than 24,000 cars per day, using only 500 total batteries in stock.

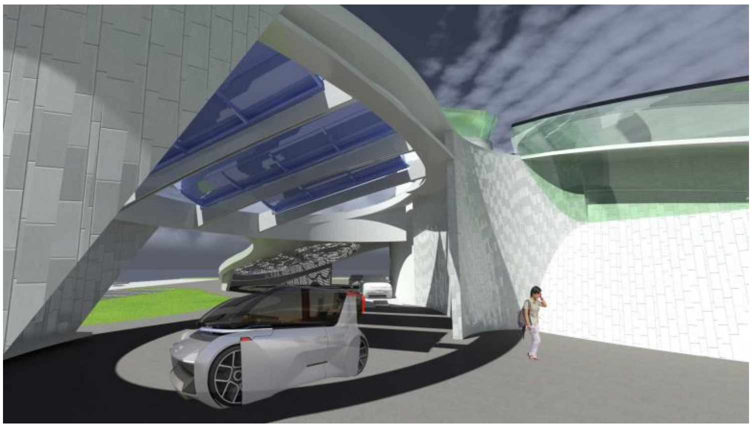


**Figure 64.** Flymovedianchè POE station rendering. Source: [40]

Among other services provided by this incredibly innovative company there is the POE mobile station to swap batteries, Dianchè BSS E-vtol (a flying concept for vertical mobility), Flymode Advantech to guarantee the completeness of the industrial chain and, finally, EVE. [40]

EVE is the new digital platform developed by Flymove to manage all vehicles and services connected to the Smart Mobility Platform. EVE uses the most advanced augmented and virtual user interface technologies, to offer full integration between the user, Dianchè vehicles, POE stations and service providers. The unique feature of its kind of EVE is that it integrates perfectly with two other 'environments' that are fundamental in a Smart City, namely the user's home - which will increasingly be able to generate its own renewable energy - and the system centralized citizen for the management of urban mobility - which must be optimized according to information provided in real time by Dianchè cars.

Actually, the company presented three car models, two city cars and an hyper-car. The Dianchè City Car BSS Cube impersonates the concept of urban mobility of the future. It is equipped with best technologies in the market and designed to be totally integrated with a smart city. Available in three modular seats, and soon also the five-seater version (also ideal for taxi fleets) it is configurable according to any need, ideal for family and work, for urban and extra-urban mobility. [40]

Dianchè cars are equipped for future autonomous driving systems and are connected to the EVE platform mentioned before. The operating autonomy is wide - about 200 km - thanks to the BSS rapid battery exchange systems in 3 minutes. With a 35 kW electric motor and a 30 kWh BSS battery, it reaches 150 km/h.

The Dianchè City Car BSS Cube will go into production by the end of 2020, will be sold exclusively through the Flymove online shop platform and, due to the fact the vehicle owner wll not buy the battery, its price will be extremely competitive. [40]

### Better Place

**Figure 65.** Logo Better place. Source: Better place

Probably this company represents the most iconic example related to battery swapping systems.

Better Place was a company founded by Shai Agassi in 2007, officially it was headquartered in Palo Alto in California, but most of the operations took place in Israel where both Agassi and the main investors lived. The company filed for bankruptcy on May 26, 2013 due to the financial difficulties caused by high investments required by their battery swapping system combined with a penetration level on the market far below expectations. Better Place raised approximately $ 850 million from private investors of the likes of Morgan Stanley, Israel Corporation, General Electric HSBC, announcing their intention to create a network of battery replacement stations in Australia, California, Canada, Denmark, Hawaii and of course Israel. [47]

The company's business model involved signing a contract for the purchase of mileage shares in a similar way to what happens in the mobile phone market where consumers sign contracts based on

minutes of conversation. Better Place's goal was to sell electric vehicles at a lower price than traditional motor fees (5000$ less in the US) as the monthly subscription would cover the costs of the battery pack and the energy together with those incurred by the company relating to the charging infrastructure and replacement plants, as well as costs related to maintenance, safety, battery life.
In Denmark, Better Place offered two tariffs, up to 20,000 km per year were paid from 199 to 249 € per month (2,388 - 2,988 € per year), while up to 40,000 km per year were paid 399 € per month (€ 4,788 per year). [49] In Israel, on the other hand, the car package plus the service of recharging and replacing batteries for three years was sold for $ 46,000 if they travelled less than 25,000 km per year. On a three-year basis it could have been a saving of 35% on fuel costs. You could also opt for a $320 or $470 monthly contract if you travelled less than 20,000 or 30,000 km respectively. [50]


Figure 66. Better place swapping station and operation. Source: [48]

The Better Place mechanism provided that the car entered a special corridor, similar to a car wash, where it was hooked up by special guides and an automated system then exchanged the battery pack, stored and recharged the exhausted batteries. The system designed by Better Place, however, had two major problems, firstly each exchange station cost $500,000 and secondly, the only model supported was the Renault Fluence ZE, over the course of six years in fact, the managers have not been able to convince any other manufacturer to design a compatible vehicle, partly also due to the particular shape and positioning of the used battery pack and despite the fact that during Reanult Laguna and specially modified Nissan eRogue, so it was a standardization problem again. A third problem of the Better Place business model is related to the global diffusion of its charging infrastructure. The strategy envisaged the simultaneous installation of exchange centres in different countries of the world very distant from each other such as Israel, Norway and Australia, thus losing the possibility of creating a network. [48]

According to Shai Agassi, CEO of Better Place, "his battery swapping stations would cost $500,000 to build, and that they would look like car washes." In spite of customer satisfaction, Better Place failed to gain much with general public and didn't have the support of car makers. There were less than a thousand cars on the roads of Israel and a few hundred in Denmark before bankruptcy was declared in 2013, surely too few to make business sustainable. This kind of innovation was probably ahead of its times. [47]

### Tesla

Figure 67. Logo Tesla. Source: [51]

Tesla's goal is to be able to sell an electric vehicle that can be purchased by the average consumer, but while waiting for the market to mature and for battery prices to decrease, it is pursuing a strategy typical of consumer electronics by marketing high-end products. aimed at market pioneers, leaders and trend setters.

Tesla's business model has several peculiarities, one of which is to sell their cars directly from their showrooms and online, unlike other car manufacturers who instead rely on dealerships and car showrooms. On a technological level Tesla claims to have a cost advantage over one of the fundamental elements for an electric vehicle, the battery pack. J.B. Straubel, chief technical officer and co-founder of Tesla, says that their battery costs could be half or even a quarter of the average in the sector, mainly thanks to the strategy of using thousands of common batteries rather than battery packs specialized as other players on the market do. [32]

In June 2013 (about a month after Better Place filed for bankruptcy), Tesla presented to the public its battery swapping mechanism capable of replacing the battery pack in about 90 seconds and declaring its intention to install one at each charging station.

They setup Battery Swapping Stations at a custom-built facility at Harris Ranch in Coalinga (Calif), each station is expected to cost around $ 500,000 and have nearly 50 batteries available without a reservation. The service should be offered at a price between 60 and 80 dollars. [32]

The replaced battery can be recovered on return by paying the exchange fee again (including energy for full recharge) or you can choose to keep the new battery by paying a difference based on the difference in age or based on the difference in capacity if you switch from a 60 kWh battery to an 85 kWh battery. A second possibility of the Tesla model provides that the old battery is sent to the home of the user who made the exchange by paying the transport costs. Musk, Tesla's CEO, during a meeting with the company's shareholders, opened the possibility of installing replacement stations within urban contexts where it is difficult to find charging stations such as central London. It then left open the possibility for third parties to create battery replacement centres for Tesla vehicles as long as they are able to maintain the same level of service. One of the main differences with Better Place's business model is that Tesla is a vehicle manufacturer, and it is from this activity that it derives its profits while Better Place was focusing on battery rents and power supply. Where the Israeli company saw Battery Swapping as the core of its model, Tesla sees a sales support service for its cars, therefore it does not want to generate profits from Battery Swapping itself, which indeed could represent a cost, but wants to create a functional ecosystem for its electric vehicles in a similar way to what Apple did with the creation of iTunes for the iPod.

However, the Tesla system has a problem in common with that of Better Place. Both systems are designed to serve a single model of cars or better batteries. The Tesla Model S was designed from the outset to be compatible with the battery pack replacement mechanism, but this occupies the entire floor of the car making the whole exchange system linked to that system. They accommodated Model S Owners driving between Los Angeles and San Francisco. [32]

There is therefore no flexibility that could allow the use of Battery Swapping stations by different car models and in fact also Tesla's next car, Model X, will share the same platform together with 60% of the Model S’s components. An unclear point of the Tesla model is related to battery recovery once it has been changed. In fact, if you decide to return to your home without recovering the old battery, it is sent home, but Tesla has not specified how the user could reassemble the battery on his vehicle instead of the exchanged battery. [32]

Another problem was that people don’t care about pack swap and the availability of free superchargers right across the street made its diffusion much more problematic.

### Ecospazio

**Figure 68.** Logo Ecospazio. Source: [52]

Ecospazio is the division dedicated to charging systems for electric vehicles of Logiss Srl, an Italian company based in Rovereto, leader in the sector of design and construction of warehouse handling systems. It has already created a complete range of products for charging electric vehicles such as photovoltaic shelters, columns for charging bicycles, scooters and electric cars, cyclo-stations for charging and bike sharing.

Taking advantage of the know-how of the parent company in the field of industrial automation, it has designed a fully automated station for the exchange of batteries for electric cars with an attached storage warehouse for recharging called Energy Exchange Station (EES). [32]

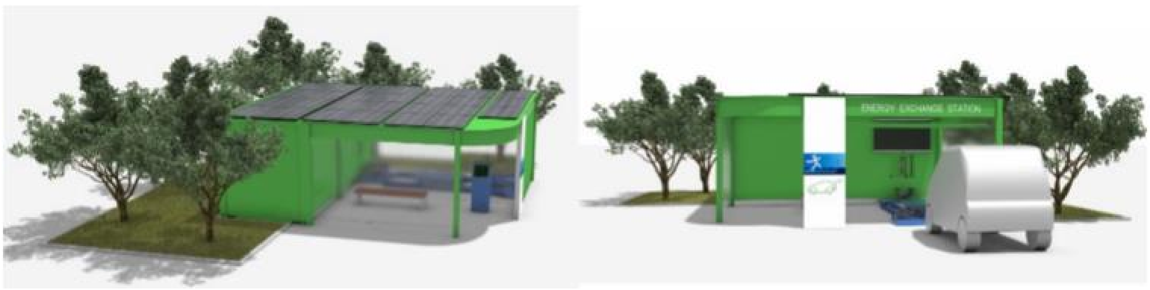


**Figure 69.** Rendering of an Ecospazio BS station. Source: [52]

The Ecospazio station has been designed with ease of installation and transport, it is in fact equipped with identical attachments to the containers and is therefore transportable by truck or by ship, it does not require construction works for placement, nor any special permits construction as it is not fixed to the ground, it is ready for use in less than two days of work. It is available in two versions, from 51 square meters (20 feet) with 54 batteries or double storage, that is, from 102 square meters (40 feet) with 120 batteries storage. It can be divided into two areas, one dedicated to battery pickup / deposit and one dedicated to waiting with a refreshment corner. It is also covered with customizable panels on request and is constantly monitored by remote assistance. The 51 square meter version costs € 250,000 and the exchange takes about 3 minutes. The goal of Ecospazio is to spread a standard format of batteries that can be used by several car manufacturers so that they can then use their exchange stations and therefore make the whole sector benefit from economies of scale and the possibility of restoring the autonomy of electric vehicles as quickly as possible. To achieve this, Ecospazio executives had made contact with Renault after Better Place's bankruptcy by offering it to take over the Battery Swapping service for Fluence Z.E., but the French company is not willing to continue on this path. The company has therefore developed a strategy that envisages market penetration through the marketing of two electric vehicles, both produced by GSLMotors srl, also based in Rovereto. Ecospazio's business model provides for the direct sale of vehicles, including batteries, plus a fee for any replacement of the battery pack. [32]

### Greenway Operator

**Figure 70.** Logo GreenWay. Source: [53]

Greenway is a company based in Bratislava in the Czech Republic that operates in the B2B electric mobility sector. Its business model is based on the long-term rental of light commercial vehicles (Citroen Jumper with an autonomy of 200 kilometres) to freight transport and delivery companies, couriers and logistics operators. Upon payment of a monthly instalment calculated on the basis of the kilometres actually travelled, GreenWay covers the rental of the vehicle, the supply of electricity, the use of the Battery Swapping infrastructure, online monitoring, maintenance and other costs related to the vehicle such as insurance and property tax. GreenWay's goal is to provide a service that can easily get around problems related to electric mobility or high purchase costs, anxiety about autonomy and the lack of recharging infrastructure. GreenWay takes charge of providing the client company with a semi-automatic battery replacement station. [32]

Unlike the cases seen above, it is in fact necessary for a duly trained operator to recharge by replacing the exhausted battery pack, placed inside the vehicle compartment, with a load taken from a cabinet, with the aid of a special forklift. charging station placed at the customer's site. The batteries occupy about 1 cubic meter and a trained operator is able to perform the exchange in a time varying between 5 and a half minutes and 7 minutes depending on the skill. [32]


**Figure 71.** GreenWay's vehicle battery pack substitution. Source: [53]

GreeenWay offers two packages, the GW70 and the GW40. The first costs € 20.040 per year and covers up to 70,000 kilometres, an unlimited number of battery replacements and of course the rental of the vehicle together with all related costs and assistance. The second costs € 15.240 per year and instead covers up to 40,000 kilometres, all costs related to the vehicle, its rental and assistance, but a small amount must be paid for each battery replacement. [32]

If the odds of kilometres of the package were to pass, 0.13 cents will have to be paid for each extra kilometre (GreenWay s.d.). GreenWay's Battery Swapping system is designed to serve only the rental vehicles with its program and overall it is a well coordinated system because it manages to create that ecosystem capable of providing the customer with everything he needs. It is important to note how GreenWay manages to provide stations for Battery Swapping to each individual customer thanks to the fact of renouncing automation by focusing instead on a manual replacement. [32]

Kandi

**Figure 72.** Logo Kandi. Source: [54]

Kandi Technologies Group is a Chinese electric vehicle manufacturer led by CEO Xiaoming Hu who bases his business model for electric cars on short-term rental and car sharing. To support its business model and to overcome congestion problems and limited parking spaces, Kandi has designed an automated garage similar to a vending machine, in which vehicles are stored vertically in a building that can accommodate from 30 to 300 vehicles. The customer who needs a car can go to these buildings and rent one for 20 yuan per hour, around € 2.40. Kandi also offers the possibility of a long-term rental up to a maximum of three years or 60,000 kilometres with the payment of a rate that varies from 130 to 160 dollars per month and also covers insurance, maintenance and electricity costs. [32]

However, as Chinese customers may have some difficulty installing a column for home charging, Kandi has put in place a quick battery replacement system called Quick Battery Exchange (QBEX).

**Figure 73.** Kandi's Quick Battery Exchange and a mechanical automated arm's operation. Source: [54]

The system developed by Kandi provides that the batteries can be extracted laterally from the vehicle with the help of an automated mechanical arm which will deposit the exhausted batteries in a charging cabinet from which it will then take the charged batteries and reinsert them in the vehicle where these will engage thanks to the interlocking connectors. Each vehicle is equipped with two batteries with a total capacity of 14 kWh which can be extracted separately. Both the innovative car sharing system and the battery swapping stations were initially installed in the city of Hangzhou where they receive the support of SGCC (State Grid Corporation of China), the producer and distributor of 80% of the national energy, the most of these stations will also be used by a taxi fleet. Kandi's business model appears to be well-conceived, the possibility of renting vehicles through car sharing is probably the most suitable for the Chinese market, in particular for the population groups that have not yet gained the opportunity to buy a car. Of particular relevance is the use of two batteries for each vehicle instead of a single battery. In fact, this system leaves open the possibility of designing new vehicles, but of different sizes which nevertheless use the same type of batteries, but in greater numbers or with a different arrangement. The Quick Battery Exchange system designed by Kandi appears much less expensive than those designed by Better Place, Tesla and Ecospazio, in fact, no special structures, bridges or trolleys are needed, but a mechanical arm and a cabinet for recharging the batteries are sufficient exhausted. [32]

### BSS strategy advice

To avoid bankruptcy as in case of BetterPlace it is clear that a wise planning on the number of stations, locations and cost per station needs to be performed. A pilot project may be introduced in order to test the impact on consumers with basic automated stations without other complementary services or particularly expensive design. In the future, in case of positive impact, the stations may increase in number, performances, design and service pack.

Their installation should take place near the arteries that connect the suburbs to the city in order to be visible and usable by the commuters who travel through them every day. These are those who would benefit most from the purchase of an electric vehicle as they travel a higher mileage and are therefore more sensitive to the price of fuels. In addition, exposure to road traffic would represent an important factor in increasing customer awareness. The autonomy of an electric car should still be sufficient to cover common mobility needs, but the presence of a Battery Swapping station on busy roads should have a calming effect on range problems. Battery exchange stations would in fact become important marketing tools by communicating, simply with their presence, the overcoming of the problem of limited autonomy. In fact, the average consumer does not really need it, being able to safely cover the daily distance with a full charge, however the presence of a Battery Swapping station communicates the possibility of quickly restoring autonomy in case of need.

If Battery Swapping stations in an urban context would primarily serve as marketing and communication tools, they prove to be necessary in an extra-urban context. They are in fact indispensable along the motorway routes to allow electric vehicles to pass from one city to another. Tesla with its supercharger network is the example to follow in this field.

The positioning of the Battery Swapping stations should in fact take place in order to create corridors passable by electric cars where they can stop and quickly restore their autonomy and then continue their journey. The spread of stations on motorway routes should take place gradually and coordinated with the installation of stations in an urban context in order to concentrate marketing and communication activities in the cities already served.

# 4.3 Batteries main features

Clearly in a swapping system everything is about batteries. It is very important to understand how batteries are classified, composed and evolved in order to address some critical issues to enable a BSS project, like their modularity useful for standardization and compatibility.

## 4.3.1 Classifications

Battery is the energy source of the electric vehicle as well its main component under many perspectives. It provides power to the electric engine. The battery charging, discharging, control strategy and operations are all managed by the so called battery management System (BMS) which is trying to discourage wrong behaviours, protect the battery, monitor its working process and reporting data in order to preserve its state of health and range.

Many players decided to adopt similar solutions for batteries, however many possibilities are present on the market.

**Technologies**

Batteries, besides being so important, are also the most problematic components in the electric vehicles in terms of weight, price, capacity, lifetime, electrical parameters and dimensions. However, in the last ten years this sector evolved a lot and huge innovations shaped the market. An enormous progress has been made in terms of dimensions, weight and density of energy stored. Forecasted progress for the next years is not going to slow down in terms of materials and processes, even if a physical/chemical limit is going to be reached.

Nowadays we can identify the following battery technologies:

- Nickel-Metal Hydride batteries (NiHM)
- Sodium-Nickel Chloride batteries (NaNiCl)
- Lithium-ion batteries (Li-Ion)
- Lithium-Metal Polymer batteries (LMP)
- Zinc-Air batteries (Zinc-air)
- Lithium-Sulfur batteries (Li-Sulfur)
- Lithium-Metal-Air batteries (Li-Oxygen)
- Lithium-Air batteries (Li-air)

<u>Lithium ion batteries</u>

Lithium ion batteries are today considered as the standard battery technology/typology for electric vehicles' application. There are many types of li-ion batteries with different feature, even if longevity remains the most appreciated one. This battery type can be designed using various cathode and anode materials such as lithium titanate, lithium-cobalt or lithium-iron-phosphorus. Many benefits, compared to other solutions, justify the choice. The main advantages are:

- Very high specific energy and density
- Extraordinary retaining energy

- Performing charging cycles
- Lifetime

There are also some odds in the adoption of these batteries. Among them it is possible to identify some safety issues regarding overcharging and overheating and also their price. Anyway, great efforts have been made in the last years in both directions. [55]

In Figure 74. the results of a research conducted by BCG group [56] are highlighted. A 5 dimensions comparison of the principal Li-ion battery technologies are presented, in order to opt for the best trade-off possible.

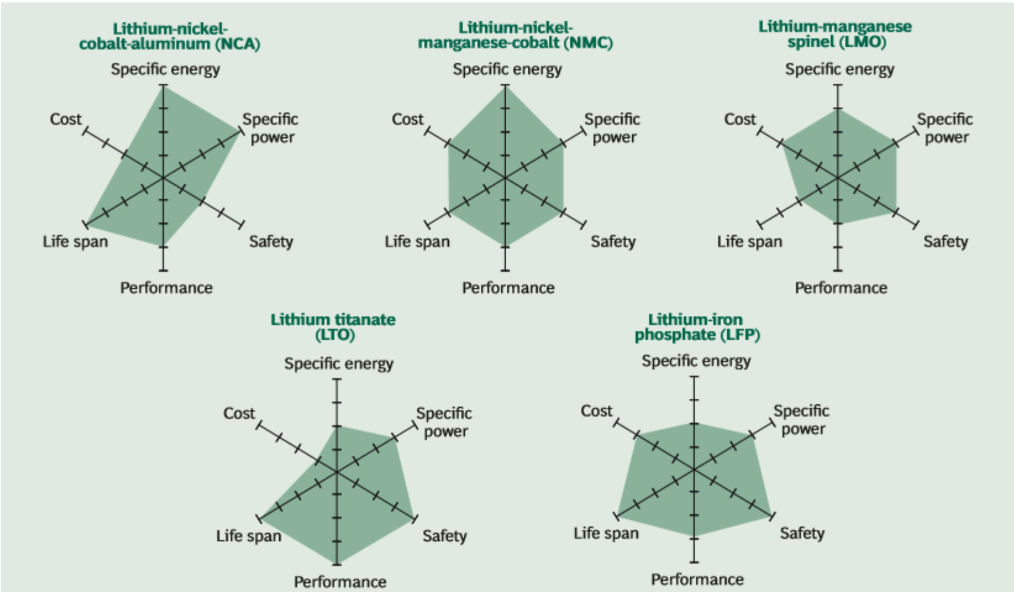



**Figure 74.** Trade-offs among the five principal Li-Ion Battery technologies. Source: [56]

Future developments will still focus on increase of energy storage capacity, high current charging and extended range (lifetime).

Lead acid batteries and Nickel-Metal Hydride batteries

These battery technologies today are considered to be mature and obsolete for the purpose of today's full electric vehicles. Lead acid batteries are quite inexpensive and were commonly used on traditional ICEs powered vehicles. Some of their features and performances make their usage very little adequate in electric mobility, in particular these batteries have poor specific energy.

NiMH batteries, instead, have more than double the specific energy compared to lead acid ones and energy density, this allows them to be lighter and require smaller spaces. They can be used for these reasons on EVs, however the drawbacks are not absent. The main issues regard charging and discharging efficiencies which show bad performances, particularly in hotter environments. [55]

There are, however, other types of batteries under study such as metal/air batteries capable of storing a greater amount of energy and this would lead to greater vehicle autonomy. However, these types of batteries are not rechargeable even if research is being carried out to enable this possibility. Another technology being studied are graphene batteries, which thanks to some properties of this material should be able to accumulate greater quantities of energy and speed up charging times.

Another classification can be done according to the physical state.

Solid state batteries

Evolution of lithium-ion batteries, solid-state or lithium-polymer batteries use a solid rather than liquid substance as an electrolyte. This solution increases the energy density of the battery, consequently increasing its ability to generate energy compared to the size (we speak of performance that can reach + 50%). This characteristic translates, in the automotive sector, into the ability to travel the same number of kilometres with smaller batteries or with less charged batteries. Among the advantages, also the fact that this type of battery is much less flammable and allows greater freedom in the organization of internal spaces, allowing for example to create very thin modules. Finally, solid-state batteries manage to contain temperatures even better. They were first used on a large scale by Tesla, which was specially developed by Panasonic. However, many houses are following this direction. These also include Volkswagen, Toyota and BMW. [57]

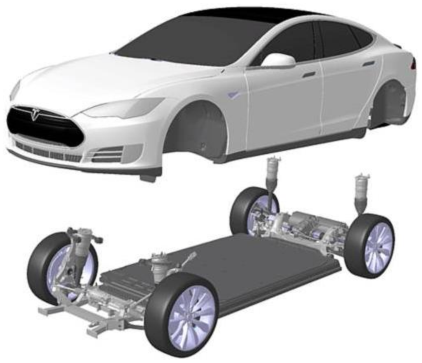


**Figure 75.** Tesla’s example of solid state battery usage. Source: [57]

Liquid refill batteries

Numerous batteries are in development that aim to win the race for electrification, guaranteeing ever greater performance. Among these, the one developed by the Bolognese start up “Battery” is particularly interesting. It's called Nessox and it is a battery that recharges in a certain sense "filling up" just like on a petrol or diesel car. The difference lies in the fact that to recharge the Nessox battery you have to fill up the liquid that it uses internally to start the production of electricity. A particular liquid which, once exhausted, can be replaced by another liquid capable of "recharging" the battery with an operation which, once the procedure has been finalized, will take a few minutes. [57]

### Format

As I said before, batteries for recent EVs mainly rely on Li-ion technologies. Main variations are linked to the cathodes used and the cells’ size.

Small-format cells

This kind of cells have been produced on large scale for almost thirty years and and are mainly used in consumer electronics. Tesla, for example, exploits this kind of cells using a combination of cathode materials typical of consumer electronics. In order to make these cells performant an advanced cooling system and battery management system to monitor the temperatures are required, because the presence of cobalt increases the risk of overheating. In fact, Tesla from the beginning decided to design and its own proprietary cutting-edge technology for cooling and BMS, producing and licensing it to other big players. [5] The market today seems to be moving more towards this technological solution.

Large-format cells

This format has always been preferred by the majority of car makers who started producing electric vehicles. They imply lower energy density and higher prices (since less economies of scale can be exploited) but they are potentially far less exposed to overheating problem.

Many cathodes solutions have been tested for these batteries ($LiMn_2O_4$, $LiNiCoAlO_2$, $LiFePO_4$…), everyone with pro and cons. [5]

It is easy to understand that technical solutions are multiple and choice is not easy, many players tried to impose their standard. In many cases the competition just waited to follow the market innovators and leaders while in other cases some players explored innovative solution (more or less efficient and successful). Car manufacturers feel the pressure of the major choice about vertically integrate the production of batteries as Tesla first did of to outsource it and partner with battery suppliers. Any of the choices is able to drive the progress and development of battery packs' technology.

Charging procedure

We already know that three main modes are available to replenish electric vehicles: normal charging, rapid charging and swapping. Key notions about these modes have already been provided in Chapter 3.

However, it may be useful to report some information about connectors and standards. In the last years many typologies of inlets and connectors have emerged globally. In order to ensure interoperability and compatibility, today charging stations and electric vehicles are providing different plugs, connectors and adapters.

For slow AC charging the EV is connected to the grid via a regular socket/outlet or dedicated wall box. Instead, if the vehicle is equipped for DC rapid charging, particular connectors are required for high power ratings.

The most diffused standardized connectors in charging stations worldwide are CHAdeMO and CCS. In Europe the Combo2 standard is the most used connector and plugin solution, allowing for both AC slow and DC fast charging modes.

## 4.3.2 Standardization and modularity

### Vehicles evolution

Evolution and changes are not affecting just the business models, value chains and players' roles but also the vehicle architecture itself. In fact, vehicles are evolving not just in the propulsion but also in dimensions and package.

The classical cars' parameters are changing or revert their tendency. As we already know, the main component is no more the engine but the battery, no more the propulsion but the range (50% of vehicle cost). The battery pack is composed by N modules, made again by N cells. Being really modular, the pack is easily scalable and customizable. In an electric vehicle design the starting point is always represented by this core around which the whole car is built. Almost all car makers are today using the same modules and cells conformation, this implies a certain uniformity of the central block in which the only thing changing is the number of modules defining the pack and, as a consequence, car autonomy. Here a breakdown in percentage showing how the space in a vehicle is occupied according to the powertrain and, consequently the whole vehicle architecture. [26]

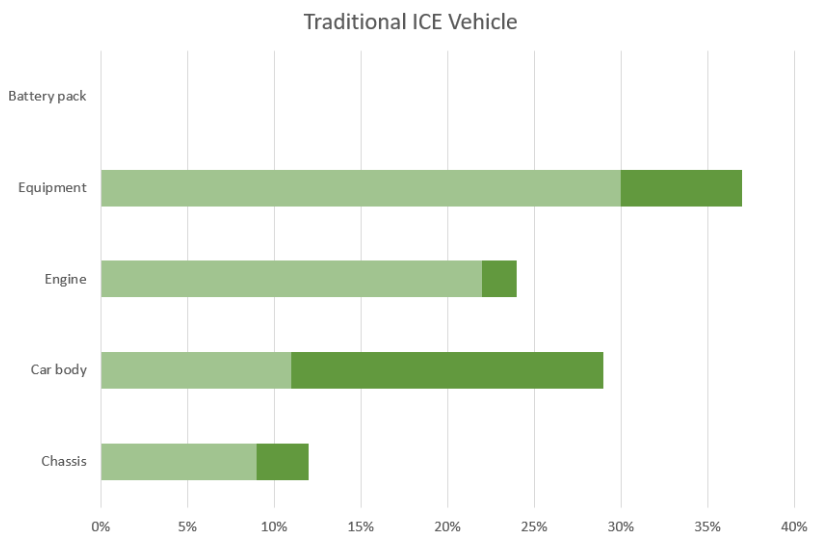



**Figure 76.** Traditional ICE vehicle occupation of space. Source: [26]

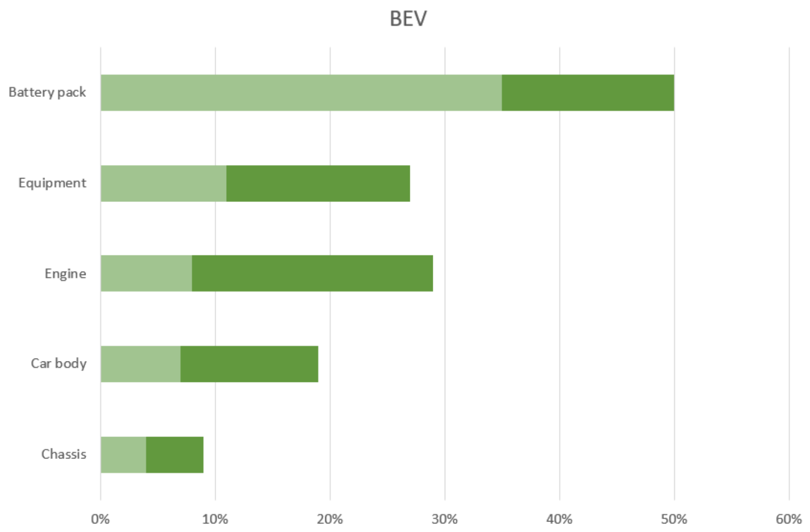



Figure 77. BEV occupation of space. Source: [26]

According to a BGC 2018 report, "current industry benchmarks suggest that the electric powertrain (including the electric motor, power electronics, and battery pack) will account for at least 50% of a BEV's cost. By comparison, the ICE powertrain typically accounts for approximately 16% of a traditional vehicle's cost. The battery pack (including the battery management system) is the major cost, accounting for about 35% of the overall vehicle cost." Surveys conducted by BCG itself suggest that "purchasers want to break even on the higher purchase price of electric vehicles in three years." [58]

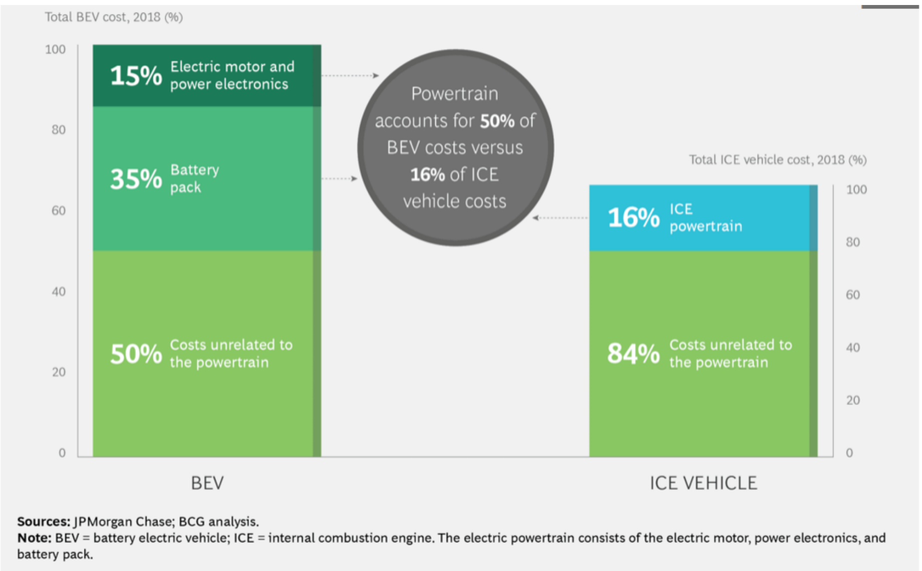



Figure 78. Total BEVs cost broken down. Source: [58]

Today in most of cases the market for battery still demands automotive starting batteries, computer batteries or cell phones batteries, however EVs batteries' interest in growing fast. Reliability and costs are the keys for the success. Besides chemistry innovation, also innovations in manufacturing for mass production are required. The cells of a battery are the essence, starting point to define its own future applications but it is the packaging that mostly impacts on performances like lifetime, cyclability, ruggedness, safety and – most of all – cost. [59]

## From Cell to Module and from Module to Pack

Starting from the simplest concept, a battery cell is the basic unit of a lithium-ion battery that exerts energy by charging and discharging. It is made by inserting cathode, anode, separator and electrolyte into a rectangular aluminium case. Cells are the most cost-intensive component, representing approximately 70% of the total cost of battery packs.

Three main typologies of cell design have evolved for being suitable for electric vehicles, and each design has advantages and disadvantages:

- Pouch cells (High density and low costs but complex integration process and cooling issues)
- Cylindrical cells (simple, low cost and high energy density but complex integration and high safety hazard)
- Prismatic cells (High energy density, low safety hazard and integration costs but higher production costs)

Prismatic cells are the most exploited in automotive market and this trend is expected to go on in the future too. [58]

The wording "battery module", instead, is usually only used associated with high-power batteries. It describes "an assembly of fixed cell packages, safety features like temperature, voltage and charge monitoring, as well as a battery management system (BMS), cooling / heating system and a base plate or housing, all put in a frame in order to protect the cells from external shocks, heat or vibration." A module is usually composed by six to twelve cells.

Single cells can be connected in series or in parallel to constitute the configuration. BMS is really important in the module because it provides insight already at cell level to monitor, prevent unsafe usage modes and react as a consequence.

The battery pack instead is the final shape of the battery when it is ready to be mounted on the electric vehicle and it is an assembly of modules and various control/protection systems. The battery pack influences the whole design of the EV as well.

Standardization is easier to obtain at the module level since the packaging is part of the unique design of each battery producer or car manufacturers integrators. The attempt to standardize the module is related to having defined dimensions and interfaces, with different number of modules put together to be exploited in several applications. This would favour economies of scale as well. Battery cells instead (chemistry and shape) would not be standardized. In this scenario differentiation is hindered but producers would have a larger client base and could focus on efficiency of production and economies of scale, this leading to reduction in costs and in investment risk. [59]

## EV battery market, towards a competition of "Module & Pack"

The major trend shaping the battery producers' market is developing batteries with the highest safety degree first and density of energy second. In this scenario a competition of "module and pack" is very fierce.

Usually even carmakers who decided to outsource battery production to external providers, perform modules and packs assembly "in-house" in order to adapt its design, spaces and cooling system to the whole vehicle itself. [58]

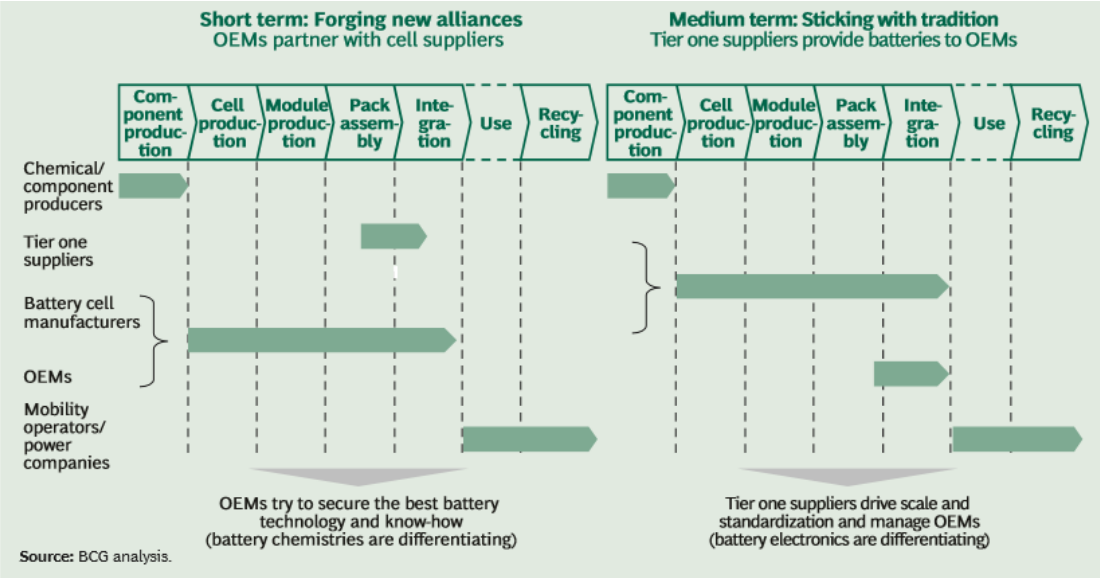



Figure 79. Alliances trends evolution. Source: [56]

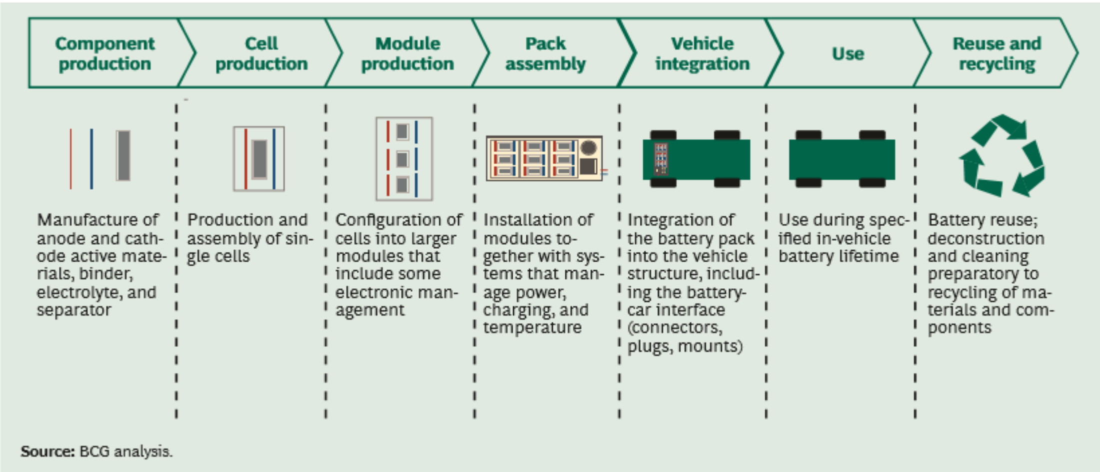



Figure 80. Value chain for EV batteries. Source: [56]

A research conducted by BCG in 2018 [58] reveals that battery cell producers are producing massive amounts to exploit economies of scale, however this will lead to an overcapacity problem that will imply price reductions to use the full capacity. According to BCG, "the global capacity for battery cell production will exceed market demand by approximately 40% in 2021 (in China, this figure will exceed 60%)." The unique solution to this problem is to improve the operational efficiency by switching to factories of the future. Only automakers relying on industry 4.0 technologies will be cost competitive before 2030. The biggest share of the market demand will come from BEVs: BCG forecasts that "the annual demand for battery capacity will increase from 70 gigawatt hours in 2017 to 800 to 900 gigawatt hours in 2030."

Price reduction anyway is an almost unavoidable consequence and according to BCG prices will reduce by more than 50% by 2030. This will lead to cost parity of BEVs with respect to ICE vehicles, increasing sales and reducing in the long run the discrepancy between supply capacity and market demand. [58]

As we said to solve the problem battery producers should focus on reducing production costs which accounts to 30%-40% of cell costs. Factory of the future concepts' applications can reduce costs not just at the cell level but at whole battery level.

To better understand how this is possible, in Figure 81. are reported the three main steps composing the battery cell production process with all their sub-processes, highlighting the cost share and the main challenges. BCG here assumes that the prismatic cells will be the dominant design. [58]

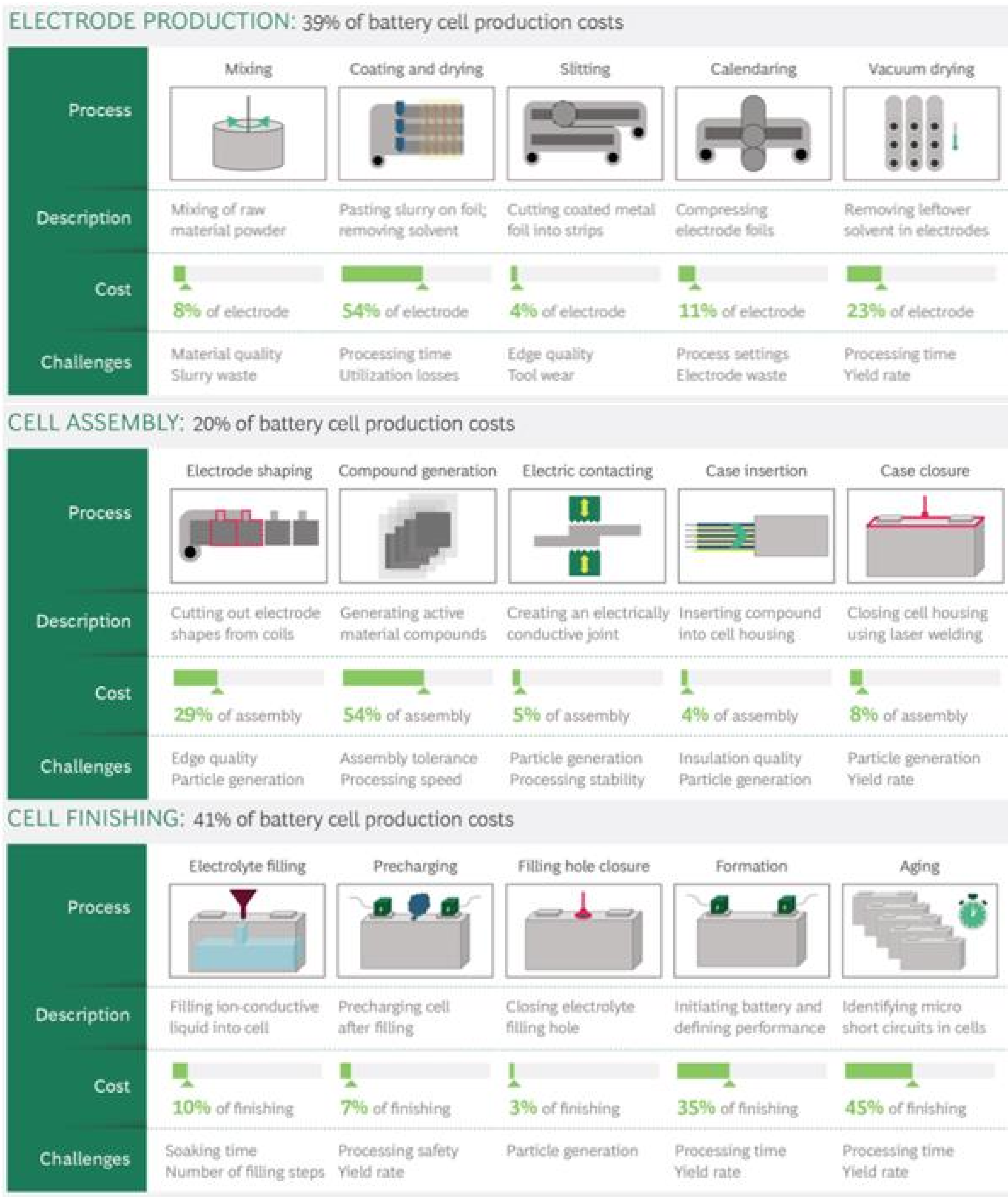



**Figure 81.** Battery cell production process. Source: [58]

Thanks to the passage to a factory of the future, according to BCG, "it would be possible to reduce battery cell costs per kWh od capacity by up to 20% and the production-related costs (excluding materials) can be reduced by 20% to 35% in each of the major steps of battery cell production." Moreover, an improvement in cell level energy density is expected around 10%-15%. These best practices may provide benefits also if applied to module and packs integration. [58]

## Final remarks related to Battery Swapping

Today cars are moving more and more towards an architectural innovation, making them increasingly modular and configurable products, more similar to a PC rather than the old concept of car.

Standardization problem is faced with different approaches around the world, in China for example the battery swapping solution, after a slow down period, is coming back in trend. Chinese government urges car manufacturers to work towards a single standard for car batteries, in order to guarantee a high percentage of compatibility among BEVs with respect to the BSS infrastructure, being it able to recognize and operate on a limited number of battery typologies (sizes mainly). If a too low number of vehicles adopt these compatible batteries then the BSS turns out to be useless for the market as a whole, commercially speaking. [39]

By standardization we mean that all battery packs must be of the same size and shape or, at most, in few possible configurations so as to be able to build Bs stations able to recognize them and perform a correct swap (it would be otherwise impossible without an almost complete standardization).

The debate on battery standardization is also open in Europe. But the opposites more than outweigh the favourable ones. In fact, batteries are key components in the design of electric cars. Standardizing them would mean giving up any possibility of diversifying and characterizing the various models, performance and market segment. In addition, the world battery industry would end up being monopolized by Asian manufacturers, already equipped to produce them on a very large scale.

According to the words of the vice president of Mercedes, the manufacturers are not willing to adopt a common and shared standard for safety and responsibility problems. However, car manufacturers already resort to modular design, with some common components between models of different brands.

Analysing the market, it is noted that it is common practice to place the batteries on the car floor and under the seats for weight distribution, dimensions and practicality. However, since each battery pack is different, it would be expensive to create a network of replacement stations equipped with the different models. In order for a network of Battery Swapping stations to spread, able to quickly restore the charge and therefore the autonomy of electric vehicles, it is necessary that a common standard is spread that is able to guarantee the necessary flexibility in the design phase in order to be able to be adapted to the different types of cars offered on the market by the various car manufacturers. A single battery would not be able to adapt to the different dimensions of the vehicles and it is therefore necessary to resort to a smaller battery, possibly usable in greater numbers in larger vehicles. A strategy of this type has already been adopted by Kandi, for his cars he uses two identical 7 kWh batteries each. More compact vehicles will use fewer batteries, while larger vehicles will use the larger surface of their platforms to accommodate a larger number. In the diagram proposed below it can be seen how a standard size battery could be used in vehicles of different sizes. [32]

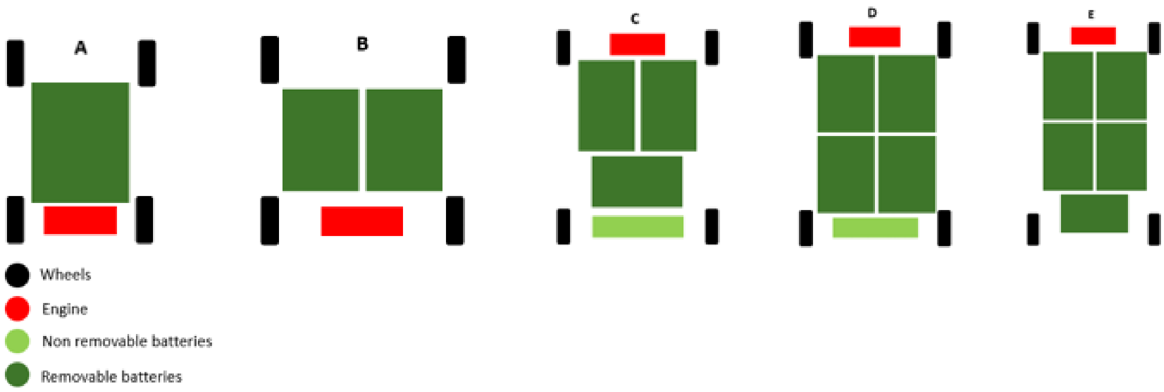



Figure 82. Modularity scheme for the battery pack. Source: [32]

It would be enough for industries to come together to create a standard form at that point each car as needed could mount more modules in series or in parallel according to the needs (heavy cars will need to mount more modules in series to increase the voltage, lighter cars will be able to install them in parallel to increase the autonomy) at the same time the use of a module could allow to place elements in different points of the car with a double effect of optimizing the available spaces and distributing the weight. so that they can also be handled by human personnel (batteries weigh quite a lot). at the end 150Kg of battery divided into 15Kg modules could be installed in less than 10 minutes. And this would avoid the need to create too stringent standards especially at this stage.

Case "A" represents a very compact in-line two-seater vehicle such as the Renault Twizy or another similar vehicle. The dimensions of the vehicle allow the use of a single battery. The case "B" refers instead to a two-seater vehicle such as the Smart Fortwo or a microcar, the greater width of the vehicle allows for two batteries. The cases "C" "D" and "E" refer to vehicles of larger dimensions that can carry a greater number of replaceable batteries and possibly also host non-removable batteries to take advantage of spaces that cannot be used by those compatible with Battery Swapping.

With the adoption of this solution, vehicles of different sizes could therefore go to the same replacement centre, make the exchange by regenerating their autonomy in a few minutes and restart leaving the batteries to recharge at the exchange station. With the presence of several batteries on board, the Battery Swapping could also be only partial, that is to say replace the discharged batteries and leave the charged ones on the vehicle instead. [32]

The design freedom of the houses would still be guaranteed by the flexibility that a modular solution allows. Even if manufacturers like Mercedes have declared themselves opposed to a vision of this type, it is likely that once a charging infrastructure has spread, they give in to the idea of adopting the common standard in order to give their models the opportunity to recharge at the Battery Swapping stations and not to suffer from competitive disadvantages.

# 5. Case study

Here the attempt is to apply in a more practical way most of the concepts highlighted and reported in the previous chapters. The chosen sector is the commercial transport, in particular the commercial heavy-duty road transport (i.e. the heavy trucks) for long - hauls. There are a few different categorizations (both national and international) according to different parameters like loaded and unloaded mass of the vehicle or number of axes, thus leading to different road regulations and licences.

## 5.1 Commercial road transport – Heavy truck case introduction

The commercial road transport category includes fleets composed by light, medium and heavy (trucks) commercial vehicles.

Let's start to introduce and contextualize this market.

According to ISTAT and ANFIA annual reports, the transport and logistic sector has a really important role in Italian economy, ranking Italy among the most competitive players in the road transportation and logistic sector in Europe. The numbers behind it tell us that, in 2017, the commercial road transport reached 885,5 million tons transported, 119,7 B tons*Km with 7,75 B vehicles*Km. Part of these transports are national, in particular the 89% happens inside out country, among them 59% is composed by trucks, which, in the almost half of the cases are travelling for more than 300 kilometres (49%).

Putting together all these key pieces of information we can conclude that the total number of vehicles used for transportation is around 57.33 million in 2017 and around 0.26 of these vehicles is composed by trucks covering more than 300 kilometres inside our country, 14.75 million. [60][61]

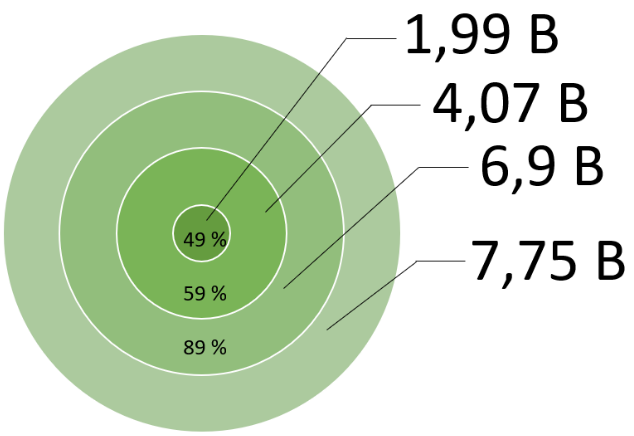



**Figure 83.** Italian truck market circles. Source: Personal elaboration

It is quite interesting, however, to underline how in the ten years going from 2008 to 2017, traffic flow for goods (freight) in Italy, decreased year on year. In 2008 this value amounted to 11,196 million vehicles kilometre, while it slowed down to 7.975 in 2012, registering a decrease of -29 % and, finally, to 7.754 in 2017 with a – 3 % with respect to previous measurement.


Figure 84. Commercial traffic flow in Italy, 2008-2017. Source: Personal elaboration

Analysing the new registrations of vehicles in Italy, for what concerns medium and heavy trucks (i.e. trucks able to load at least 3500 kilograms inside), a positive variation of + 5.1 % is registered from 2017 to 2018, moving from 24.347 to 25.582 trucks. [61]


Figure 85. Heavy trucks new registrations in Italy, 2017-2018. Source: Personal elaboration

It is pretty intuitive that the increase in trucks registrations year on year, a well as the general relevance of the heavy commercial transport sector in our country, raise great attention and concern on the environmental issues coming mainly from CO2 emissions and, as we already mentioned in the first chapter, all the problems related to traditional mobility as it is. We know that transport sector in EU-28 (see image below), takes 32% of the total CO2 emissions, by breaking down this slice we focus on road transport, responsible for 73,2 % of transport CO2 emissions. A further breakdown of the road transport highlights that heavy trucks represent 25,8 % of road transport CO2 emissions. In the end, what comes out from this view, is that heavy transport in Europe is responsible for around 0,22 GtCO2. [62]

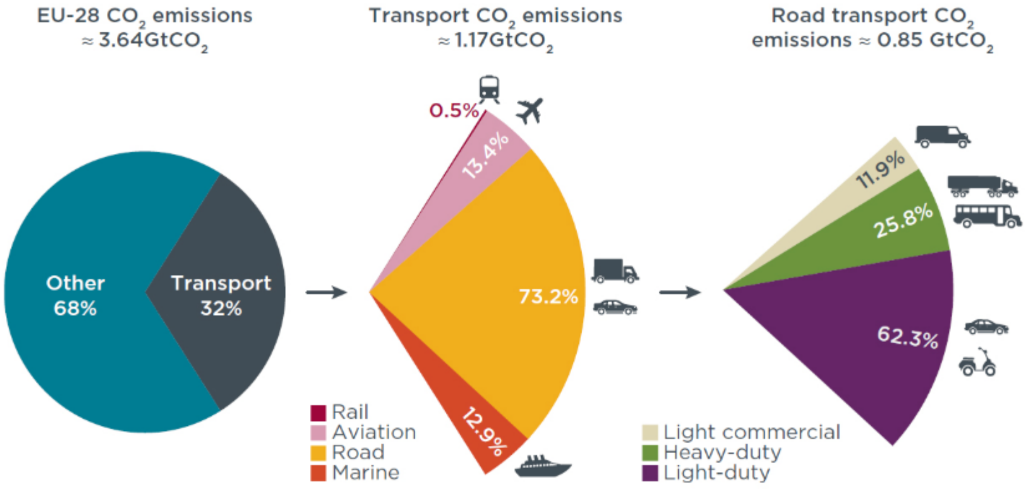



Figure 86. CO2 emissions in Europe by sector, 2018. Source: [62]

So, to reduce emissions and solve the mobility issues a lot of attention must be paid to heavy transport sector. Obviously incremental improvements in traditional engines for truck (ICE, gasoline or diesel) are no more sufficient, a more radical change is required and it is actually taking place, even if a slower rate in Italy with respect to other countries in the world. The images below, courtesy of a specialized sectorial blog, show how the fuel consumption evolved in the time period 2002-2016 for the main truck manufacturers, highlighting a quite flat trend, that means no big efforts have really been made to reduce it. On the contrary, the second image, puts evidence on how the fuel emissions are required and forecasted for the next 10 year (2035 horizon) due to stringent policies in each country. [62]

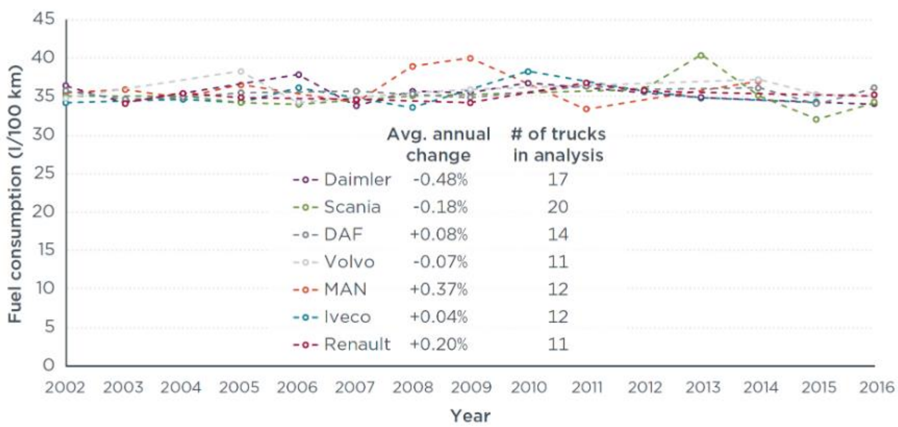



Figure 87. Fuel consumption by truck manufacturer, 2002-2016, Source: [62]

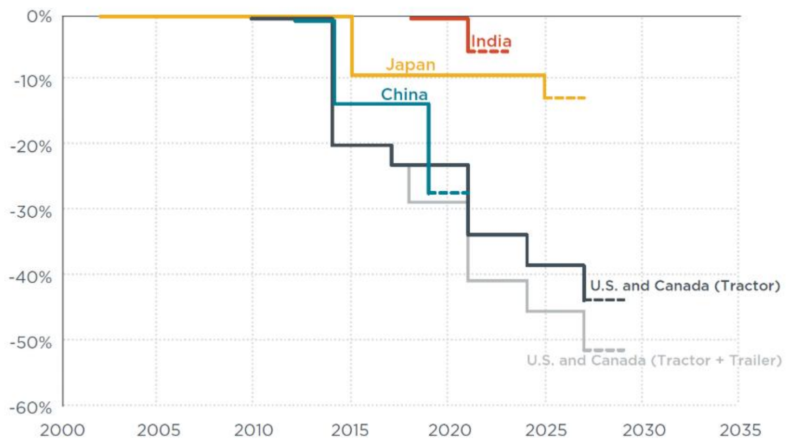



**Figure 88.** Percentage reduction of truck's fuel consumption by country, horizon 2035. Source: [62]

Compared to 2019 emissions values, to fully comply with European policies and restrictions, the heavy transport sector will be required to reduce by 15 % the GHG emissions before 2025 and -30 % by 2030.

Developing an environmentally friendly solution for commercial transports gives great benefits to companies buying trucks (i.e. customers) since fuel consumption weights around 30% of the operating costs on average.

Almost all experts are looking at the direct and indirect electrification as the main technological driver and paradigm shaping the future of trucks mobility. Hybrid and fully electric trucks on the long term will dominate the markets, even if a considerable percentage of market share will be taken up by hydrogen, with fuel cell vehicles.

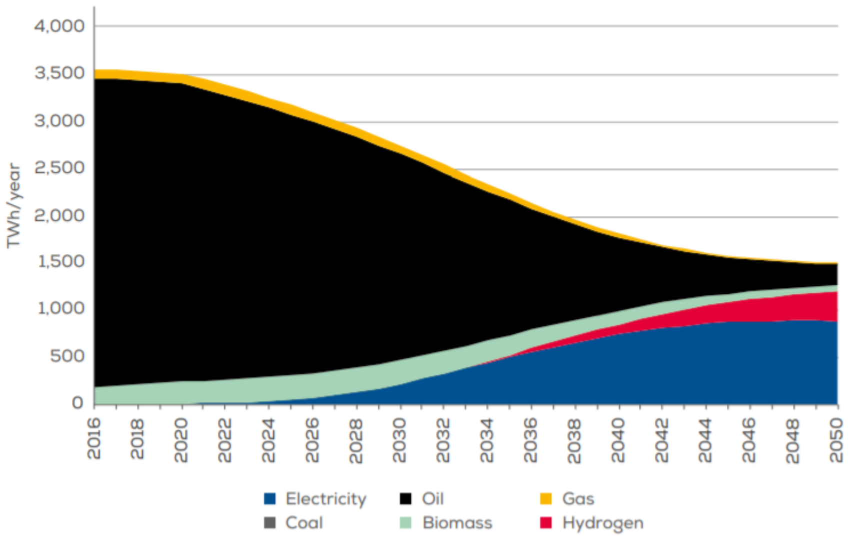



**Figure 89.** Fuel use in road transport – Paris compatible scenario. Source: [4]

The image, from the annual report by DNV GL for WindEurope 2018, gives evidence of the progressive growth from today to 2050 long term Paris-compatible scenario. This is one of the two possible scenarios, based on different policy levers, elaborated by EU to reduce pollution problems. The other, more aggressive scenario, whose realization is more critical as well, is called accelerated scenario.

By courtesy of this annual paper, again, analysing the European market for electric vehicles we report the following images defining exactly, according to Paris scenario, how the electric commercial vehicles will evolve in time. Heavy vehicles evolution is forecasted to be slower with respect to light vehicles one. By 2025, around 10% of the total heavy vehicles fleet is expected to be fully electric, growing to 30% in 2030, 75% in 2040 and, finally, 80% in 2050, assuming the typical shape of a technological s-curve. [4]

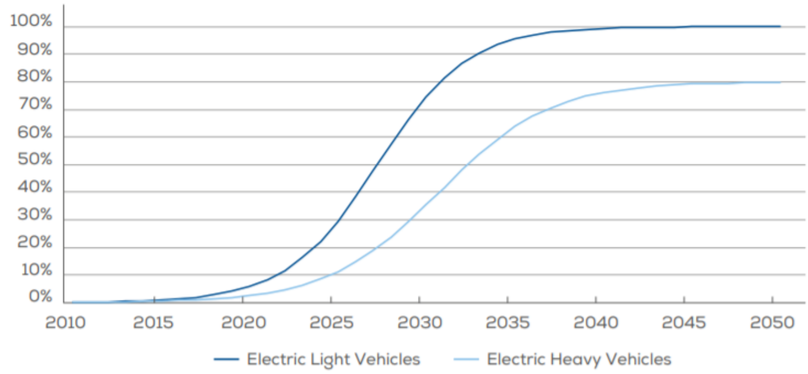



**Figure 90.** EV share in new sales of light passengers and heavy vehicles. Source: [4]

Speaking about absolute values, in Europe in 2050, DNV GL expects to reach around 50 million electric heavy trucks on the roads, against just 20 millions of traditional ICE. [4]

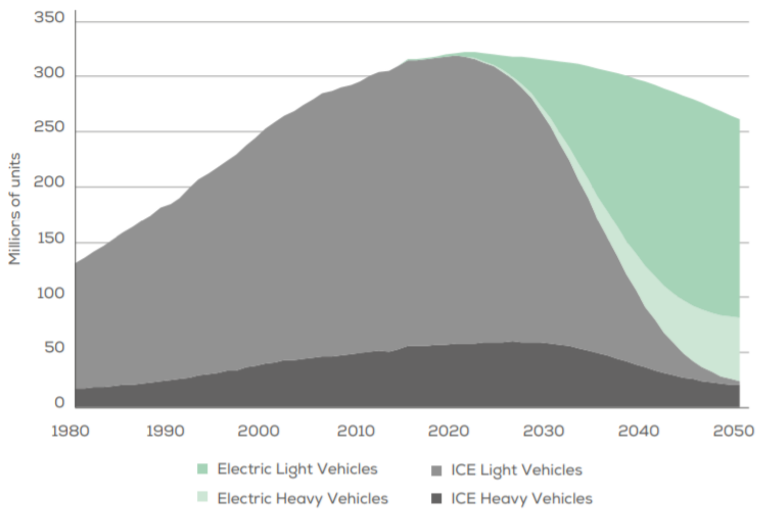



**Figure 91.** Shifting drive train and vehicle fleet numbers – Paris compatible scenario. Source: [4]

Looking at this phenomenon from a broader lens, according to a research conducted by PSMarketResearch, globally the market for BEV category is expected to grow at the fastest pace from now on. Global electric truck market numbers, thanks to strong government support and massive R&D research, show very high CAGR (compound annual growth rate) in the recorded period 2018-2025, both for total electric trucks and for heavy duty specifically (i.e. +150% in 2018 compared to 2013, + 175% in 2021 compared to 2018 and +257% in 2025 compared to 2021). [63]

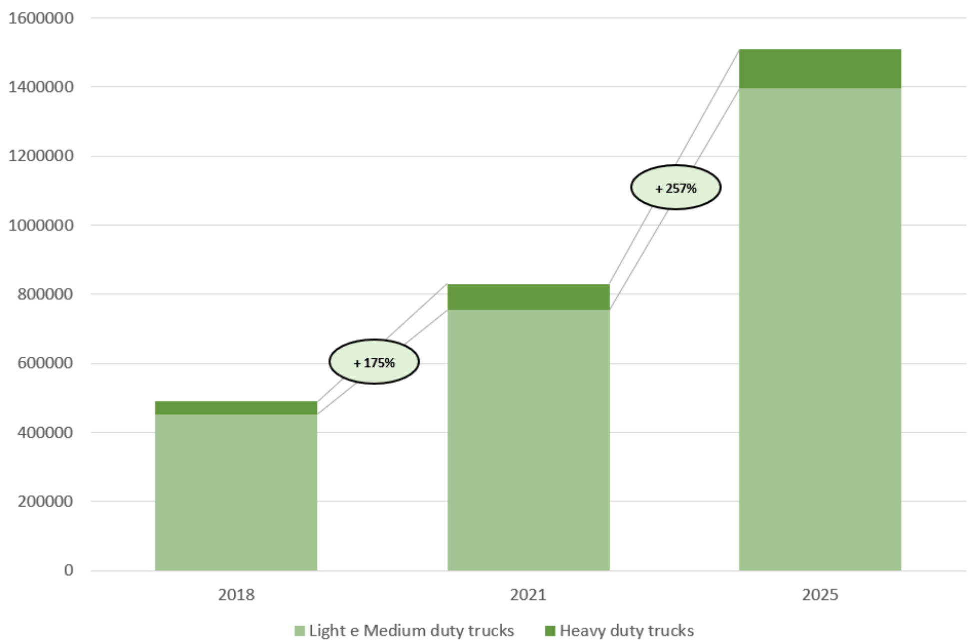



Figure 92. Global electric truck market. Source [63]

Globally, heavy-duty trucks are expected to grow at the fastest rate due to development of countries like China and the fast-growing freight demand. In US and EU the demand for long haul freight is growing at the fastest pace. In North America, for instance, as illustrated in the graph below, by 2025 around 67% of electric trucks demand on the market is related to trucks with a range above 240 kilometres. [63]

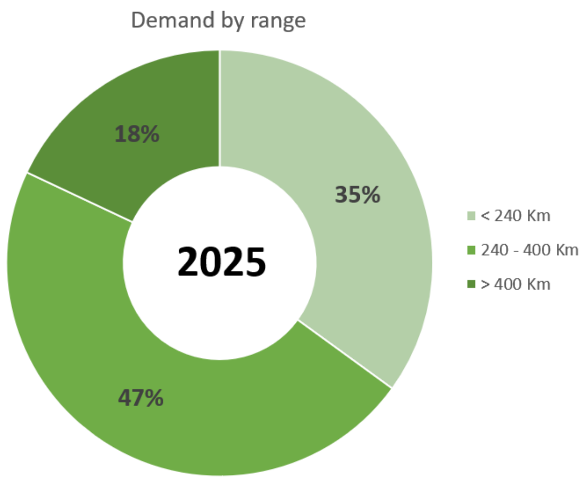



Figure 93. Demand of electric trucks in North America by range. Source: [63]

Apart from government restrictions and regulations, another key driver to the diffusion of electric trucks, from owners' point of view, is the reduction of operating and maintenance costs compared to traditional alternatives which, on the long term, may more than compensate the initial investment. As we already mentioned in the previous chapter, in the same way as for buses, also heavy commercial road transport vehicles are not owned directly by the driver, they instead belong to a logistic company.

Let's take a deeper look and focus on Italian market. According to ANFIA, from 2017 to 2018 volumes of alternative fuel trucks more than doubled in a single year (+ 105%), reaching 1.157 units, thus meaning the 4,5% of market share (with respect to 2,3% in 2017, meaning 591 units).

By alternative fuel we mean not just electric vehicles obviously, in fact a great performance by GNL fuels (699 units, + 131%) must be registered, fully dominated by IVECO. In Italy the distribution network today includes around 40 GNL distribution systems. Hybrid and pure electric heavy trucks sold in Italy in 2018, amounts to 141 units, still little significant considering that it covers less than 1% of the market.

Talking about truck manufacturers' market in Italy, it is a very concentrated market with few players owning almost all the share. First of the class is IVECO representing 36% of the totality, followed in the ordered rankings by Scania, Volvo, Mercedes and DAF.

Geographically, the market distribution is not homogeneous, 57% of sales market is concentrated in northern Italy, dominated by Lombardy (18% market share), followed by Veneto (11%) and Emilia Romagna (10%). On fourth place is ranked Campania in the South of Italy, with 9,4% market share. [61]

Many players are competing globally on the market to develop the best electrified solution for heavy duty commercial transport. Interestingly, it is possible to see a growing number of model announcements in the HDT segment, even if total cost of ownership will still be higher than diesel for around ten years according to McKinsey. The global electric truck market is dominated by Chinese players, taking advantage of the economic growth, urbanization and advanced green electrification process compared to many other countries. With 25% of market share in 2017, Dongfeng is the market leader. This company provides a wide range of products and has partnerships in Europe as well. Anyway, for the scope of this paper I decided to focus just on heavy-duty trucks, by reporting the most innovative and relevant manufacturers and truck models for a benchmark. [63]

How not to start from the highest valued company in the automotive history, Tesla. Innovative by definition, the American brand is trying to revolutionize the heavy transportation sector as well by developing its own electric truck, called Semi. Presented in 2017, actually in a testing phase, the official commercial launch is scheduled for the end of 2020. It is a 36 tons payload truck (very big) powered by full electric engine, battery capacity of 800/1000 kWh, ensuring a driving autonomy (range) between 480 and 800 Km. [38]

**Figure 94.** Tesla Semi truck. Source: Tesla: [51]

Volvo, in the same way, is very active in this sector and in 2018 revealed two fully electric trucks, ready to be sold in Europe starting from spring 2019. The two models (Volvo FE Electric and Volvo FL Electric) are quite similar from many point of view but differ for what concerns the dimensions. The former has a 200-300 kWh lithium-ion battery capacity providing 200 Km autonomy. The payload is 27 tons and its main use is quite specific, it was thought as a waste collector. Two charging systems/modes are supported, the first in CC at a maximum power of 150 kW and the second in low power charging Ac at 22 kW. The latter shows some differences although the application is the same, it has 16 tons of maximum supported payload, 100-300 kWh of battery capacity and an autonomy reaching 300 Km. [64]

We go on with the e-TRUCK by MAN, it is a smaller trucks in dimensions, allowing "just" for 8 tons payload. Fully electric engine, battery capacity of 264 kWh with an autonomy of around 200 Km. This truck model has been presented on September 2016 and, in the last two years, have been on test in nine different companies, CNL partners.

A mention is deserved for the e-Force One AG even if it has been presented in 2012 (a real innovator) and commercially sold starting from 2014. Its specifics are 26 tons payload, from 440 to 550 kWh battery capacity ensuring around 500 Km range for the driver.

Another big player of the automotive industry, Renault, developed its own electric heavy truck models. Production and sales started long time ago, in 2010 with a few models differing in dimensions and batteries, from 3,1 to 26 tons, from 33 to 200 kWh battery capacity and, finally, from 120 to 200 Km of autonomy. [38]

In 2019, Renault unveiled its second generation of electric trucks, again with a range of models with a wide spectrum of technical specifics (Renault master Z.E., Renault D Z.E. and Renault D Wide Z.E.). Renault Trucks predicts that electric vehicles will represent 10% of its sales volume by 2025. [65]

I previously mentioned the Chinese market as a proliferative one, two big players are Dongfeng and BYD, although the first one just focused on electric light commercial vehicles. BYD, instead, is planning to bring to Europe by the end of the current year a full range of battery electric vehicles, including two heavy truck models, a 7,5 tons and a 19 tons rigid distribution trucks. [66]

Even if we focus our effort on the full battery electric solution for heavy-duty trucks, I fell that a special mention should be made to an American start up which has been growing at a shocking rate during the last 2 years. Its name is NIKOLA, a hydrogen-powered truck manufacturer which is planning to shake the commercial truck industry with zero-emission and fuel-efficient vehicles, by challenging the innovation-leader position of Elon Musk who which is suing her for design infringement against Tesla. While industrial hydrogen typically comes from natural gas, new methods for generating "green" hydrogen from water and electricity from solar or wind farms have made fuel much more attractive to institutions in California, Europe, Japan, South Korea and China. There has been a constant interest in hydrogen intended to power heavy vehicles, particularly long-haul vehicles, as fuel cell fuel systems are much more lightweight batteries and can be refuelled at the same speed as diesel and petrol models, it is actually the only alternative that in the long term future will probably be able to keep up with battery electric technology. [67]

**Figure 95.** The Nikola3 truck. Source: [67]

**Figure 96.** The Nikola3's command dashboard. Source: [67]

The production of Nikola Tre electric trucks will begin in Europe in 2021 with partner CNH / Iveco, with some units that will be exported to the United States in view of the opening of the US Nikola plant, which will build fuel cell and hydrogen cell models. Despite hard competition and legal issues, Nikola is not going to slow down its plans, the company just made its IPO at Wall Street and is working on the construction of the plant, opening of a hydrogen charging network and battery charging stations for its futuristic vehicles and also on the construction of a pickup. Nikola can count already on many commercial partners, from more traditional ones to alternative energy companies (solar panel manufacturers). So far, Nikola hasn't generated much revenue, but estimates that sales will jump from $ 150 million in 2021 to $ 3.2 billion by 2024 as production increases. In 2024, it plans to sell or rent 7,000 battery-powered units and 5,000 hydrogen trucks. [67]

According to TransportEnvironment research, Europe, and Italy as part of it, needs an ambitious electrification program for heavy trucks in order to decarbonise the freight sector. EU cannot lack (chicken and egg problem) a strategic approach to electric trucks charging infrastructure investments to address the main infrastructure needs (coverage and standardization), because this limits a lot the volumes of electric trucks to be produced in the next decades. Lack of clarity on fuels and technologies that EU wants for future circulating trucks is a terrible obstacle to decarbonisation. Zero emissions technologies should be the exclusive priority right now. [68] Developing a capillary and adequate infrastructure requires not just huge upfront investments but also a structured and planned collaboration among many players. Governments, utility companies and private entities such as OEMs and electric vehicle supply equipment providers should collaborate to create a strong network to boost the electrification process properly.

Heavy-duty trucks require fast recharging of huge battery packs, allowing to move these giants on the road for hundreds of kilometres in the fast paced evolution of logistic and transport sector. Efficiency and rapidity are key words in this sector today and the fourth technological industrial revolution, based on technologies like AI, IoT and blockchain, opens the doors to many new business solutions. In the next paragraph the main charging alternatives are compared and discussed.

# 5.2 Compared charging technologies for electric trucks

Referring to the previous sub chapter, we aim at expanding the alternatives analysis for heavy-duty trucks (long haul) charging technologies and infrastructures, adjusting every consideration to our specific case study.

Let's link to our previous considerations and start form the only three things that are quite sure about the future of heavy-duty trucks. The first is that direct electrification will be the most efficient way to take by far. A research from TransportEnvironment calculated that the direct electrification has an overall efficiency, considering well to tank and tank to wheel efficiency, that amounts to 77% today and improved to 81% in 2050. Among the other solutions the only one, as we previously reported while describing Nikola motors, able to at least compete in the hydrogen pathway (fuel cell vehicles), with an overall efficiency of 33% today able to scale up to 42% in 2050. [68]

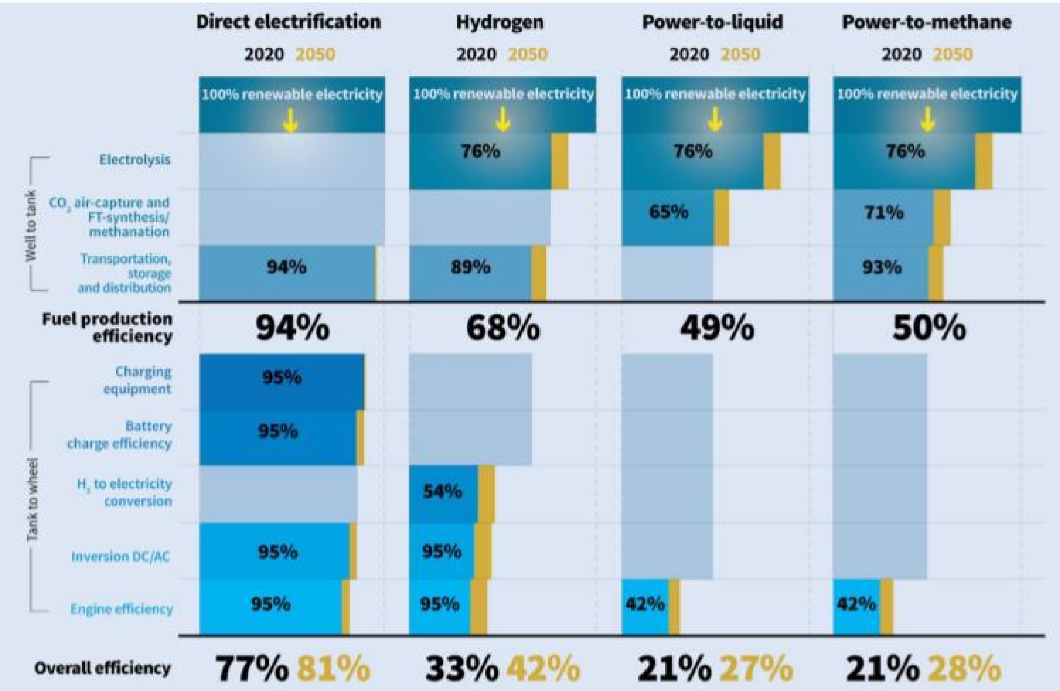



Figure 97. Efficiency of different technological paths. Source: [68]

The second thing is that this process will be, in any case, very long and full of obstacles. According to McKinsey, “Commercial-vehicle (CV) electrification will be driven at different rates across segments, depending on the specific characteristics of use cases”. As we can see from Figure 98., the heavy-duty point-to-point long haul reaches the cost parity with respect to Diesel very late, it is the last one in 2030 or more, due to higher battery costs (size-driven). This happens because the need for bigger batteries causes a higher cost difference and makes the application harder for weight maximisers. However, as we reported, many companies will introduce on the market electric trucks far before 2030 trying to increase benefits and efficiency and reach cost parity as early as 2023. They are going to act in this way due to three main reasons. The first is that many of them are going to pay a lot of attention to efficiency by increasing utilization, exploiting mid-day charging and minimize the unfavourable payload. Second reason is that many truck-makers company or operators need to reach imposed European or national emissions targets and want to give a “greener” image to their company and, so, introduce new electric models. Third, in the same way, some buyers care more and more about environment and, so total cost of ownership is no more the most important driver. For sake of completeness, it is useful to remind that efficiency and range could improve a lot in the next decade thanks to platooning trucks development. Truck platooning is the “linking of two or more trucks in convoy, using connectivity technology and automated driving support systems. In this way they maintain a fixed, close distance while connected during certain parts of the journey, like in motorways”. [69]

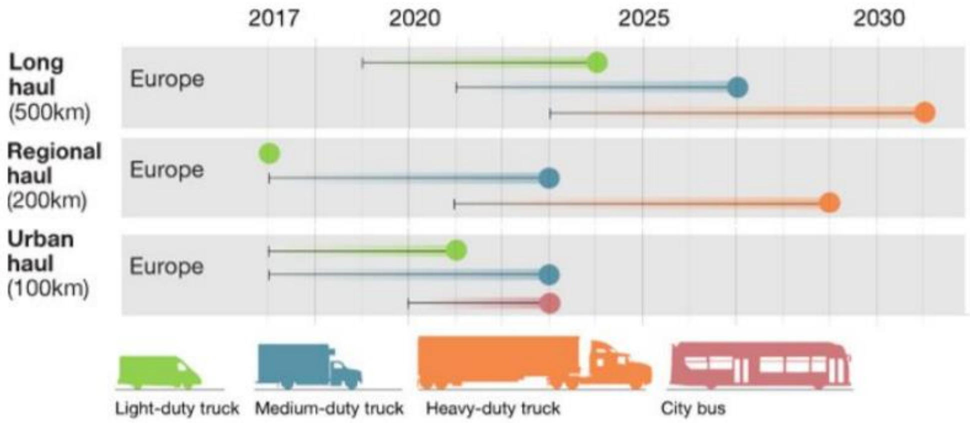



Figure 98. Timing of BEV TCO parity with respect to diesel. Source: [69]

The third thing is that current AFID (Alternative Fuels Infrastructure Directive) is not suitable for electric trucks diffusion, a revision of it urges in order to address electric trucks’ specific charging needs. A roadmap for the deployment of a new infrastructure for electric trucks charging has been reported in Figure 99. [68]. This is an ideal roadmap for a game-changing revolution in the infrastructure system. It provides suggestions about time sequence and precedence of actions with clear policies to deliver the final output. The plan starts with urban and regional deliveries, while long-haul commercial transport is the last category to be addressed, from 2030.

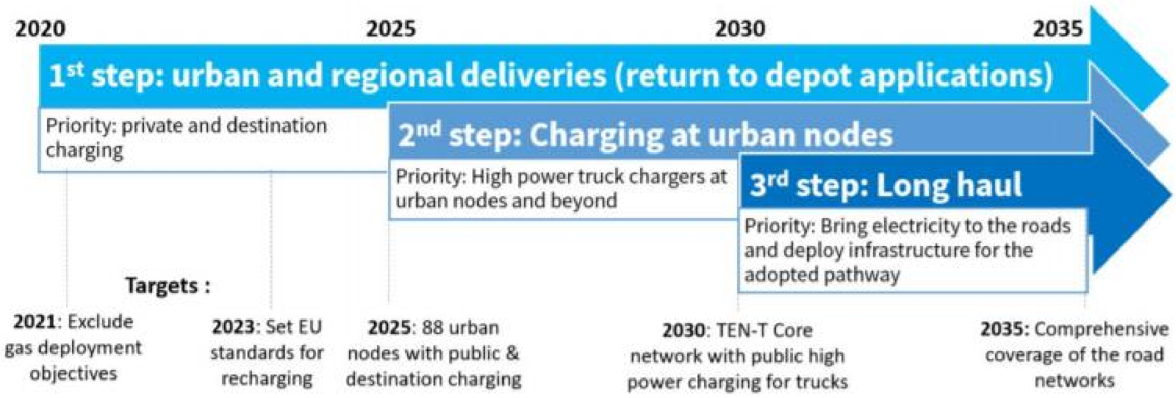



Figure 99. Electric trucks infrastructure deployment roadmap. Source: [68]

Electric vehicle fleets such as trucks require very different charging infrastructure from the existing infrastructure developed for private cars owners. The rising population of electric vehicle fleets, trucks in particular, represents huge opportunities for developing dedicated charging infrastructure for electric buses and trucks. Electric fleet charging represents less than 5% of the total charging infrastructure in volume, it constitutes over 30% of the total market value of the charging industry, according to IDTechEx. [27] For this reason it is easy to understand how critical and strategic can be to invest on a common shared project of infrastructure and charging technology in our country. The best possible long term project should be financed by collaboration among stakeholders involved.

The choice of the sector for this analysis was not random, I decided to focus on heavy-duty trucks for long hauls due to some particularities that could make the analysis more interesting, specific, easier and really suitable to alternative charging modes as a problem solution. Heavy trucks (and buses), unlike private cars, taxis, shared/pooled cars, are designed to drive on fixed paths everyday (i.e. point-to-point), repeated many times over the year. They are required to drive for very long distances in big extra urban highways at almost constant speed. Their journey is often precisely planned and their stops as well both in time and location. For this reason, it is easier to monitor and forecast their movements across the country and, as a consequence, strategically planning an infrastructure network since variables are reduced by far, with respect to the harder challenge of the urban EVs charging. Planning strategically means first of all choosing the most suitable charging technology for this market, then the magnitude of the investment (e.g. number of stations and charging points) in order to ensure an efficient service to the circulating fleet while keeping investment costs as low as possible and finally their geographical optimal location on the map. Further considerations are required. Speaking about a charging network for heavy-duty commercial transport means speaking about highways. The aim of such a project is to allow these fascinating and gigantic vehicles to charge their battery at the strictly necessary percentage to reach, obviously considering a statistical margin, the following available charging point. This practice would optimize times and energy required.

Before going into more detail, it is important to underline that there are three different use cases for electric truck recharging: depot/private, destination and public charging. These use cases are related to different needs, trucks dimensions and utilization and determine where a truck is going to be charged.

- Depot charging: It is not shared, it is a private charging, usually overnight, at the depot of a logistic company. It is the same as residential or workplace private chargers for passengers EVs

- Destination charging: Located at the distribution/logistics centres and used while loading and unloading operations of trucks, on a non-discriminatory basis. Being able to charge during these operations could reduce battery size requirements, leading to lower prices and so earlier adoption.
- Public charging: it is a charging point available 24/7, accessible indiscriminately to all trucks, safe and may include pre-booking systems. It fits perfectly to resting areas, ports, toll stations etc. [68]

For the purpose of our case study on long-hauls heavy-duty trucks, all three charging use cases can be useful with particular focus on in-route public charging on the highways' resting areas. The already mentioned concept of high level of predictability of long-haul routes allows for concentrated investment in charging infrastructure. Investments need to be prioritized by identifying key routes, traffic nodes and, as a consequence, charging points, as I did for the simulation of the following chapter. According to McKinsey analysis, on popular routes a charging point every 80 to 100 kilometres could be sufficient for the early phases of heavy-duty trucks, so that the pure number of charging stations should not be the bottleneck of the project. [69] In the long run two drivers will shape the market since on one hand the number of electric trucks will be far higher but, on the other hand, the improvement in batteries technologies for autonomy range and the improved journeys scheduling efficiency may lead to a reduction in required charging points.

**Figure 100.** Examples of electric trucks charging possibilities. Source: [68]

For long journeys, beyond the range of the electric truck, public charging on the road is essential. Clearly, the more the network grows the less important, relatively, the maximum distance covered by a single charge is. These drivers are crucial to a definitive switch to electric trucks even for operations requiring long journeys. Public charging may also be used via a pre-booking system, in order to book the charging station during a break, avoiding lines and space problems.

The two main alternatives and categories of charging in this sector are static charging and dynamic charging, with relative applications, advantages and disadvantages. Charging statically means using a plug while the truck is not travelling (engine off), charging dynamically means charging while moving with a catenary system, a rail or wireless (by induction). According to Transport

Environment, this second alternative seems to be much more efficient and environmental-friendly, even if the deployment is very challenging and need strong government interventions and cohesion around Europe. Making a standard emerge is such a critical issue to be solved, some players like Siemens, Scania or Alstom are running pilot project in Sweden and Germany but only EU intervention can make a unique standard emerge. "On the other hand, battery electric trucks can charge statically at 'megacharger' (also called HPCCV or High Power Charging for Commercial Vehicles) sites along the main highways and placed at truck rest areas and natural stops on the roads. Truck drivers are mandated to take a 45 minutes break every 4.5 hours (EU Regulation (EC)561/2006), and this time period could be used to recharge the trucks' batteries". [68]

Although quite different, these solutions are not prevented from co-existence in future with the common goal of road transport (freight) decarbonization as soon as possible. Trucks are quite easy to adapt to different technologies, as declared by Volvo and Scania, so starting with static charging infrastructure deployment and then move towards dynamical charging could be a good strategy to reach acceptable volumes. Hydrogen can be part of the solution, being optimal for long distances thanks to range and flexibility. We know that hydrogen production on a large scale implies a lot of money and requires a lot of energy, it is just delocalising the problem making the process less efficient if we look at it as a whole. These odds may be overcome in a future optimistic scenario in which renewable electricity becomes very cheap and deployed rapidly on a large scale.
It may have sense to make two quick notes about possibility of regenerative braking charging (KERS-Kinetic Energy Recovery System) and future autonomous driving trucks.
First, KERS technological solution is useful both for electric and traditionally powered trucks and "it is an intelligent system comprising two control units (one on the tractor and one on the trailer). During acceleration, the tractor control unit communicates with the trailer to manage the boost provided by the trailer's electrically - motorised axle. Power is provided by a bank of ultracapacitors. During braking, instead, the motor becomes a generator, recovering kinetic energy that would otherwise be lost as heat and storing it in the ultracapacitors. According to Adgero, on average an ICE powered truck travelling 20.000 km/year consumes 6.900 litres/year of fuel. KERS may reduce fuel usage and, consequently, $CO_2$ emissions up to 25%. [74]
Second, autonomous driving technology will for sure be part of our future and the great advantage will be "the ability to drive without having to stop for mandatory breaks". This solution would be compatible with a dynamic charging system since stopping to charging statically would just be a loss of time as breaks to have lunch, sleeping etc. aren't required anymore, the driving process runs instead 24/7. Under this perspective, dynamic charging seems to be the optimal solution in the long term.
A mixed solution could be to use dynamic charging to charge the main battery and use an hydrogen fuel cell as a range extender. [68]
Often the power requirement to charge electric trucks in high power charging points (HPCCVs) is very significant and the grid structure and performance is put under pressure and must be improved. Charging infrastructure investments today focus much more on passenger cars and, whereas LDTs and MDTs can leverage on the same infrastructure, this is not possible for HDTs unfortunately. HDT which cannot exploit the passenger cars infrastructure. Costly civil engineering work could be required, fort his reason the pre-existing grid infrastructure must be taken into consideration and the new design and installation must be optimised by location. [69]
Efforts to smoothen the energy demand curve by balancing the charging load will be crucial, in order to optimize charging power required in each moment according to excess or not of energy and redistribute it as well. The charging process, in a smart connected grid view, will be adjusted according to price, grid signals of energy availability. [68]
Based on TCO for users and companies and on the impact on society in the next years the comparative analysis of infrastructure and charging technologies, followed by clear regulations, will be updated after more certain scenarios will appear.

It is in light of these aspects that I try to link the battery swap technology to the heavy-duty truck market for long-haul. Battery swapping systems may partially solve some of these problems. This system, as we already know, is far better designer and projected to perfectly integrate with a smart grid in which energy is completely managed and optimized, since the charging process is price-driven and more flexible in time. Charging the batteries through a swapping mechanism often allows to charge at a slower rate, not only flattening the energy demand curve by distributing it over the day but also preserving the battery from degradation coming from ultra-fast charging. Moreover, a big mistake would be not to consider another factor: space. These vehicles are the bulkiest on the roads so moving them, standing in lines, parking is anything but easy. In traditional stationary charging (by wire) reaching a station with all the chargers already taken, without having the possibility to reach the following charging point, would imply enormous consequences in terms of spaces required for trucks and timings. This issue would not exist in case of battery swapping stations in which just 3 minutes (plus a reasonable waiting time) is required to restart the journey, leaving free space in the station. Clearly a swap station for HDT would require, on the other hand, more storage and operating space for large batteries and entry/exit of trucks.

## 5.3 Battery swap business model

Given all the issues hindering the high power (mega-chargers) solution, both in terms of infrastructure re-design and building and in terms of stress impact on the grid, my analysis and simulation from now on is based on the concept of a battery swapping stations network across the whole Italy, working specifically on the full electric battery heavy-duty truck use case on long-haul paths, considering either depot and destination and public (on the road) charging.

Figure 101. Loading/unloading and battery swap operation on Iveco truck. Source: [70]

In a point-to-point long journey, the electric trucks start at full charge after a deposit charging then charge or swap their battery at fixed locations on the path and finally charge it once the destination is reached, during unloading operations. The possibility to charge while loading/unloading has the potential to reduce the stress on battery requirements. In depot and destination charging the process is easier and does not create problems both in terms of energy management and timing. The biggest challenge concerns the public charging on the road.

In order to really take the most out of the benefits already explained in the previous sections, a battery swapping network requires an outstanding business model, to be analysed from several perspectives. The idea is to try to give, after a solid inquiry and reasoning development on the topic, my personal opinion related to the most innovative, efficient and achievable business model for this case study, with the aim of highlighting a win-win strategy for all the stakeholders involved. I would like to describe a business model largely effective in a couple of years as well as in 2050, for this reason giving exact numbers it hard and counterproductive since everything (fees, costs, choices…) should be pivoted around future scenarios in this sector which I'm not able to forecast with accuracy now, due to time and tools constraints. For this reason, in case of huge projects like this one often a stage and gate approach based on real-options is exploited in professional field.

As we mentioned more than once, the main obstacle and starting point will always be the huge upfront investment required. Funding for such a national-scope project cannot come exclusively from private or public players, a proportioned mix, instead of debt and equity capital should be raised by both categories (joint funding). The majority share of the project funding should come from both European and national government subsidies, incentives and non-repayable loans and Autostrade per l'Italia S.p.a. which is the Italian company managing the national highway system with major participation (around 86%) coming from Atlantia Holding S.p.a. However, investing in such a revolutionary project, may rise attention of many other categories of stakeholders as well, everyone with different personal business interests (e.g. truck-manufacturers and logistic/transportation companies, oil and gas stations owners on the highways, charging station specialists and utilities' providers). A Special Purpose Vehicle (SPV) company would be perfect to raise funds, study the feasibility, design, manufacture and scale-up the project, with all the partnerships, contractors and subcontractors required.

Since generating enough revenues to recoup such an investment is not easy, some charging service providers decided to provide both hardware and back-office services (such as payments and billing services as a turnkey solution for customers like retailers, municipalities and businesses with parking lots for customers and employees. They are paying for hardware and installation of charging points and, as a result, the infrastructure is funded by many different parties who are free to manage, operate their station and decide their pricing model. For the charging services provider, revenues are generated by the hardware sales and back office services. [5]

In our specific case this funding and business model is not properly viable cause no specific customers like retailers of municipalities are available apart from oil and gas stations owners, whose relationship and deals should be separately addressed (e.g. Buying/easing their spots to build BSS once electric transport will have almost substituted ice vehicles? How to manage existing human capital? Leaving a sort of franchising contract for the management of each single station?).

Supposing the electrification process of HDT industry sector will reach expected values in the next ten to thirty years and correct funding, creation of a SPV company and infrastructure development is possible, let's now understand how a viable business model could involve all the stakeholders and the related implications for everyone.

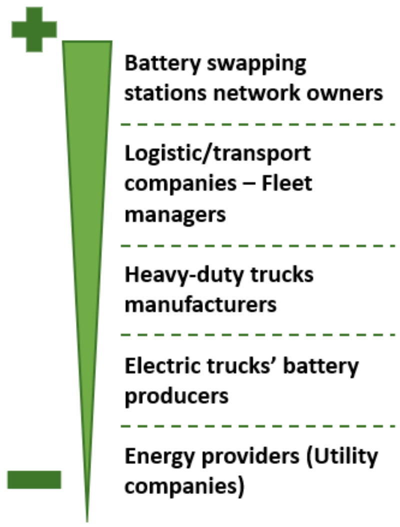



Figure 102. Impact of new business model of different stakeholders. Source: Personal elaboration

### Battery swapping stations network owners

Investing in this specific sector leads to less uncertainty and risk as the HDT paths, consumptions, volumes, frequencies and behaviours are easier to be predicted and quantified with respect to a complex use case of electric passenger cars in a big city requiring elaborate mathematical models. The model here could be compared to a bicycle chain or a conveyor belt in which trucks continuously move up and down the county for long fixed hauls.

The most complex analysis to be performed, however, is from this point of view. Supposing that an investment in such an infrastructure could be followed by a proportional increase in electrification of trucks, models produced and sold to final customers, the idea is that the electric trucks business can be substantially different than today's traditional ICE trucks business. Whereas today the ICE truck is seen as hardware with potentially selected "on-top" services, electric trucks can lead to an holistic service concept as a business model. The big cities are becoming smarter and smarter and thanks to IoT technologies the digital monitoring of traffic flows to forecast situations and plan operations to increase efficiency and profitability is now possible and it is even more precious in HDT sector. The starting point is the installation of a smart capillary network of battery swap stations across the country in strategic places chosen on the base of actual traffic nodes, common paths and space constraints. The HDTs can travel across the country and forget range anxiety by planning its trips and stopping to quickly swap the exhausted battery in few minutes at the closest station on the map.

The core concept for the fleets is the "servitization" of the product, around which the business model is built. The battery swapping service (range extension) is provided as part of a bundle of services already paid by fleets and drivers (e.g. toll stations payment by Telepass, road assistance services, maintenance etc.) as happening for mobile phones service plans. Battery is no more owned by drivers/fleet managers, isn't a cost anymore, it is a service. This services bundle could be sold to logistic/transportation companies in exchange for a fixed tiered annual fee.

Some years ago, many trials in this direction led to the development of pricing models based on the pay-per-swap or pay-per-energy consumed. In the second case, instead of paying the same price for every swap, the payment is proportioned to the difference between the entry energy of the exhausted battery and the energy inside the new battery provided. In this way "the price is not set on the battery itself and the economic essence is no more battery leasing but energy leasing". [76]

The idea was to make price dependent also on availability of batteries in that specific moment, energy levels in the warehouse and on customers behaviour (truck drivers). Anyway, this pricing model is obsolete, proved to be unsuccessful and is not suitable for our case study in which customers want to take advantage for habitual and planned usage of the technology (i.e. through a fee payment).

Calculating the optimal fee is not an easy affair, being it driven by many parameters in different possible scenarios. The payment could be billed annually or monthly, at the discretion of the customer (i.e. fleets) and should be paid by each logistic/transportation company for each HDT included in the fleet according to single needs. In order to get the most out of the market demand and optimally exploit the specific customers' willingness to pay, I propose to shift from a uniform pricing across customers segments to differentiated value-based pricing. A certain number of periodic fees' categories may be agreed at the beginning according to expected mileages to be driven during the year by each truck, number of subscribed trucks and based on the type of battery needed for each truck. Clearly, for a matter of standardization, only a very limited number of battery typologies will be allowed in the system. This turns out to be another great benefit of this specific sector as the standardization and compatibility problem would impact much less the battery swapping system for trucks and would be much easier to solve due to more limited range of truck models and battery producers available on the market. In case of overruns of miles/swaps the truck could pay for the single swap (or agreed number of swaps) at a tiered optimized price based on time slot and battery type.

Some players like Gogoro with its GoStation for bikes' battery swap are proposing a "mixed" pricing model, billing a fixed monthly rate (9.60 $/month) to be added to 7 cent per Ah used. In this way more virtuous behaviours as well as a wiser driving is boosted. [73]

According to my proposal, the system could be manged digitally thanks to "Autostrade per l'Italia" mobile platform application. Payment of fees, upgrade/downgrade of subscription, monitoring of real-time traffic in stations and are all examples of the main in-app offered services.

Potentially, the most interesting service offered is a pre-booking (reservation) system, to book the battery to be swapped at a certain time in a certain station. This service fits particularly well to the case study due to the fact that "commercial-vehicle customers focus on cost more intensely than passenger-car owners. Fleets usually adopt more efficient and consistent routes compared to consumers. The fixed routes typical of freight transport allow fleets to pursue more effective charging-point planning". [69] For this reason, booking the swapping could be really beneficial both for fleets in order to be sure to have immediately an almost fully charged battery and be able to schedule the journey accurately and for the charging stations' owners to effectively optimize batteries swapping process, in charging and discharging batteries and being ready to provide the agreed state of charge. With reservations in advance, all vehicle service strategies (e.g., routing and swapping battery types) can be calculated according to their origins and destinations (ODs), their initial battery power level, etc.

Another key issue to be solved in the past was the location and centralization of the battery warehouse for charging. A centralized warehouse may be a solution in urban context, implying anyway costs for short daily transportation, but in our case it would not have any sense. A decentralised system of warehouses on site at every battery swapping station of the highways, as there are no space constraints (as in cities) and to avoid long and expensive transportation journeys.

The decision of decentralized warehouses leaves the floor to a broader concept of battery swap shared network of stations in which all national swapping stations are connected in a sort of IoT system and managed by a swapping network central management system, which is providing remote assistance as well. The goal is to establish and foster a communication system among stations regarding traffic flows, bookings, batteries degradation state (KPI), number of batteries in the warehouses, energy levels per station in order to manage any inconvenience, balance all KPIs values and optimize global efficiency. Even movements of batteries among stations, in case of particular needs, is possible.

As a long term investment the battery swap stations network could perfectly become a complementary infrastructure with respect to wireless dynamic charging by induction, even more in the scenario of the unavoidable development of autonomous driving electric HDTs. This solution, besides cutting the main operating costs (i.e. the driver), would allow to drive 24/7 without the need for breaks anymore. The consequence is that we will need an infrastructure able to recharge the batteries autonomously cause no human being can connect the wire anymore and the optimal opportunity to wisely recharge during compulsory driver breaks is not exploitable anymore, encouraging once again the swapping solution against a fast charging by wire solution.

We know that battery packs are completely modular (i.e. constituted by N modules together) and some research has been made on the possibility to distinguish between removable (swappable) and not removable batteries. Swapping only some modules of the battery pack would reduce the weight and dimensions of the batteries involved in the process, however, as far as concerns this case study I didn't consider this possibility, for sake of simplicity. In the future, when coupling with dynamic charging on Italian highways will be hypothetically working, this solution may fit perfectly since most of the modules will be charged while driving and the swapping of removable batteries could guarantee a solution to driving peaks or temporarily unavailability of dynamic charging in a particular section.

In case of extreme need some "mobile swapping points" could be provided on the highways network. These light vehicles may be equipped to carry and swap a single electric truck battery thanks to experts' job.

Finally, an interesting possibility for a further "green" investment (capex) consists in the installation of solar panels on the roof of the swapping stations in order to accumulate renewable energy with the aim to become partially self-powered and self-sufficient. It was demonstrated, in an academic research paper [71], that "the BSS provides a viable approach in capturing the solar generation variability as well as helping the utility grids for hosting a higher penetration of solar generation". This innovative solution is favoured by the flattening of energy demand curves thanks to the benefit of a battery swap solution. The swapping demand peaks could be managed by electricity supply from the grid while the accumulated solar energy may be useful to charge the warehouse during valley demand time slots.

<u>A glimpse of financials (driven by the operating model)</u>

To give a deeper understanding of the business model sustainability some basic benchmarked actual data and insight on procedures are delivered here below.

From the service provider point of view (swapping stations network owner) the business is very capital intensive. In this qualitative analysis I assume that the subject is able to raise sufficient capital to finance the investment at the first year of operations, both through equity and debt.

Profitability of investments of this scope can be evaluated in many ways, the most common and simple method is the well known Net Present Value (NPV), which in capital budgeting is defined as the difference between the present value of cash inflows and the present value of cash outflows over a period of time.

$$NPV = -Io + \sum_{t=1}^{n} \frac{CFs(t)}{(1+r)^t}$$

The initial investment (i.e. Capex) roughly consists in the installation of the network of stations all over the national highway system. Being each station quite expensive, it is really important to quantify the correct number of swapping points to build. Clearly the investment is strictly dependent of future progressive evolution of trucks electrification curve (customer base) and, after an initial investment for a pilot project, the network may be expended through subsequent capital increase and expenditures (incremental number of positions, capex distributed over years). Usually, in many papers, to quantify the optimal number of stations and warehouse dimensions, the ratio $\frac{Customers}{BS\ stations}$ is considered and it differs according to vehicle class and location (e.g. urban etc.). For sure in our case a deep analysis of main traffic nodes, frequencies, common drive patterns and time slots must be performed. The capital invested may vary according to another design choice as well. The swapping stations may be unique for both driving directions on the highway, implying a single structure but also a common way to reach it and wide spaces or, on the contrary, two specular stations (one for each driving direction) requiring double investment but less space and easier access.

As an indicative data, according to GCIA Mestre, the daily average number of heavy trucks driving on Italian highways is 9.085 in 2017 [78] and, looking at the projections these values are not going to change much in the future, balanced by opposite drivers. But how much does such a station cost? Well, this is a quite complex questions, little benchmark is available on previous trials. Better Place's CEO stated their stations would cost 500 k€ each but the facts were different and their stations ended up costing even 6 times this number. Tesla as well declared that the cost for each swapping station was around 500 k€, with a warehouse composed of 50 batteries without pre-booking possibility. Ecospazio even declared 250 k€ per station (54 batteries) integrated with solar panels as well. An important remark to be done is that we are speaking about car stations and not HDTs. No benchmark is actually available in this sense and, for sure, the larger dimensions of batteries and trucks themselves would require larger stations both in terms of mechanical and electrical components, operating mechanisms, space required and warehouse, leading to higher prices (i.e. 1-3 M€ hypothesis). As a discounting rate, giving information about riskiness of investment, usually, the choice falls on the weighted average cost of capital (Rwacc, around 5%-15%), considering both estimated cost of equity and debt. This is a long term investment, with very high pay-back times, probably supposed in the order of 15-20 years.

Annual cash flows are usually calculated with an indirect method starting from the annual net income (expected profits), obtained by subtracting from the annual revenues all operating expenses, amortization/depreciations, interests and taxes. Assets mainly include the battery swapping structure, the swapping network central management system and the batteries. Asset depreciation is annualized over the useful life (e.g. 5%/yr.) and the corporate taxes can be assumed around 25%-40%. From a quick research I can conclude that, on average, a vehicle's battery life may range from 6 to 14 years (around 2000 cycles assuming 80% DoD). [72]

Annual revenues are mainly coming from the period fees paid by customers. In many cases, it has been proved to be really difficult to reach profitability just with this entry so additional revenue stream should be considered. First of all, my advice is to consider, as previously mentioned, a multi-tie fee to capture the whole customers' willingness to pay, then the downcycling (disposal or recycling) of batteries may bring additional cash-in and, finally the B2G discharge to sell energy to stabilize the grid when possible and convenient. The core revenue stream (fees) is difficult to estimate. It may be estimated from a backward pricing model consisting in constructing the NPV with some values fixed and some other variables and develop different scenarios to determine iteratively in each of them the optimal fee to become profitable under certain assumptions and within specified time constraints (goal seeking). Revenues from fees are driven by volumes of electrifies trucks in the delta years considered for the investment (market evolution), by the rate of subscription to the service and the price of the fees. That is:

$$\sum_{i=1}^{n} Pi * Ni$$

Where Pi is the price applied to a particular tier of customers and Ni is the volumes of truck subscribed to this kind of fee. A Price penetration scheme could be used to boost adoption by applying discounted fees to fleets composed by more than a minimum limit number of subscribed trucks. Anyway, the fee must be high enough to cover electricity, battery leasing and swap operation costs. The unique benchmark for fee estimation is from GreenWay even if it is a quite different market and operating model. They operate in light commercial vehicles' market and the fee includes the vehicle leasing too. They charge 20.040 €/year for 70.000 kilometres, assistance, maintenance and unlimited swaps.

Another approach could be starting from an easier benchmark of the "price-per-swap" applied by Tesla and better Place and, after a quick research, it comes out that an average range for single swap price may be around 60$-100$. The price includes the margins due to swapping benefits with respect to other solutions (e.g. no waiting time, lower battery degradation etc.). Please note that this is a price value referred to passenger cars, HDTs swaps may cost more due to higher operation and battery costs. After an estimation year by year of two drivers such as the total number of customers (HDTs) and the average number of swaps per year made by each customer we can easily compute the annual revenues by using the following formula:

$$Annual\ revenues = Avg.Price\ x\ swap * Avg.\#swaps\ x\ HDT * Number\ of\ customers$$

The number of swaps per HDT depends on how long on average a single heavy truck drives, on the typology of battery mounted and on technological improvement of batteries in terms of autonomy range.

For a simple and rough calculation, as the number of customers, we may use our available data of daily average number of heavy trucks driving on Italian highways in 2017 (i.e. 9.085).

Also with this approach a differentiated price may be applied in the same way as before.

Let's now consider the operating expenses (Opex). The main operating expense is electricity, paid to the energy provider according to commercial electricity price curve evolution year on year. Its price is dependent on the time slot in the day and the contract may include a flat price, variable price or a combination of the two in order to manage demand peaks. The annual amount should be computed by multiplying the number of subscribers by the average energy consumption (based on average number of annual swaps) of each one in a year. The idea behind energy cost management, which is driving the customers' fee calculation as well, is to optimize the price-based charging/discharging order strategy, in order to provide benefits both to station owners and final users. To this aim, charging and accumulation is performed during "convenient" time slots in order to manage demand peaks at the best. In case of prolonged peaks the priority becomes the fast continuous recharging of batteries in the warehouse and not the efficiency clearly. The possibility to sell energy to the grid (B2G, additional revenue stream) should be scheduled in low BS demand and high electricity price. It is a matter of optimally combining the hourly price of electricity (let's say 3 daily time slots: valley, average and peak) with the hourly demand of BSS by HDTs. More price-sensitive customers will be able to plan their journeys so as to swap batteries during the most convenient time slots. The final goal is to provide the right battery type to the customer (HDTs) selecting the one with the highest SoC available at the moment (to fulfil the pre-booking requirements) and doing it in the smallest possible time.


**Figure 103.** Battery swapping fee as a function of charging/discharging price. Source: Personal elaboration based on [72]

For sake of completeness, we report the average estimated price for a commercial company offering charging for electric vehicles to its final customers. The final price for charging service amounts to 378 €/MWh (including VAT). This price includes price for pure electric energy (84 €/MWh, in line with free market price in Italy), general and administrative expenses, taxes and non-energetic costs. [75]

Total daily energy required by a swapping station is given by the difference between state of charge of entry and exit for each battery in the warehouse in 24 hours.

$$Daily\ energy\ required = \Delta batterySoC * \#Batteries\ swapped\ in\ 24h$$

In case of a traditional charging by wire (DO), instead, the daily average energy required by a charging points with N positions is given by N * number of vehicles who charged the battery per station * average energy requirement to fully charge a battery, clearly differentiated for battery types and charging behaviours.

Other operating expenses include maintenance of the equipment to be estimated for each station (hypothesis: 20-100 k€/year), salaries to workers monitoring stations' operations and managing the central system, salaries to workers checking batteries degradation and mechanisms, hypothetical battery transport from station to station, moving charging points' operation and other miscellaneous recurring costs. General and administrative expenses should finally be estimated (hypothesis: 50-200 €/subscriber*year). [22]

A further deep-dive in other expenditures is required for a better understanding of the system.

I spoke about swapping station cost but how to quantify single expenditures? Which additional costs may the project incur in?

Speaking about a swapping station the main costs are related to swapping mechanical and electronic mechanisms, transfer vehicles, thermal management system, computers, batteries, chargers as well as design, installation, commissioning and other related costs.

Clearly, the expenditure for batteries, especially in the starting phases of the project represents a big share. Finding the suitable number of batteries and chargers per each station is very important to maximize economic benefits coming from this type of solution. The number of batteries in the system are given by the number of circulating customers added to the number of batteries in the warehouses of the stations in the network. Annually, the number of batteries purchased by stations' network owners is equal to:

$$\#New\ customers + \#Batteries\ in\ newly\ installed\ stations + \#Replaced\ batteries$$

Batteries in the warehouses need to be constantly monitored in order to allow a prompt replacement of degraded ones due to wear. After a quick research I found that a battery may be considered eligible for replacement once its range at EOL (End-of-Life) is smaller than a chosen target (as a percentage of battery range at beginning-of-life). [22] One of the main benefits of battery swapping, as we know, is the slower degradation of batteries, improving their useful life due to slower and more controlled and distributed charging and reducing the depreciation cost of batteries. Quantifying the improvement of each battery's useful life compared to a direct ownership BEV solution is a hard affair but it could be another key parameter from the perspective of battery stations network's owner, since battery management and maintenance is shifted from truck owner to station owner in this business scenario.

The number of batteries purchased for a swapping station is usually equivalent to the number of chargers installed.

Considering taxes and the “manufacturing-to-retail mark-up” for the battery purchase, the cost of each battery can be estimated through a benchmark, in order to compute ideally the annual total battery expenditure. According to TransportEnvironment, “The conditions for battery electric trucks (BETs) have drastically changed since 2010, a year when lithium-ion battery prices were around $US 750-1000/kWh with energy densities of around 110 Wh/kg. Compared to 2018, lithium-ion batteries’ prices have come down by around a factor of four and densities have more than doubled. Today, the real price is somewhere within €70/kWh and probably around €100/kWh or more, in fact Tesla Semi to cover only the cost for the ~1000 kW battery, would find a battery cost of €150/kWh, aligning with battery pack cost predictions made for 2020”. [77]

In accordance to a scientific experiment conducted on this topic, after performing a sensitivity analysis it emerged that “across the range of variables considered, the cost of batteries, cost of financing and the battery swapping stations utilization rates are the most predominant factors driving the service fee value”. The service fee in this case has been estimated to lay in the range of 100 $ - 600 $. Again, this is applied to a passenger-cars scenario in the U.S. under certain conditions, so, for sake of our case study the estimated fee may be even higher. [22]

Additional costs not considered may include marketing (to improve customer awareness), feasibility studies, engineering, management staff, licenses and concessions and training (investment in human capital and new competences’ development).

As a final remark I would like to stress again that investing in this specific sector has many benefits but has also some odds and major obstacles, one of, for sure not encouraging such an investment, may be the difficulty to capture benefits from scaling up the business through synergies with passenger cars and light commercial vehicles’ supply chain and infrastructure, being them quite different from heavy duty trucks’ ones.

In general, the main design, installation and operation parameters and choices affecting revenues, operating costs and capital expenditure are the following:

- #Swapping stations in the network
- Single warehouse dimensions (# stored batteries)
- Single batteries capacities
- #Chargers
- Charging power of chargers
- #Swapping bays per station
- Warehouse automated systems’ performances

### Logistic/transport companies – Fleet managers

These companies dealing with transportation of goods for commercial aims can take several advantages from electrification. Electric trucks proved to be reliable and require less maintenance (operating expenses) compared to traditional gasoline trucks and, clearly, costs to recharge the truck are much lower compared to fuel expenses which accounts for around 30% of the total operating expenses. Costs associated to owning a HDT are mainly fuel, insurance, possession fee, maintenance (labor force, spare parts etc.). Apart from fuel, it is quite hard to quantify the exact discrepancy between traditional ICE tracks and electric ones, even if many companies tried to estimate the variation over years (as we already saw) of the wear.

The biggest odd to all this is the huge investment required to buy or lease an electric fleet. Incentives, tax reductions, subsidies are growing year by year both from local government and from European Union but will not be relevant enough by themselves. Here comes the battery swapping solution and the concept of battery leasing. In this innovative business model the biggest obstacle to electrification of heavy fleets is removed by cutting the selling/leasing price of HDTs tanks to battery absence, sold by producers directly to swapping stations. It is worth noting that the battery is the most expensive component of an electric vehicle, independently on its dimensions. Clearly the period tiered fee to be paid for each truck to swapping stations' network owners is, proportionally, higher that pure charging energy cost since it includes the lease of the battery and the swapping operation cost as well. This allows to swapping stations' network owners to reduce the time needed to recover the initial investment (i.e. pay-back time) while ensuring convenience in any case to customers.

This solution allows to relieve the customer from taking care of the battery state of health and the periodic fee, as we said, may include also toll stations' cost, road assistance and trucks' maintenance as a complete bundle of services.

This business model allows to forget about range anxiety, schedule every route and every swap and allows to avoid time loss due to long charging times (for these enormous batteries) in that kind of journeys too long to be done with a single charge and too short for a night break to recharge. "The opportunity to cut operating costs across a fleet of trucks in today's competitive logistics sector can drive rapid action, as heavy commercial-vehicle customers focus on cost more intensely than passenger-car owners. Fleets usually adopt more efficient and consistent routes compared to consumers, since the fixed routes typical of freight transport allow fleets to pursue more effective swapping-point planning". [69]

Taking this business model to an even more futuristic concept I appreciate McKinsey's statement according to which "while today fleet operators buy/lease trucks, in the future this business may rely on usage-based delivery models, providing delivery-mobility to the final customer, instead of the hardware. [69]

Finally, I would like to make two further considerations. First, in the long run, the process towards autonomous driving is going to pivot again their business model. As we said, a battery swapping solution coupled with dynamic charging may be favoured against the others and another big cut in operating expenses will come from human drivers' absence. Second, as we go on, the corporate "green" image at the society's eyes will gain more and more importance and, although it not really a cost, the possibility to have a 100% emission-free fleet may drive some transport companies towards adoption.

### Heavy-duty trucks manufacturers

From the HDTs manufacturers' perspective a considerable impact is expected in this business scenario.

After the supply chain revolution as a consequence of the electrification process of mobility, now with this specific solution, brand new value chains are triggered by the shift of battery ownership concept and the architectural innovation coming from electrification of vehicles. The electric vehicle will be intended as a customizable assembly of standardized modules. As I previously mentioned, compared to passenger vehicles, the market for trucks batteries is more standardisable and limited in players' number. Electric trucks manufacturers can opt for different levels of integration of the business and so, as well as in passenger cars' industry, they can choose to fully outsource battery design and production (under clear specifications) or can decide to vertically integrate the chain by designing and producing their own batteries. The first ones, in this ideal scenario, wouldn't be required to acquire batteries anymore since electric trucks will be sold to customers without battery pack and, for this reason, the batteries will be sold directly from producers to swapping stations network owners in a close collaboration with trucks manufacturers for design and specifications to guarantee an high degree of standardization and compatibility, commonly agreed by majority of players. Vertically integrated players (e.g. Tesla), far less diffused, instead, could sell the trucks without battery packs while selling batteries to swapping stations' owners, developing two different businesses based on identification of two revenue streams' channels and enjoying great scale effects. In the last case, possible conflicts of interests in the business may arise since truck manufacturers would sell batteries to the company owning and managing the network in which they possibly co-invested for a minority of shares. However, it should not be a big deal in today's complex business world, easily solvable by clearly define terms and conditions and planning deals based on volumes expectations and forecasts.

From an income perspective, vertically integrated truck manufacturers should earn the same margins from the separate selling of trucks and batteries while this business model may be a little unfavourable for less integrated truck makers. Battery is the most expensive and strategic component of an electric HDT and in the last years the lion's share in the value chain was in battery producers' hands, however the situation is changing and battery prices are decreasing year on year whereas competition for producers is increasing with hard competition of prices leading to margins' squeezing. In this scenario, according to an "as-is" business model, truck manufacturers could opt for the best solution in outsourcing battery production, acquiring lower price batteries and obtaining higher margins on the final product sold to the customer. In our "to-be" business model, instead, battery wouldn't be a deal anymore, thus reducing both relative (%) and absolute margins. Nevertheless, such a loss may easily be compensated by a simplified supply chain and time to market, possibly increasing sales (and market share).

### Electric trucks' battery producers

The impact on their business operations is less considerable compared to previously mentioned stakeholders involved. Their core business remains untouched, what is changing is just the final customer. They would be required to sell battery lots to stations network's owners by probably redefining the contract typologies and the volumes estimations parameters. Clearly the battery stock in the system would be constituted by the total number of batteries inside the warehouses added to the batteries currently assembled on the circulating trucks' fleet. So, to start this radical innovation each new registered electric truck should be released to customers with the battery even if this component, as I said, should not be acquired and then billed to customers due to the overcoming of the ownership concept. The battery is still billed to battery swapping station network owners who monitor and correct the degradation level of the battery stock in the network leveraging on two drivers: New trucks registration and old battery (close to EOL) replacement in the warehouses. A complex network of deals, contracts, habits should be rethought and redefined in order to reach new efficiency targets and economies of scale, impossible to achieve without the efforts of all the stakeholders together.

### Energy providers (Utility companies)

Energy providers may just benefit from a battery swapping solution since energy management may be optimized by peak shaving and demand distribution in time, allowing to flatten the electricity demand curves, reduce the stress applied to the grid and enabling an easier and more effective planning. Bi-directional electricity flows with V2G solutions in all the network of stations can drive the smart energy revolution. What's more, installation of solar panels proved to work well in helping the utility grids for hosting a higher penetration of solar generation. Receiving the support of these players would not be difficult, being usually primary promoters of green solutions allowing to integrate multiple daily services from transportation to buildings.

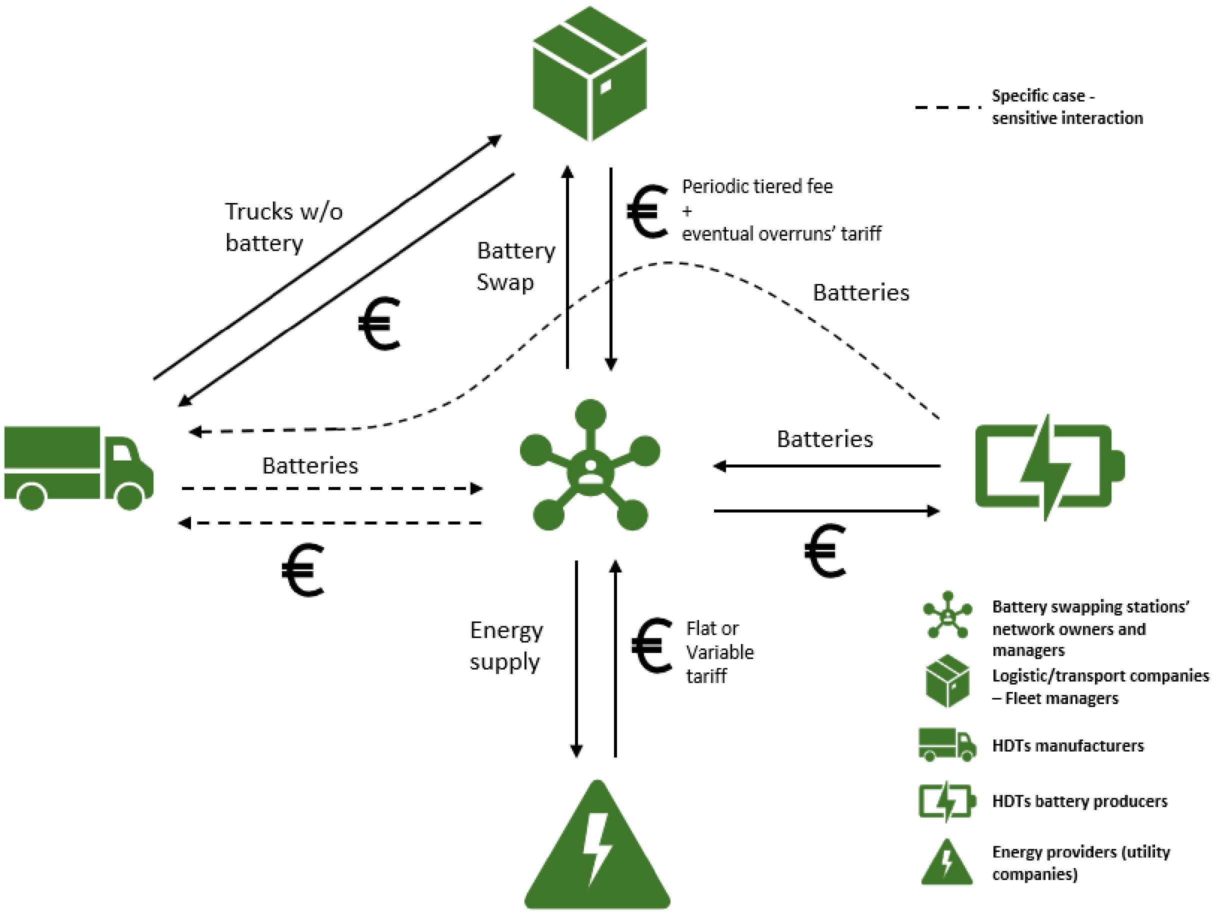



Figure 104. Interaction among stakeholders in the selected business model scenario. Source: Personal elaboration

# 6. Simulation

All the data and key insights to approximately size, define and analyse the market for this specific sector, were extremely useful to set the ground for a personally developed scenario simulation, based on battery swap technology and applied to Italian long-haul heavy trucks market. I performed some quick simulations based on a few ideal assumptions to simplify the scenario. I worked on FlexSim software for discrete-event simulations, exploiting an existing model that I personally modified.

## 6.1 Introduction to discrete event simulation

### Introduction

A discrete-event simulation (DES) aims at modelling the operation of a system as a discrete sequence of events in time. Each event occurs at a particular instant in time and defines a change of state in the system. Between consecutive events, it is assumed that no changes in the system occur; thus, the simulation time can directly move to the occurrence time of the next event, which is called next-event time progression.

Another alternative approach is to break down time into small time slices and to update the system state according to the events or activities that happen in each time slice, this approach is called fixed-increment time progression. Since not every time slice needs to be simulated, a next-event time simulation can usually run much faster than a corresponding fixed-increment time simulation.

These approaches for DES represent the opposite of continuous simulation in which "system state is changed continuously over time on the basis of a set of differential equations defining the rates of change of state variables." [79]

Methods based on discrete-events are particularly suitable if the examined system's behaviour can be described as a set of stochastically influenced, connected components, which change their states at discrete points in time. Common applications go from communications to transportation, passing through logistics, supply management and especially cover the simulation of technical systems in a wider sense.

While discrete-event simulation is easily understandable, it is also very expressive and powerful. It is useful for researchers, students, or practitioners to be able to create high validity models and evaluate their behaviour. Discrete-event simulation includes three views: activity-oriented, process-oriented, and event-oriented simulation, all of them using the same modelling principles. My focus will be on event-oriented modelling. [79]

### Event-oriented modelling

The modelling process begins by examining and analysing the real-world system to be modelled. It is decomposed into components which perform processes, execute events and interact by passing the messages. It must be decided which components should be part of the model, which should be parametrized and which shouldn't be considered at all. Generally, if an entity or a process has a strong influence on the core behaviour of the model, it should be incorporated. Discrete-event modelling is useful if we deal with a set of interrelated entities which only change their state (and subsequently the system's state) at discrete points in time as a consequence of their own behaviour or other entities' behaviour. The entities are the components of the system under investigation and must be modelled in order to represent the system's behaviour important for the simulation study.

Each entity is described through attributes, they describe the entity's current state and their values affect the entity's behaviour. This potential behaviour is modelled as a set of activities, which are a sequence of actions in a timeframe which may change the state of the acting entity or other entities of the model. The event is defined as the point in simulation time at which a change in a state occurs. Therefore, activities are always framed by events and their relationship must be defined by the modeller according to the objectives of the simulation study. This includes specifically the specification of the durations of the activities, which can be modelled both as deterministic and as based on stochastically influenced parameters. The latter case is usually modelled using drawings from random distributions, whose type and parameters are acquired by analysing relevant input data.

In discrete modelling some distribution types are especially useful: normal, lognormal, Poisson, exponential, triangular and uniform.

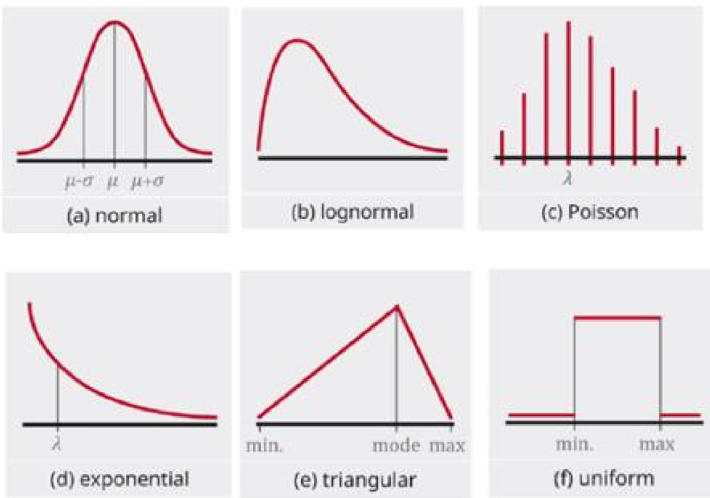



**Figure 105.** Most common distributions in DES. Source: [79]

If the available data is insufficient to determine a distribution's type and parameters, insights can be elaborated through interview or researches. Since the model state changes only when an event occurs, then it follows that between two subsequent events it doesn't change and in general an activity can't be influenced by an event which occurred after the activity has already started. This methodology takes advantage of this and describes the passage of time in the real-world system exploiting variable time steps to increment the simulation time, which means that the simulation time jumps from the occurrence of one event to the next one. Therefore, the event-oriented simulation can be seen as a sequence of snapshots of the state of the model, starting from simulation time t=0 8first snapshot) and ending when there aren't snapshots generated anymore. The first snapshot of the sequence is quite particular since it has to be defined by the modeller in order to initialize manually the states of all the model's entities. Events can be exogenous or endogenous according to their lying inside or outside the system's boundaries. Often, in these kind of simulations, the modeller's objective is not to examine the model's regular behaviour, but to test its reaction to particular disruptions or disturbances. At the starting of the simulation, it performs the routine events, until it encounters the exogenous event. [79]

# 6.2 FlexSim software

### Introduction

Figure 106. FlexSim logo. Source: [80]

To increase business efficiency often scenarios and forecasts are recommended, and usually they involve visualization and modelling. "Still nowadays large corporations often rehearse certain business processes, but simulation software solutions like FlexSim have largely replaced this practice." [80]

FlexSim Software Products is one of the most known simulation software producers in the world. "In the beginning, FlexSim was mostly used as manufacturing simulation software; over the years, it has evolved into a discrete-event simulation solution that can be applied in sectors other than manufacturing and assembly". In essence, FlexSim allows companies to create computer-based modelling scenarios or simulations of business processes and systems. "Users can access a wide range of intuitive tools that automatically scale to many scenarios. The physical layout can be imported or drawn, and objects can be added by dragging them from the library menus to the model itself."

FlexSim usually "supports all engineers, managers, and decision makers who are looking to validate, improve, or learn more about their processes." [80]

Although users in the manufacturing industry have traditionally been the main FlexSim target users, other sectors can optimize their processes with this software too (healthcare, retail distribution, fuel production, mining, packaging, customer support, and logistics). Notable FlexSim features include:

- Extensive objects library
- Powerful graphics engine for full animations
- Smart process analysis
- Free add-on modules for specific sectors

[80]

### Competitors

Many discrete-event simulation programs are available on the market but, after an accurate comparison, we decided to opt for FlexSim for many reasons.

The main competitors we found are AnyLogic (by AnyLogic Company), Arena (by Rockwell automation) and Simio (by Simio). Any of these provides the turbulence modelling and the only main odd of FlexSim with respect to the competitors is the agent-based modelling. But, on the contrary, FlexSim is the unique software providing both an Industry specific database and the motion modelling.

Going on, FlexSim shows higher ratings as well in terms of value for money, features & functionalities, customer support, ease of use. All of them are available and compatible with Windows on PC and need an activation license. [80]

# 6.3 Simulation model

This section aims to describe the FlexSim model both in its single constituent elements and the basic process flow. Simulating with FlexSim allowed to intuitively get an idea about how a battery swapping stations' network may work in our highway system. Even if it cannot provide real accurate results, it can give some insights and help identifying problems. The model itself was built by another master's degree student during its final thesis work, I decided to exploit it as a starting point for some data analysis and I thought it could have been useful trying to decline it in a real context. I tried to simulate a broader scenario from a higher point of view by assuming some realistic input data, optimizing the model structure and performances under stress test conditions, using the model repeated to represent each node of the network and looking for some potentially useful approximate results.

The model is constituted by several objects with specific attributes, variables and visual properties. The "flowitem" which flows through the model is a box, standing for the electric truck's battery which should represent the truck itself driving up and down our country. In the model there are fixed resources sending and receiving the items and task executers which are mobile resources performing assigned tasks. Task executers define the transfer times between the fixed resources and execute pre-defined task sequences. The total time in a FlexSim system is determined by buffers, processes and transportations. Objects are connected through input, output or centre ports. To each single flowing item a series of labels is associated in each object of the model so that at the end it is possible to have the whole history available of each item flown.

In our specific case the flowitem (battery) is associated to the attribute "ItemType" which distinguishes two types of flowitems in the model. The Type 1 represents a battery with 300 kwh capacity associated to an electric truck with range autonomy of 400 km while the Type 2 item is a 500 kWh capacity battery associated to a 550 km range autonomy electric truck.

Except for the flowitems, every object has a triggers panel to decide what to do when events occur. Labels are linked to triggers in entrance and exit from each element.

The process flow of the simulation is used to describe the task sequences of each object and how they are related, it a flow chart.

Each object's statics after simulation can be easily accessed from the object's options, these statistics can be displayed in global tables (as in our case) which update automatically as long as the simulation is running. These tables are fully customizable and can display the most suitable and useful parameters associated to the simulation. They are useful to be read and written by all the objects in the model. Global tables can be exported in Excel in order to perform data analysis on the data they provide.

Task executors move items on fixed paths through connected nodes.

Going into the detail, I am going to describe the swapping station with automated warehouse basic model that I exploited to simulate a sequence of swapping stations dislocated across two fixed path crossing Italy from both coasts. The model that we used for the pilot project and the full experiment are very similar and based on the same principles. The basic model can be constructed with one, two or three swapping bays to which, however, must be associated respectively one, two or three waiting queues and AGVs, implying more complex routings and paths connecting nodes.

A source introduces flowitems in the model in fixed proportions between type 1 and type 2 and is sending them to the input buffer (waiting queue). Each box (battery) is numbered in order to allow for data process and storage about its process. In case of multiple buffers it sends the item to the buffer with the shortest queue. Items are generated with an inter-arrival time based on hourly rates over the day since the simulation lasts 24 hours. Different labels are managed in the trigger panel, from colour linked to type 1 and 2 items to SoC entry level (probably the most important). The maximum SoC is fixed to 90%. The waiting queue is connected to the swapping bay simulated by again by a queue. The SwapBay maximum content is set to one item at a time and a label defines its actual state between busy and free (1 or 0). Through the triggers panel the output process is defined, according to which an AGV takes the box to the storing bay (queue). Paths can generally be straight or curved. An AGV is an automated guided vehicle following a directed path and taking operating decisions at control points. Each AGV (task executer) is described by technical specifications like loading/unloading time, capacity, speed, acceleration, deceleration. Each AGV can transport only one item at a time and through labels is managed its position and state (busy or free, 1 or 0).

The storing bay has the maximum content set to one as well. Then, from the storing bay an ASRS takes the battery to the warehouse and position in the free space ("pass to first available"), determined by coordinates (row and bay). The ASRS again is described through some technical specifications like speed, height, capacity, acceleration, deceleration and load/unload time. The most charged battery of the correspondent type in the rack is now chosen and taken by the ASRS to a retrieval bay (queue). From this retrieval bay the item is sent to the first available AGV which takes it to the sink. The sink represents the end of the process and ideally means that the truck is ready to restart driving until the next station (new battery required). The sink, through the trigger panel, allows to manage the exit label of the item by recording and storing in global tables all the customer's useful data.

The rack simulates a warehouse and, so, stores the flowitems. Its dimensions can be specified in terms of rows and levels (and relative height and width) as well as storage and picking criteria and a minimum dwelling time. In our case no dwell time is used and the item is stored randomly in the first available place. The rack allows, through the triggers panel, to record and register data about batteries SoC, energy required and timings while in the warehouse (on entry and exit). The rack is connected to the source rack which fills the rack with 90% SoC batteries at the beginning of the simulation and sets the labels referred to the numbered batteries.

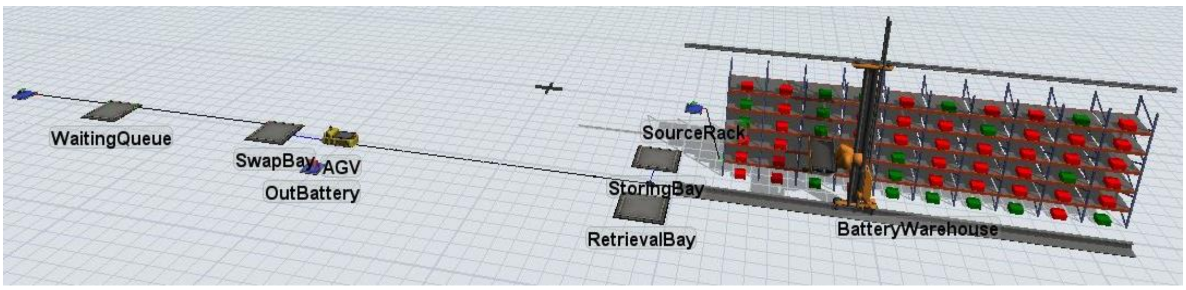



**Figure 107.** Example of single swapping bay station on FlexSim. Source: Colleague's elaboration

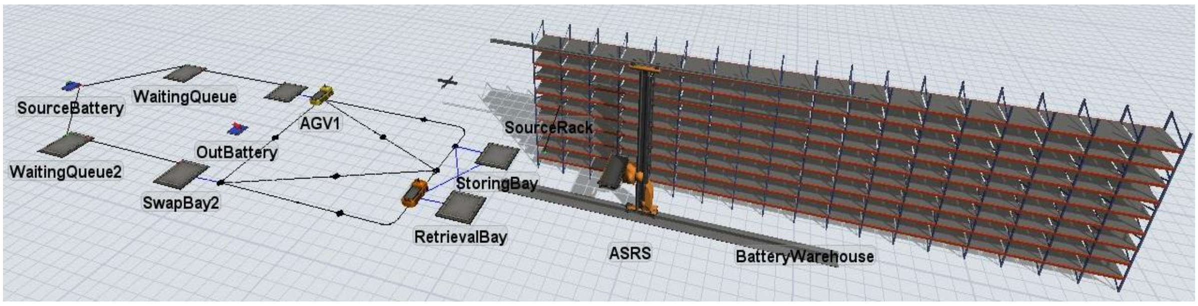



**Figure 108.** Example of single swapping bay station on FlexSim. Source: Colleague's elaboration

**Figure 109.** Example of HDT as an object on FlexSim. Source: Personal elaboration

Each place in the rack matrix is provided with a 22 kW charger (low charging mode) as reported in the first input global table. The second input global table refers to the battery capacity of type 1 and 2. The simulation time is 86.400 seconds, corresponding to 24 hours and, at the end, the output global table are automatically filled with requested data about batteries and customers. "BatteryTable" and "CustomersTable" are exported to perform data analysis.

| | Type | Capacity | StoringSoC | SoC | EntryTime | MaxSocTime | OutTime | State | Energy | StayTime | StayTimeToM | ChargingTim |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Battery 1 | 1 | 41 | 90 | 90 | 0 | 0 | 615.51 | -1 | 0 | 615.51 | 615.51 | 0 |

**Figure 110.** Example of "BatteryTable" structure. Source: Colleague's elaboration

| | StartWait | EndWait | StartService | EndService | TimeOfWait | TimeOfService | TimeInStatior |
|---|---|---|---|---|---|---|---|
| Customer 1 | 600 | 600 | 600 | 678.48 | 0 | 78.48 | 78.48 |

**Figure 111.** Example of "CustomersTable" structure. Source: Colleague's elaboration

From this model, I designed two experiments to be conducted, representing respectively a short term trial and a long-term full project idea. This is a “universal” model working for almost every vehicle and I decided to use it for heavy trucks since battery swap stations for HDT have the same operation workflow with respect to passenger cars’ ones but are built differently since the truck cannot be lifted and needs more space.

The first experiment that I performed was a pilot project (described in the next chapter) in which I exploited a single swapping bay station to perform a sort of stress test.

The second experiment, more complex, involved the design of a “model” ideally built as a sequence of double bay swapping stations (described before) to simulate a heavy-duty trucks’ traffic flow in the whole country. In this case the input (dependent) variables of the system were the number of total stations (and their distance), the number of swapping bays per station, the automated warehouse throughput determined by technical specifications, the rack dimension, the chargers type and, most of all, the arrival rate. As output (dependent) variables we focused on waiting times, total time in station, SoC (%) at the exit and energy demanded.

| INPUT | OUTPUT |
|---|---|
| Arrival rate | Swapping time |
| Number of stations | Total time in station |
| Number of bays per station | SoC (%) at the exit |
| SoC (%) at arrival time | Energy demanded |
| Rack dimension | |
| Throughput automated warehouse | |
| Chargers type | |

**Figure 112.** Input and output variables sum up. Source: Personal elaboration

# 6.4 Design of Experiment

“The design of experiments (DOE, DOX, or experimental design) is the design of any task that aims to describe and explain the variation of information under conditions that are hypothesized to reflect the variation.” In simple words, an experiment’s goal is to predict the outcome by introducing some changes to the initial conditions (“input” variables) under some stated assumptions. Changing these independent input variables generally leads to a change in one or more dependent variables (“output variables”). Some “control variables”, moreover, must be kept constant in order to prevent the influence of external factors on the final result. Designing an experiment means choosing the independent, dependent and control variables as well as the statistical conditions of the experiment given some available resources’ constraints. “Main concerns in experimental design include achieving appropriate levels of statistical power and sensitivity.” [81]

In this specific simulated case study, after the description of the model, process flow and inputs/outputs variables, I'm going to state some general assumptions before focusing on the description of two different experiments designed starting from the same basic model.

The first is a pilot project to be ideally realized in the short-term, whereas the second is a long-term project, a "full" experiment projected to a 2050 electrification scenario. In both cases an introduction to the experiment is provided, followed by the description of some specific hypothesis/inputs and the actual operating model.

### General assumptions

These assumptions are valid for both the experiments. As I already stated I decided to use two different trucks for the simulations whose difference lays in the battery they use. Both trucks are heavy-duty vehicles used for long-hauls and, for this reason, their payloads range from 30 to 40 tons (which are the highest values commonly adopted in trucks' design). The first heavy duty truck (Type 1) is a lighter truck with a 300 kWh battery capacity and a range autonomy of maximum 400 km while the second one is a really heavy truck equipped with a 500 kWh capacity battery ensuring a maximum range of autonomy of 550 km. Both the batteries are considered to be Lithium-Ion batteries with a maximum SoC (%) of 90%. The main benchmarks used to choose these data were the e-Force One AG (440-550 kWh capacity of the battery and 500 km of maximum range autonomy) and the Tesla Semi (800-1000 kWh battery capacity and 480/800 km of autonomy). The choice of using just two trucks typologies is linked to the standardization process required. The type 1 and type 2 occurrence in the input flow generated by the source is regulated by a Bernoulli distribution with 66.66% occurrence of type 1 and 33.33% occurrence of type 2 for all the experiments.

We suppose a linear relationship between SoC (%) and the range autonomy ensured by the vehicle and that the trucks batteries behave the same way as the car batteries used for previous given simulation, both in terms of loading/unloading and charging/discharging, they have just higher capacity.

Both the experiments are designed for long-hauls, which means crossing the whole country from North to South driving two possible different paths (A and B) in highways. This choice justifies the case study, the choice of the trucks' typologies and the flows estimations. Here below is reported through schemes and figures the description of the two paths designed. Each node in both the paths represents a swapping station where all the trucks are ideally required to stop and swap their exhaust battery with a new one with higher SoC level, allowing to extend the range and reach the following station. The stations were located in strategic points, this means important highways' nodes. Their reciprocal distance is based on the range autonomy of the trucks' typologies and on the assumption according to which every truck needs to stop at every station since it would be impossible or too risky skip one and swap at the following station. For this reason, the trucks it is assumed that the trucks starting the journey from Turin will be the same at each station in a sort of ordered ideal chain to reach the destination and come back.


Figure 113. Route A scheme. Source: Personal elaboration

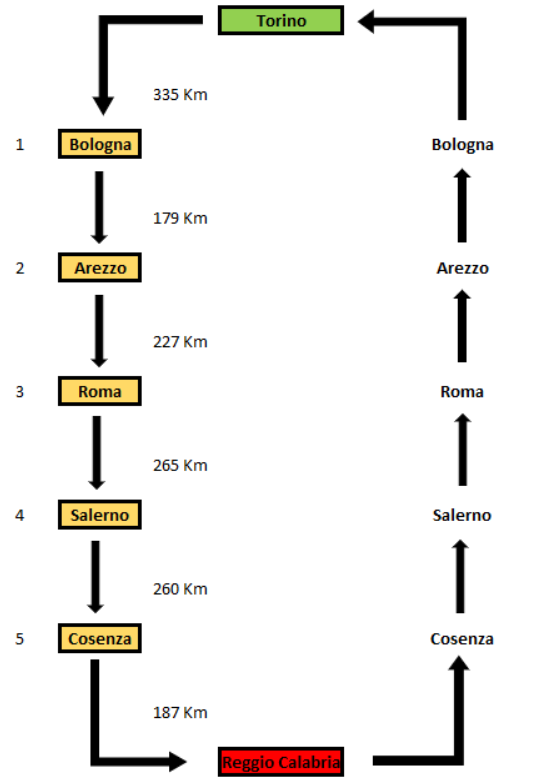



Figure 114. Route A map. Source: Personal elaboration

The first route is composed by 5 nodes on the road excluding the starting point (Turin) and the destination (Reggio Calabria), the total distance to be covered is 1.453 km per each direction (way and return). In case of Route B, instead, the stations on the road are 4 again excluding the starting point (Turin) and the destination (Lecce). The total distance is 1.204 km per each direction (way and return).

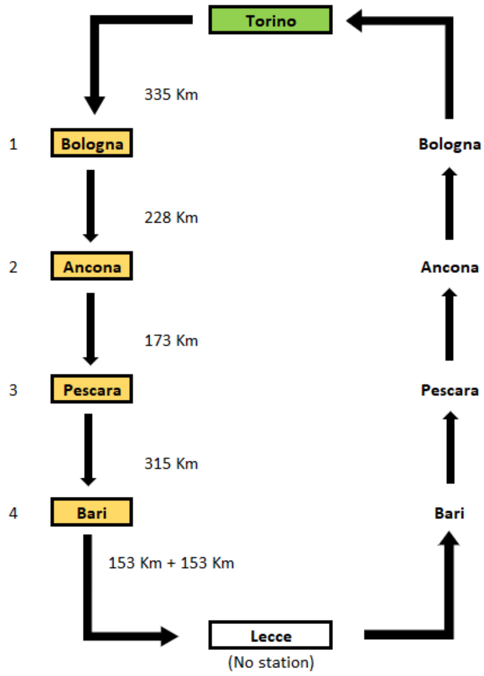




**Figure 115.** Route B scheme. Source: Personal elaboration **Figure 116.** Route B map. Source: Personal elaboration

These experiments' goals are to simulate the feasibility and to test a battery swap solution in a real hypothetical context. At the starting point in Turin a depot fast charging is required and at the destination there are two viable solutions: the first is a battery swapping station again while the second is a plug-in fast charging while loading/unloading operations are performed. The priority of the experiment's output is to ensure that every driver would be able to receive a new battery with a SoC (%) more than sufficient to reach the following station even considering driving variability affecting it and that every customer is not going to wait too much in line, since this is one of the greatest benefits from drivers' point of view compared to a traditional plug-in service for long highways commercial journeys.

The use of the simulation is justified by the insertion of variability in the two most important parameters (i.e. the incoming flow of vehicles and the entrance storing SoC of the batteries). For the first parameter it is based on estimated average hourly departure rate during the day, equally spaced in time with a variability (a normal distribution with standard deviation at 10% is used for inter-arrivals times, due to departures times and driving modes, calculated considering a suitable ± 3σ range of values). The SoC of the battery at which the truck is entering the station, instead, is linearly dependent on the distance travelled to reach the station, the starting SoC and come external factors like the driving mode. In our specific case we decided to simulate the first (and most distant) station (i.e. Bologna) starting from Turin. HDTs are supposed to leave from Turin with 90% (maximum) SoC thanks to the fast charging option at the depot and they drive the 335 km to reach Bologna. A different calculation must be performed to estimate the arrival SoC for the type 1 and type 2 trucks respectively. By using a proportion between SoC and driving range autonomy we estimated an average value of 15% entrance SoC for type 1 trucks and 35% for type 2. We considered this as the mean value around which a normal distribution has been supposed. Standard deviation for type 1 is set to 3% and for type 2 is set to 6%. This variability has been calculated starting from an estimation of a suitable ± 3σ range which includes around 99% of the values. For the type 2 truck a higher standard deviation has been hypothesized since the higher power and performances of the electric engine as well as the higher weight and dimensions may induce higher levels of variability according to the driving mode.

```
{ // ************* PickOption Start ************* //
/***popup:SetLabel*/
/**Set Label*/
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string labelname = /** \nLabel: *//***tag:label*//**/"SoC"/**/;
Variant value;

if (item.Type == 1)
 value = /** \nValue: *//***tag:value*//**/normal(15, 3,
 getstream(current))/**/;
else
 value = /** \nValue: *//***tag:value*//**/normal(35, 6,
 getstream(current))/**/;

involved.labels.assert(labelname).value = value;
} // ******* PickOption End ******* //
```

Figure 117. FlexSim code defining the entrance SoC (%) according to truck type. Source: Personal elaboration

In a hypothetical "full journey" simulation some other variability should be considered in loading/unloading times at destination.

The simulation in our specific case took into consideration just the first station which is the most critical one, anyway the reasoning can be applied to all the other stations in the two paths considered to be independent.

Each experiment is conducted in steady-state conditions and this means that data analysis starts after some time slots of actual simulation.

In the following paragraphs the methodology used to estimate the trucks' flows will be explained, however, a general assumption for all the experiments is about the daily average percentage breakdown. Looking at some real examples, I decided to assume the following breakdown, regardless of the absolute values of trucks considered in different scenarios. I divided the 24 hours-day into three time slots of 8 hours each and, of course with some variability, given 100% trucks flowing in a day this is a reasonable approximated result to be used as an input for simulations.

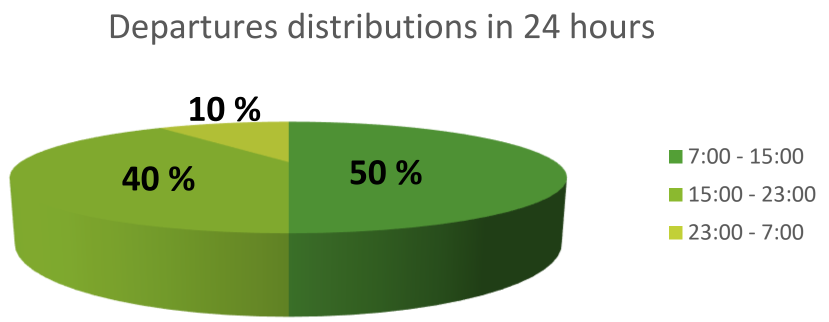



**Figure 118.** Departures/arrivals average daily distribution. Source: Personal elaboration

Regardless of the input parameters chosen for experiment's model, another common value is the power of the chargers in the warehouse. Each place in the rack is equipped with a 22 kW charger which can be active or not according to necessities and charging strategies. 22 kW is the common power value for normal (slow) charging for every vehicle, the choice of not using fast chargers is led by the relative advantage that this gives compared to plug-in traditional charging (as we will see in the next paragraphs) both in terms of grid overload and battery degradation (reduction of useful life).

Another macro-choice was about ideally using a single swapping station for both highway's directions or one for each direction. For sake of simplicity in simulations we only considered one direction, which implies the second option. This second option is better for flows management and can split the space required but at the same time demands a higher investment. The first option, instead, requires a unique highway exit and a lot of space in terms of warehouse and trucks' movements.

### Pilot project

This experiment is aimed at simulating a short-term situation with a relatively simpler model in line with the actual level of electrification of HDTs. It is intended as a pilot experiment to test the battery swap solution in this context with a lower investment and quicker realization. It is simulating an automated warehouse with an actual technology with the final goal of finding the maximum trucks' flow (maintaining the proportions stated in the previous section) that this model can bear. So, the idea behind this project is to conduct a sort of stress test.

#### Specific hypothesis/inputs

The model is constituted by a single swapping bay in the station, a warehouse (rack) of "just" 60 batteries split into the two typologies (already mentioned). The maximum supported flow of trucks is evaluated over a timeframe of 24 hours (86.400 seconds of simulation) in a steady state (i.e. valid for a random day in the year)

AGV and ASRS have standard setting in terms of horizontal speed, vertical speed and acceleration. Time for loading/unloading batteries is set to 9 seconds. These parameters determine the throughput of the warehouse and, as a consequence, the service time and the time between two consecutive swaps.

In order to evaluate a possible maximum flow manageable by this system I adopted empirical approach in which, by modifying the input flow (by maintaining the proportions between time slots in the day), I analysed the output SoC (%) and the waiting times of the hypothetical customers. As output thresholds for these two variables I opted for zero waiting times for customers in order to maximize the real benefit of a battery swapping solution and a SoC (%) minimum required to reach again the next station in any case. This means that each truck is required a SoC greater that the value required to drive for 228 km (to Ancona) considering a certain margin due to variability in driving mode.

To sum up, I tried to define the maximum frequency of trucks requiring a battery swap service in this fictitious station that can be satisfied ensuring:

$$\begin{cases} Waiting\ times = 0 \\ SoC\ (\%)\ Type\ 1 > 51.3 + n * \sigma \\ SoC\ (\%)\ Type\ 2 > 37.31 + n * \sigma \end{cases}$$

As I already clarified, this is a pilot simulation in the present, developed considering the reduced actual possible truck electrification scenario and automated warehouse technologies. This is to be intended as a first test (with limited resources required) for the full network designed considering a fully developed scenario (2050).

<u>Operating model</u>

As I mentioned before, I adopted a trial and error approach to determine the minimum suitable result for the three time slots of the 24 hours per day. The hardest issue to be solved (bottleneck) turned out to be the exit SoC instead of the waiting times, since a higher frequency flow of trucks could have been supported by the model ensuring zero waiting times but it could not provide sufficient SoC exiting the warehouse.

We could have performed this kind of simulation both with 22 kWh (normal) and with 150 kWh (fast) chargers, but this wouldn't have much sense since, whereas providing probably all 90% fully charged batteries, it would cut completely the benefits of a BSS solution in terms of energy management and batteries' life preservation.

### Full Experiment - 2050 Projections

This experiment is the main focus of the paper and it is projected in the long-term (around 2050) in order to test a BSS solution in an almost fully electrified HDTs scenario. The simulations and design of experiment are again based on the macro-network of stations for long-hauls HDTs transportation explained before. In this case we tried to estimate possible trucks traffic flows in order to design a model able to bear this traffic even in its worst condition and give back satisfying results. For time and simplicity reasons, I decided to focus only on the first swapping station as it is the most critical one (bottleneck of the system) and could be very useful to get insights about the whole network operating model, the most significant parameters to keep under control, the desired output and, possibly, the kind of analysis to be conducted.

Specific hypothesis/inputs

Looking at the last decade's data about trucks we can identify an almost flat curve in the number of circulating HDTs for long hauls and, so we suppose that in 2050 as well the heavy weight trucks traffic will be almost the same with respect to actual situation, thanks to opposite drivers. These are the development of alternative transportation modes, the increase in transport efficiency and, on the other side, the increase in logistics complexity and requirements in a digital globalized world with diversified supply chain models. In 2050, however, a high degree of electrification will be present and, according to projections (Figure 90.), around 80% of heavy vehicles in the world will be electrified. We consider this projected data as valid for Italy specifically because, even if electrification process in southern Europe results to proceed at a lower rate, in 2050 the situation is supposed to be at a steady state worldwide. The aim is now to understand, from current data, a hypothetical number of heavy trucks which may start this long-haul journey, with the clear objective to take one of the two routes (A or B) in the following 24 hours, reaching southern Italy and coming back to Turin. The estimation of these numbers is clearly very hard matter since direct data about these long paths are not present and each highway section is kind of independent since the free trucks' inlet and outlet cannot provide results about the vehicles using that specific section in order to accomplish the full designed route. I needed to find an approximately valid indicator.

Truck dispatch can be very complicated for multiple routes and pickups/drop-offs. There is a whole math theory devoted to it, but that is not necessary when considering bulk freight concepts. Let's look at something much simpler and common. High-volume bulk transport dispatch can be considered as a bicycle chain. It's a continuous belt like a bicycle chain or conveyor belt. Trucks are continually transporting cargo and returning to pick up more. Commodities like grains and bulk items are shipped this way. The transport vehicles come home empty or occasionally have cargo on return.

Even if I tried to consider the system in this way, for sake of simplicity and validity I decided to analyse just the first station in order to reduce inaccuracy due to inlets and outlets in subsequent stations.

To this aim, I started looking at data about heavy duty trucks traffic in the highway recording points of interests. Data were extracted from 2017 ANAS (Gruppo FS Italiane, [82]) published tables. I decided to use 2017 data because resulted to be more complete for out specific goal and because I based my case study introduction on 2017 ANFIA report.

ANAS tables provide annual average daily traffic (TGMA) for both light and heavy vehicles (my focus).

According to ANAS website, the TGMA is calculated from the sensor network of the PANAMA system on the basis of the data collected from the individual stations. The TGMA data are bidirectional values, calculated with reference to counting sections. If the counting section consists of two distinct stations, one for each of the two directions of travel, the section refers to the station located at the lowest kilometre. TGMA is calculated as the arithmetic mean of the traffic measured on the valid days that make up the reference sample; a day of data is considered valid if the control unit does not report malfunctions and if data is loaded on the system for at least 98% of the 288 5-minute intervals scheduled in a day. In relation to the method of calculating the TGMA, for each station it is verified that the number of days with valid data is greater than half the number of days of the year. [83]

I looked at data coming from the recording points in the provinces of the cities constituting the designed network (Figures from 113. to 116.), in order to have an idea of the number of trucks driving daily in these sections (for both route A and B). After collecting data for all the provinces of interest, I compared them in order to choose “the least busy” area and use it a starting point for the scenarios. If I want to find a hypothetical number of trucks driving the whole route, on average it is never going to be higher than the average number of trucks registered in 24 hours in one of the consecutive nodes of the system. From this analysis it is possible to take that number as an approximation for the worst-case scenario (i.e. meaning the highest possible traffic flow of HDTs). I considered this number to be in the range of 800 -1000 trucks registered over 24 hours. This number needs to be multiplied by 0.8 which is the 80% electrification process level forecasted for 2050, obtaining in this way a number between 600 and 800 HDTs, approximately valid for both route A or B since the simulation is just an exemplification for one of the two routes, whose results can then be extended. This number of trucks needs then to be distributed over the 24 hours, respecting the proportions stated in the general assumptions. So, 50% in the first time slot, 40% in the second and the remaining 10% in the third, leading to a result of around 300-350 trucks from 7:00 to 15:00, 250-300 trucks from 15:00 to 23.00 and 60 – 100 trucks from 23:00 to 7:00 again. As I previously mentioned a certain variability determines their inter-departures and, so, inter-arrivals in order to exploit the simulation potential and go beyond the equally spaced assumption.

For sake of completeness, I opted for a three-scenarios simulation (Worst case, Middle case and Best case). Starting from the number calculated approximately for the worst case, I assumed the best case (in terms of traffic flow9 to be worth 10% of the worst and the middle case to an average of the two extremes leading to (100% + 10%)/2 = 55% of the worst case value. The process for the estimation of the hourly average traffic flow is the same as the one presented above, with the 0.8 multiplying factor and the proportions applied.

These rough calculations lead to the average approximate result depicted in Figure 119. The hourly values are obtained simply by dividing each time slot value by 8 (number of constituent hours).

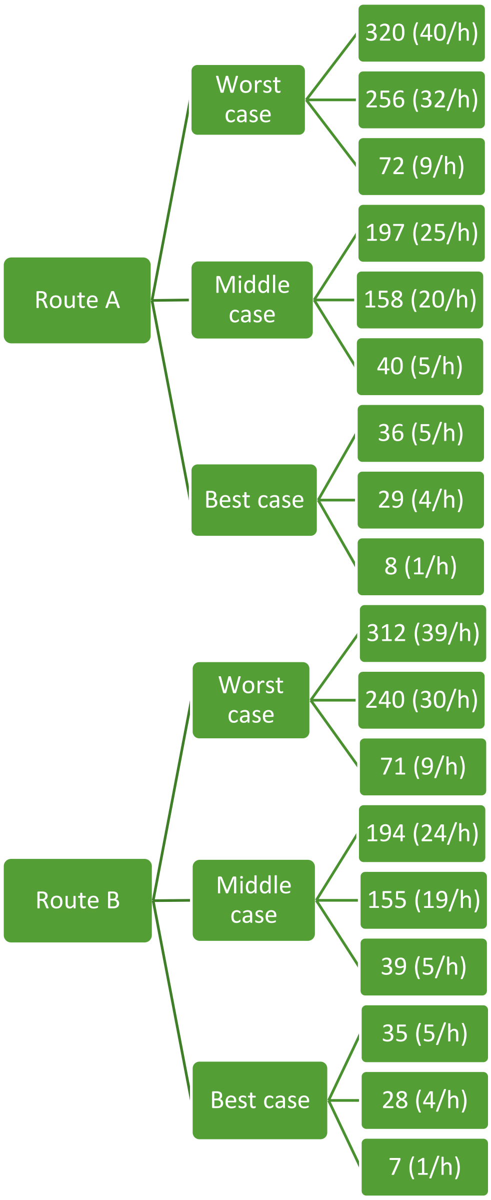



**Figure 119.** Average approximate HDTs traffic flow per route – scenario – time slot. Source: Personal elaboration based on [82]

Before describing the operating model, another important specific input/hypothesis chosen is the warehouse's technology throughput. The AGVs speed and acceleration were set in accordance to swapping times' forecasts for the future as well as the loading/unloading time (set to 7 seconds, 2 seconds less compared to actual technology used in pilot project). Also the ASRS horizontal speed, lift speed, extension speed and acceleration/deceleration are set using the same criteria. Its loading/unloading time is set to 7 seconds too. Capacity for both remains one item per time. All these parameters are going to influence the average service times and the breaks between two consecutive swaps, which in a high traffic flow scenario (model saturated) amounts to 20 seconds more or less.

Operating model

The approach that I adopted, in this case, has been to perform a trial-and-error what-if analysis in order to change one input per time in the model and evaluate the outputs, keeping the other variables fixed. The final goal was to design a model able to bear even the worst traffic flow possibly estimated by ensuring minimum acceptable results. To this aim, I analysed, as previously mentioned, the first station (i.e. Bologna, 335 km away from Turin starting point) to be then extended to all the others in terms of procedure, being it the bottleneck influencing the whole system regarding the flow times and SoC (%). The station's position is designed so that every truck can reach it with a full charged battery but at the same time needs to stop there, there is no arbitrary alternative, independently on the waiting times and exit SoC (%) available. The tests and dimensioning were clearly performed in the worst-case scenario, since the middle-case and the best-case scenarios would of course provide acceptable results, as a consequence. To each scenario, station and truck type correspond different output values.

Considering again the table reported in Figure 112., I turned some input variables into "control" fixed variables and these are in particular the chargers' type, the entrance SoC (%), the traffic flow of trucks entering the station over the 24 hours and the number of swapping stations. This last parameter has been set during the network design phase and affects some other input values as well as the output requirements to reach the following station.

So, the three main input variables which drove my what-if analysis were the number of swapping bays, the rack dimensions and the warehouse automation specifics, keeping an eye on the exit SoC (%) and waiting/service times as outputs.

In particular, the desired outputs of the worst-case scenario for the Bologna station can be summed up as follows:

$$\begin{cases} Maximum\ time\ in\ station \leq 30\ minutes \\ SoC\ (\%)\ Type\ 1 > 51.3 + n * \sigma \\ SoC\ (\%)\ Type\ 2 > 37.31 + n * \sigma \end{cases}$$

The swapping time is considered to be independent on the battery typology and the time in station is required to be lower than half an hour in order to stress the greatest advantage of battery swapping compared to a traditional plug-in solution. Again, like in the pilot project, the SoC (%) for type 1 and type 2 HDTs are all supposed to be bigger than the SoC (%) required to reach both the two following stations (Arezzo and Ancona) with a certain margin due to variability of driving mode and a minimum remaining percentage required at the destination. I considered both stations because I tried to generalize the approach.

With these variables' classification clear in mind, the following are some general considerations that came out from a sensitivity analysis performed through the simulations. The number of swapping bays is strongly affecting the waiting times (queues) in the system if properly coupled with the warehouse technologies (AGV and ASRS). The warehouse dimensions, in terms of rows and bays, affects the exit SoC (%) but after certain dimensions its influence becomes of little interest. Increasing the warehouse dimensions on one side means increasing the available SoC (%) for the batteries to be swapped but, on the other side, it increases the service (swapping) time, despite it represents a small share of the total time in station. The number of chargers in the warehouse has always been kept equal to the rack capacity (e.g. 240 spots means 240 possibly active chargers). The batteries capacities and the chargers power show relevant influence on the exit SoC (%), since bigger batteries required higher charging times and higher power chargers lead to higher exit SoC (%). However, the charging power has been fixed to 22 kW in order not to affect the BSS benefits for batteries and grid deriving from normal charging instead of fast charging. Clearly the entrance SoC (%) affects a lot the exit SoC (%) results and the same does the arrival times distribution with the customers' waiting times. The automated technologies exploited to move the items in the station (i.e. the AGV and the ASRS) affect considerably the waiting times of customers.

Based on these considerations, I tried to design the best (optimized) model for our purpose, first focusing on the number of required swapping bays. What came out is that a single swapping bay could never be able to manage such a traffic flow (Bologna station, worst case scenario), no matter the warehouse dimensions and the warehouse technologies. Having a single swapping bays is not sufficient to keep waiting times for customers relatively low, creating long queues in the buffer. Increasing the swapping bays to two and three, more acceptable results come out and, from this point, I started working on both solutions in parallel by making the same changes to the warehouses. I first focused on the rack dimension by increasing its dimension in the order of 20 spots per step. Both exit SoC (%) and waiting time results seemed to be evolve similarly and be comparable, so, in order to optimize both initial investment (capex) and operating/maintenance costs, I chose the minimum swapping bays model able to provide acceptable results (i.e. two swapping bays). I opted for 2 AGVs and a single ASRS for this specific model and I set the speed, acceleration/deceleration and Loading/unloading specifications as previously mentioned, being in line with possible future evolutions in the swapping times required. At this time I focused on the last design parameter (the warehouse) so as to find the minimum rack dimension. After many simulations (trial-and-error approach) it came out that a 240 batteries rack is enough to obtain acceptable outputs in the worst-case scenario and, as a consequence, in both the middle and best-case scenarios too.

All the results of this full experiment, for all the three possible scenarios are described in the next sub-chapter (i.e. 6.5 Results) together with a section dedicated to further analyses and comparisons.

# 6.5 Results

The experiment described above led to some interesting results. Here below the outcomes of the simulations are presented again split into the two experiments, first the pilot project and then the full experiment. The last section's goal is to provide some conclusive (mainly qualitative) analyses and insights on timings, costs, energetic demand and SoC, comparing traditional ICE powertrain, electric powertrains with DO formula for batteries (traditional wire charging) and the battery swapping solution.

### Pilot project

The results of the pilot experiment are reported in the following table, showing a potential trucks' flow distribution in three time slots (10% - 50% - 40%).

| Inter-Arrival time | |
| --- | --- |
| Time slot | Trucks # |
| 0:00 - 1:00 | 3 |
| 1:00 - 2:00 | 3 |
| 2:00 - 3:00 | 3 |
| 3:00 - 4:00 | 3 |
| 4:00 - 5:00 | 3 |
| 5:00 - 6:00 | 3 |
| 6:00 - 7:00 | 3 |
| 7:00 - 8:00 | 11 |
| 8:00 - 9:00 | 11 |
| 9:00 - 10:00 | 11 |
| 10:00 - 11:00 | 11 |
| 11:00 - 12:00 | 11 |
| 12:00 - 13:00 | 11 |
| 13:00 - 14:00 | 11 |
| 14:00 - 15:00 | 11 |
| 15:00 - 16:00 | 9 |
| 16:00 - 17:00 | 9 |
| 17:00 - 18:00 | 9 |
| 18:00 - 19:00 | 9 |
| 19:00 - 20:00 | 9 |
| 20:00 - 21:00 | 9 |
| 21:00 - 22:00 | 9 |
| 22:00 - 23:00 | 9 |
| 23:00 - 24:00 | 3 |

**Figure 120.** Resulting inter-arrival time in 24 hours simulation for pilot project. Source: Personal elaboration

This inter-arrival schedule is able to ensure an average state of charge for type 1 batteries of 70.28 % with values ranging from to 53.74% and 90%. The minimum SoC is able to provide 239 km of range autonomy on average, supposing a linear relationship between the two parameters. Here below two graphs to describe the SoC level for type 1 batteries.

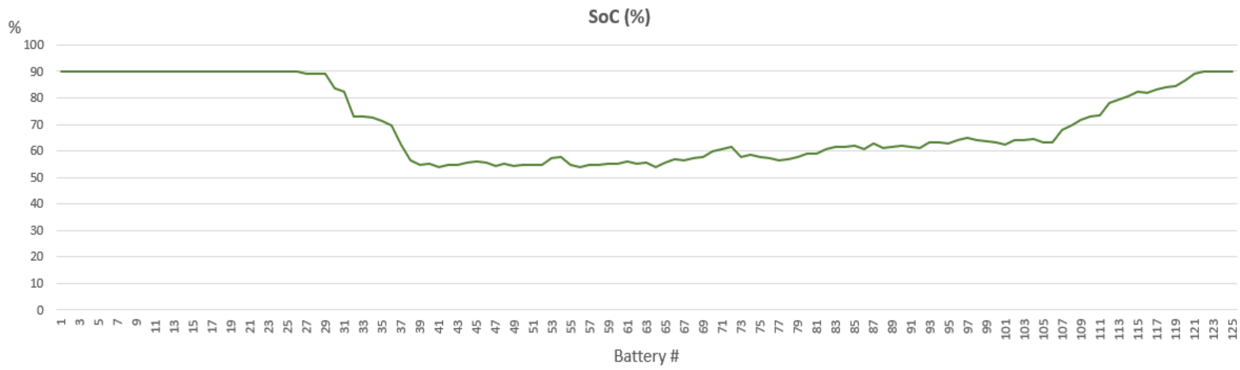



**Figure 121.** SoC (%) graph for type 1 trucks in pilot project. Source: personal elaboration

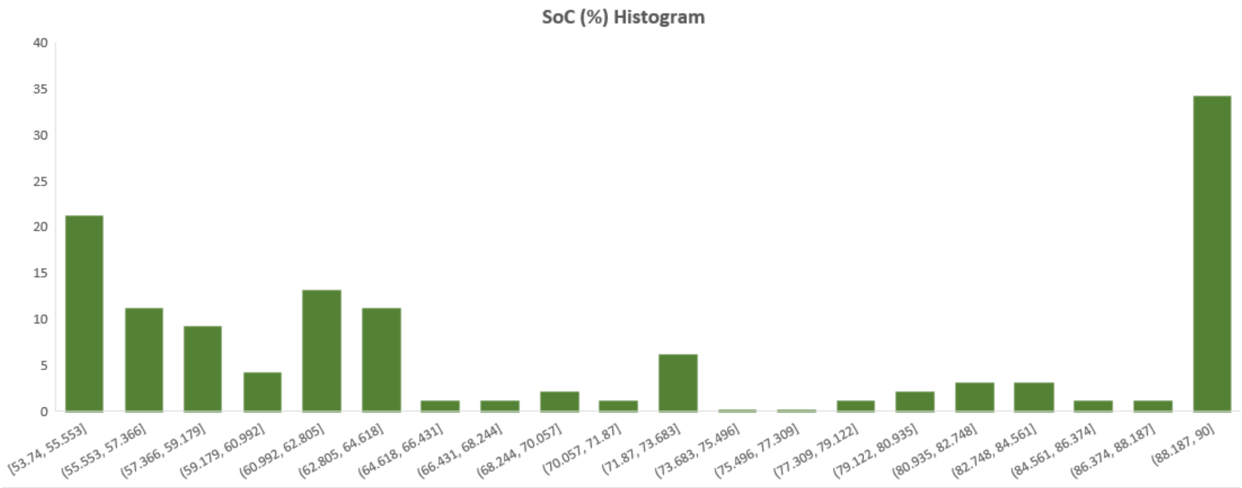



**Figure 122.** SoC (%) histogram for type 1 trucks in pilot project. Source: personal elaboration

In the same way, this schedule can guarantee an average state of charge for type 2 batteries of 69.95% with a minimum value of 55.86% and a maximum value of 90%. The minimum value corresponds to 341 km of range autonomy. Here below the two corresponding graphs.

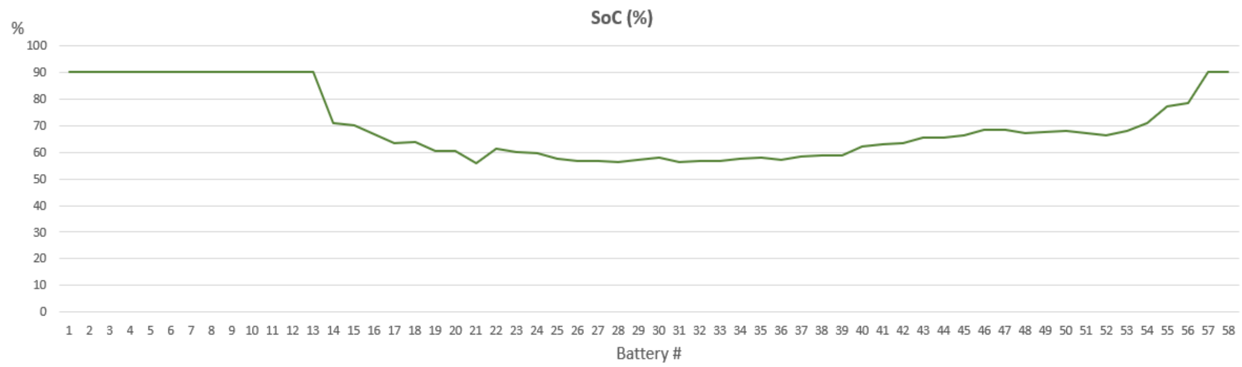



**Figure 123.** SoC (%) graph for type 2 trucks in pilot project. Source: personal elaboration

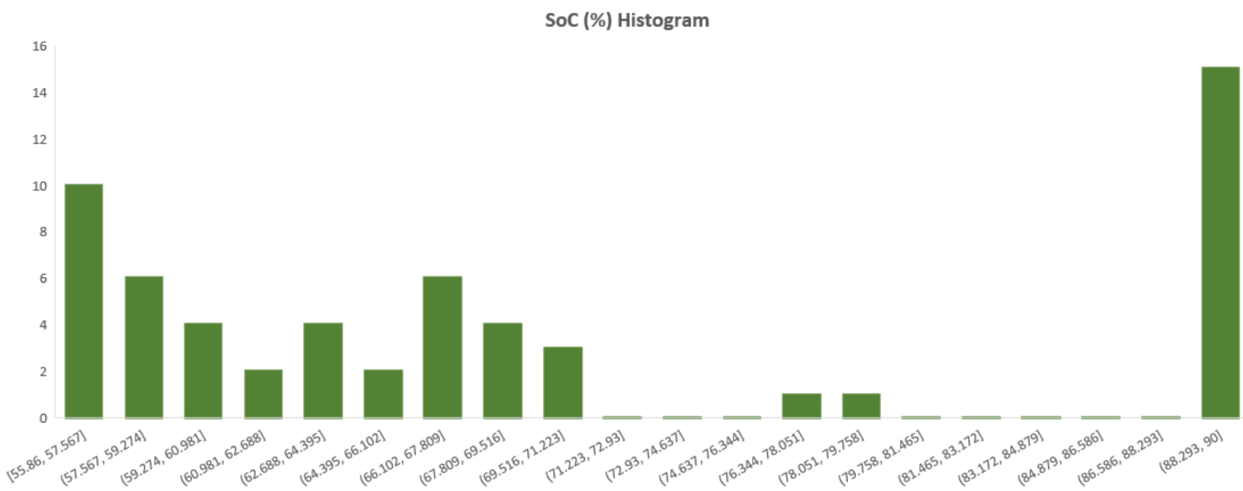



**Figure 124.** SoC (%) histogram for type 1 trucks in pilot project. Source: Personal elaboration

For what concerns the customers' experience, the waiting times are all zero as I said, so, the only relevant parameter is the service time in seconds, corresponding in this case to the time in station of each truck. The average time in station amounts to 89 seconds with a standard deviation of 5 seconds and the maximum value is just 1 minutes and 45 seconds, witnessing how beneficial the battery swapping solution may be for the drivers.

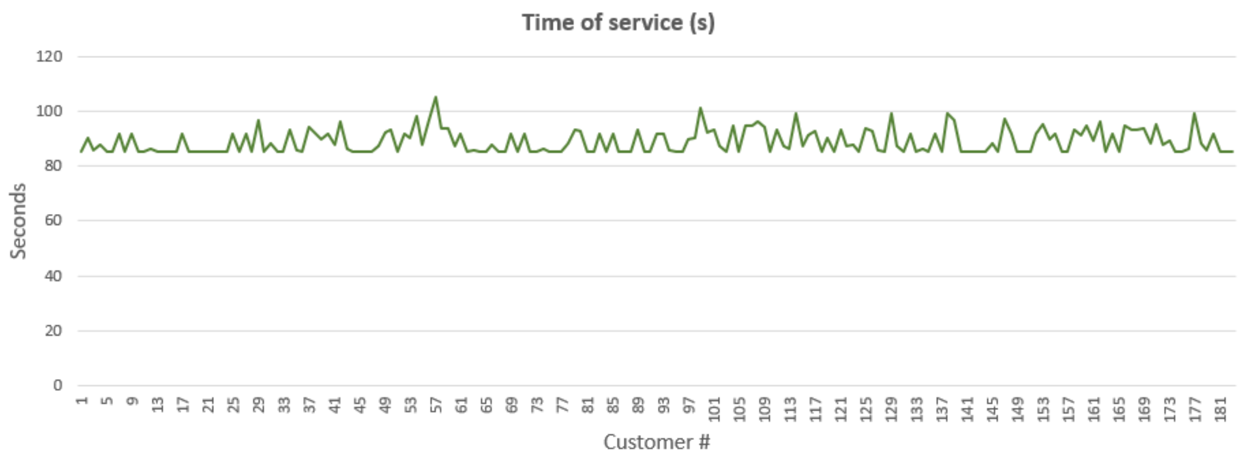



**Figure 125.** Time of service graph for pilot project. Source: Personal elaboration

### Full experiment – 2050 projection

The final model described in the previous sub-chapter was used to simulate the three scenarios over 24 hours (from 7 a.m.) at steady state. Here the results related to each scenario, with particular attention to the worst case.

In the worst-case scenario we analysed 425 type 1 trucks and 221 type 2 trucks over 24 hours (Bernoulli distribution 66% - 34%) and the swapping stations following Bologna are, again, considered to be Arezzo for route A (179 km far away) and Ancona for route B (228 km far away).

Figure 126., derived from the batteries' global table exported from FlexSim to Excel, shows the exit SoC (%) trend for the type 1 trucks in this scenario, highlighting a depression of the values from a certain battery on, before coming back to full charge at the end. The minimum SoC (%) values required for these trucks to reach the following stations, based again on a linear relationship proportion (to which a certain margin should then be applied), are respectively 40.28% for route A and 51.30% for route B. The average exit SoC (%) of type 1 trucks is 75.21% while the maximum amounts to 90% and the minimum (most relevant value to be considered) amounts to 59.43%, allowing, with a linear proportion, 264.13 km of range autonomy which is higher that both minimum required values considering a variability margin as well. The dispersion of the output values (range, std. dev…) is quite high. The histogram in Figure 127. highlights the frequency of each exit SoC (%) cluster, split into 20 bins between minimum and maximum SoC (%) output values.

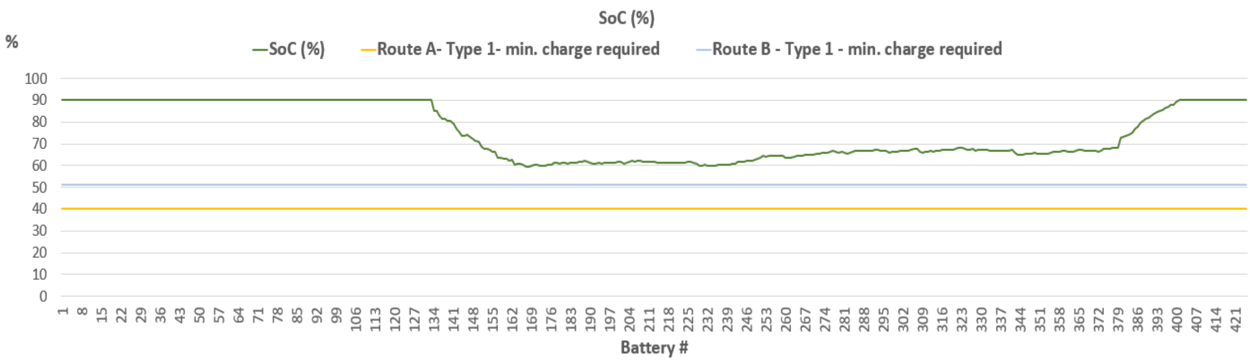



Figure 126. SoC (%) graph for type 1 trucks in full experiment - worst case scenario. Source: personal elaboration

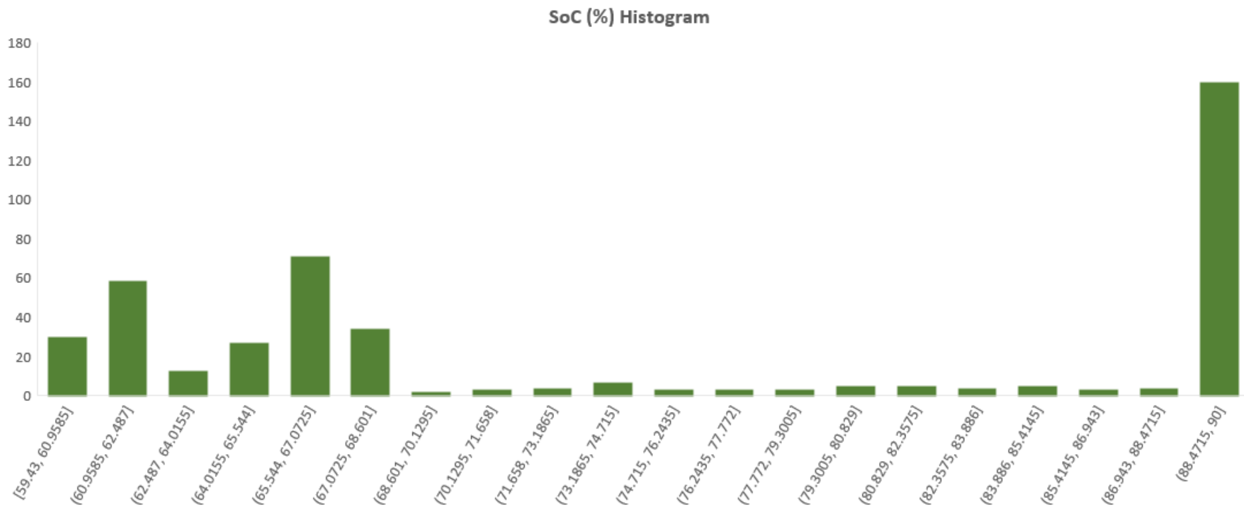



Figure 127. SoC (%) histogram for type 1 trucks in full experiment - worst case scenario. Source: personal elaboration

The same reasoning is applied to type 2 trucks, in which the average exit SoC (%) is a bit lower and the curve seems to struggle more to come back to full charge values. However, the average SoC (%) value is 72.72%, the maximum value amounts to 90% and the minimum amounts to 59.65%. Even the minimum value allows for a range autonomy value (364.53 km) which is higher that both routes' requirements, considering a high variability margin as well. The minimum required exit SoC (%) plotted on the graph are, respectively, 29.29% for route A and 37.31% for route B.

The histogram in Figure 129. mirrors these considerations, showing higher frequencies in the lower bins and reducing the frequency of the full charge bin.

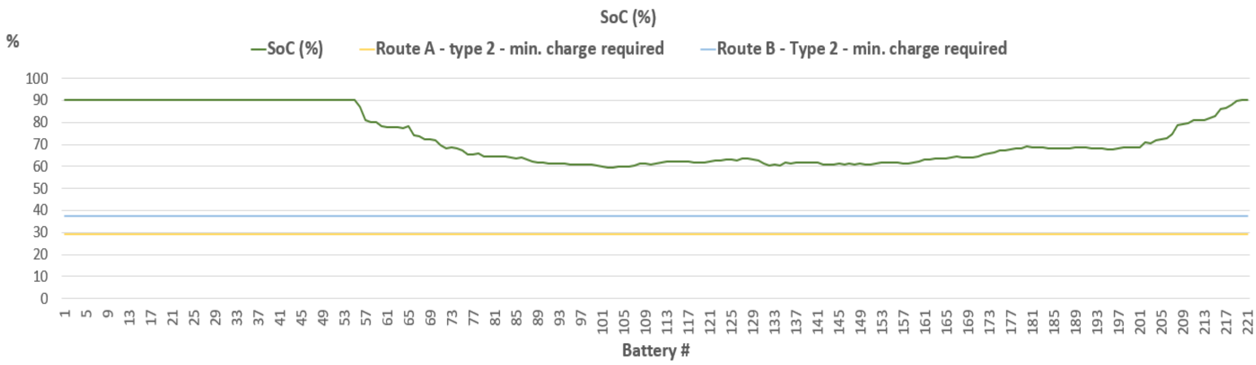



Figure 128. SoC (%) graph for type 2 trucks in full experiment – worst case scenario. Source: personal elaboration

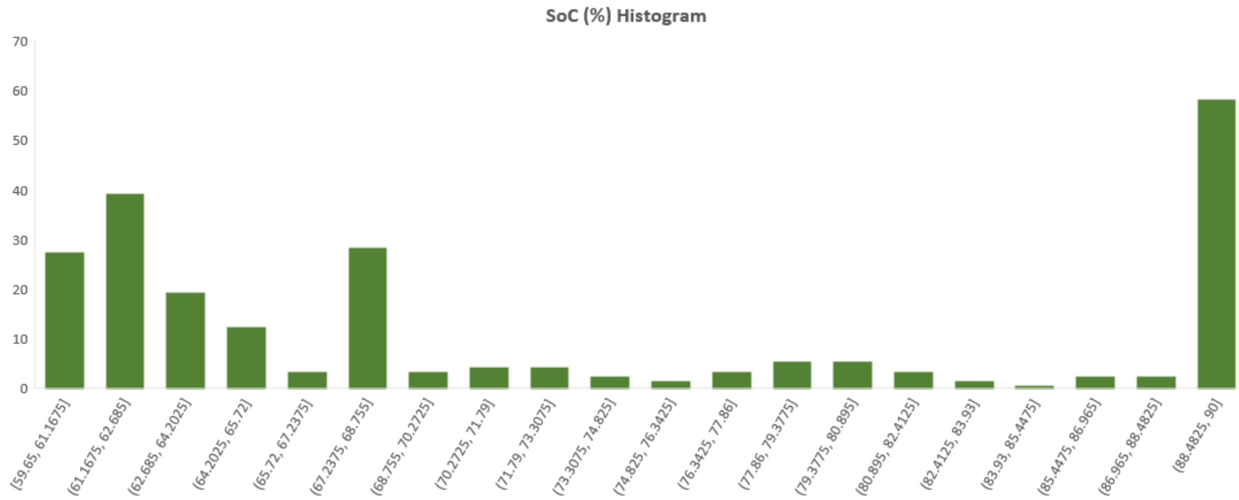



Figure 129. SoC (%) histogram for type 2 trucks in full experiment – worst case scenario. Source: personal elaboration

Looking now at the customers' global table exported, it is possible to plot the waiting times of drivers and the time of service (swapping) in Bologna station. Clearly the waiting times suffer an increase in the values, reaching the peak and then going down, during the highest traffic period, since the station hour after hour accumulates a longer queue, until it is able to manage and dispose it. The average waiting time amounts to 151 seconds while the maximum time in station, given by the waiting time plus the time of service, amounts to 1.083 seconds (i.e. 18.05 minutes) with an average value of 272 seconds. This maximum value is, anyway, well below the 30 minutes time limit imposed.

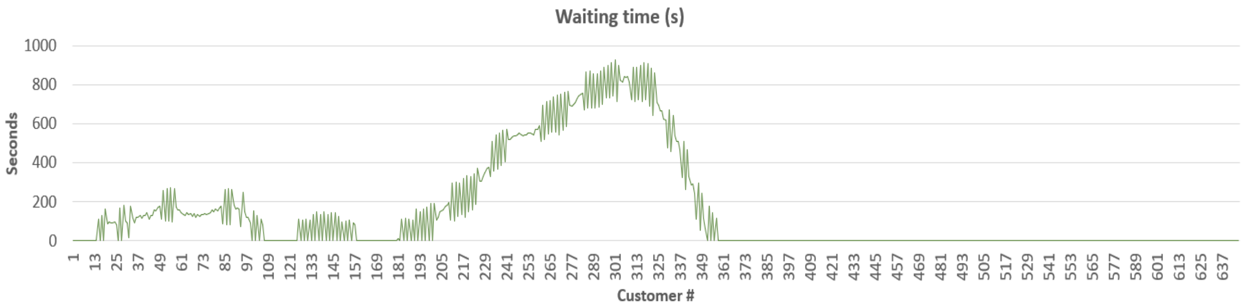



Figure 130. Customers' waiting time graph for full experiment – worst case scenario. Source: personal elaboration

The time of service graph obviously shows a flatter curve which is less influenced by the model choices. In this case the average time of service amounts to 121 seconds with a standard deviation of 42 seconds.

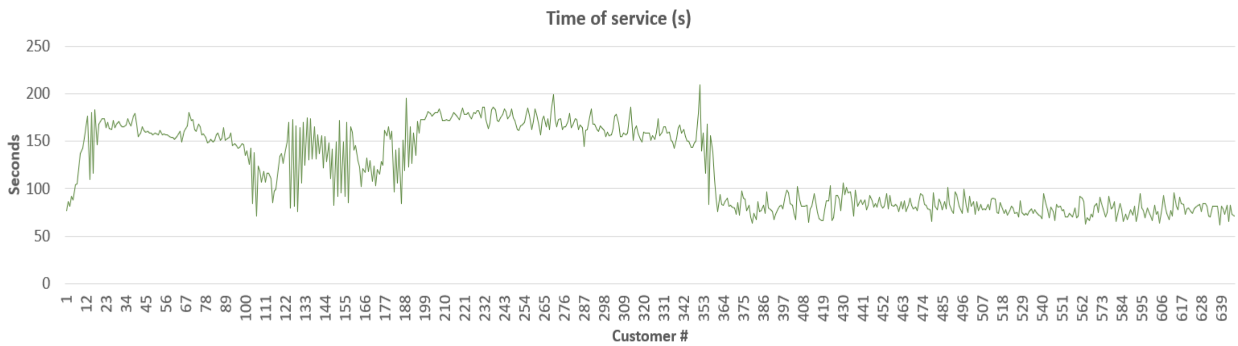



Figure 131. Time of service graph for full experiment – worst case scenario. Source: personal elaboration

Focusing now on the middle-case scenario, I propose a quite similar analysis coming from the batteries and customers table as well. The model exploited is exactly the same, what changes are just the traffic flows as described in the previous sub-chapter. The type 1 trucks analysed are 257 while the type 2 trucks are 146. In this case, applying a proportionate reduction of trucks' flows during the 24 hours of simulation at steady state, the waiting times immediately went down to zero for all the customers providing an extremely satisfying service to the drivers compared to other traditional range extension solutions.

Looking at the exit SoC (%) values, they improved if compared to the worst-case solution both in the average values and the minimum values. In case of type 1 trucks the histogram in Figure 133. clearly shows very high frequencies on 90% (full charge) output. The average value amounts to 89.9% while the minimum one to 89.25%, ensuring 396 km of range autonomy to the HDT. The minimum thresholds are the same described for the worst-case scenario.

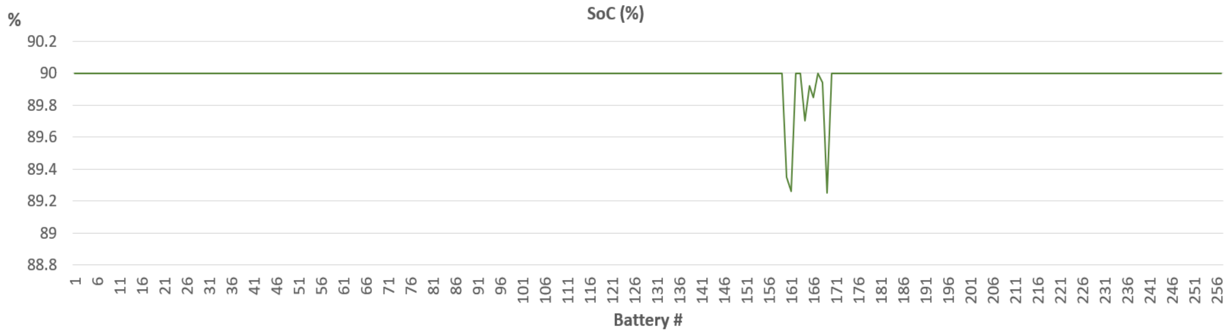



Figure 132. SoC (%) graph for type 1 trucks in full experiment – middle case scenario. Source: personal elaboration

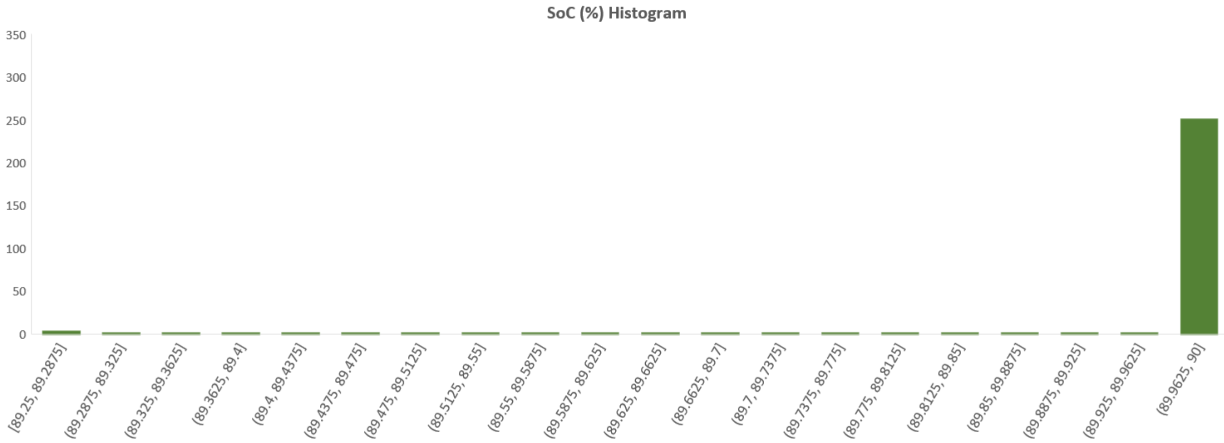



Figure 133. SoC (%) histogram for type 1 trucks in full experiment – middle case scenario. Source: personal elaboration

The improvement for type 2 trucks is less marked with respect to type 1 in the passage to a middle-case scenario. However, even in this case the histogram frequencies are very high at 90% full charge values. The depression of the exit SoC (%) curve leads to a minimum SoC (%) of 75.6%, ensuring 462 km of range autonomy at the exit of the Bologna station. The average SoC (%) value amounts to 85.81%.

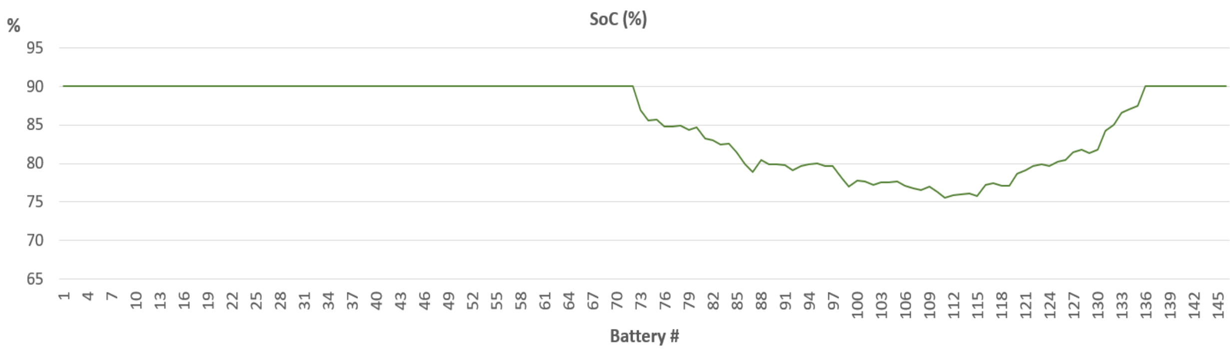



Figure 134. SoC (%) graph for type 2 trucks in full experiment – middle case scenario. Source: personal elaboration

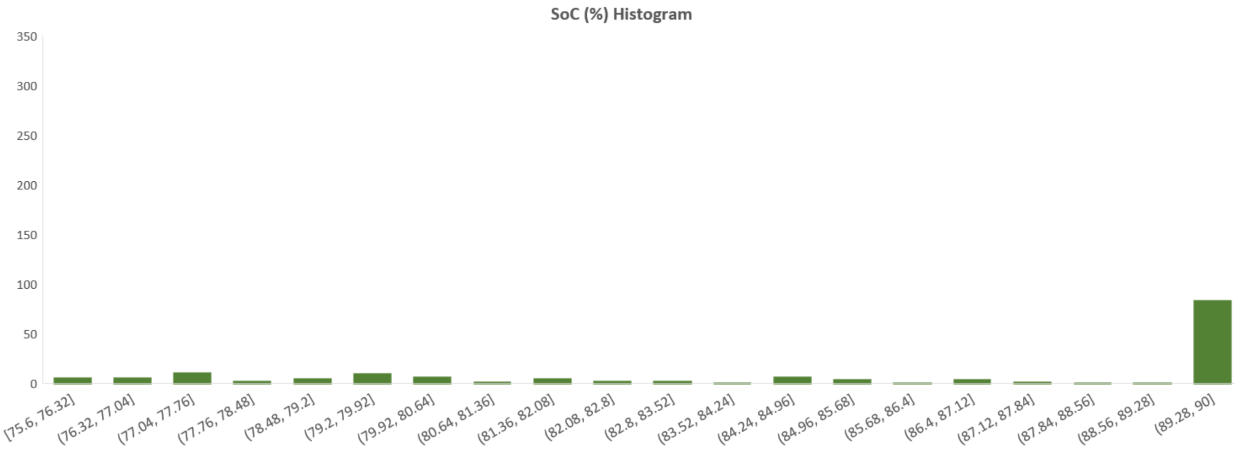



Figure 135. SoC (%) histogram for type 2 trucks in full experiment – middle case scenario. Source: personal elaboration

Being the waiting times null, I decided to plot and report just the customers' time in station (which equals the time of service). This variable has an average value of 76.34 seconds with a standard deviation of 8 seconds and the maximum time in station for a driver amounts to 100 seconds (1.67 minutes). The reduction of times of services is the consequence of the estimated improvement applied to the automated warehouse technologies (i.e. AGVs and ASRS).

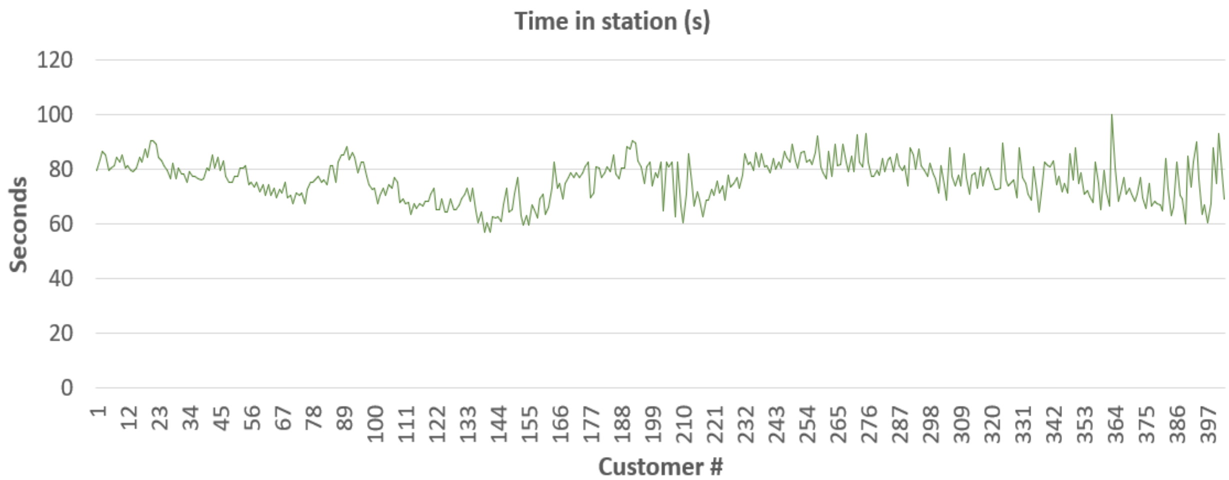



Figure 136. Customers' time in station graph for full experiment – middle case scenario. Source: personal elaboration

Finally, focusing on the best-case scenario, the considerations to be made are more limited. In this case very low traffic flows' input values were chosen with the specific aim to verify (as it happened) that, apart from null waiting times result which has already been obtained in the middle-case, exit SoC (%) are always 905 values (full charge) for both trucks' types 1 and 2. The number of type 1 truck analysed amounts to 52, whereas the number of type 2 trucks is equal to 29.

To conclude, the system is perfectly able to manage the traffic flow over 24 hours in any of the three scenarios, giving back optimal timing results already in the middle-case scenario and optimal exit SoC

(%) results in the best-case scenario, this means that the station requires a number of battery packs that exceeds by a certain percentage the daily requirement for each station (probably more than 100%).

## Analyses and comparisons

Starting from the model outlined before with its inputs and outputs, I decided to conduct some analysis from an energetic (demand and supply) and economic point of view with the aim to compare a battery swap solution to a more traditional plug-in solution. I tried to link some considerations made in the business model sub-chapter to the practical simulations and, finally, to draw some coherent conclusions ("so what") from different stakeholders' point of view.

I performed my calculations and considerations based on the worst-case scenario, since obtaining "favourable" results in such a scenario would mean obtaining even better results in the other scenarios with a higher margin of improvement.

Starting from some energetic considerations, the idea was to compare over a steady state 24 hours of simulation the energetic profile of the demand to the grid which is linked to a plug-in solution and a BSS solution, in order to provide very similar outputs from SoC (%) and timings point of view. This may be important in order to understand if the battery swap technology may really give some unique benefits to some stakeholders with the aim to conduct a final comprehensive 360 degrees comparison of the two macro solutions.

First of all I tried to evaluate an average hourly energetic demand ideally distributed over the 24 hours (completely flat curve) in order to use it as a comparison parameter and as a starting point for supply strategies. In order to obtain an estimate of this data, considering that some error can derive from variability applied to more than one parameter, I sum the total energy required by every single truck (i.e. 645 in the simulation) of both type 1 and type 2, calculated as the difference between entry and exit SoC (%) of the battery, converted into kWh through a linear proportion between state of charge and energy filled. Clearly, we exploit the individual tracking of each battery and map it once it exits the racks from 7 a.m. on, for the following 24 hours, even if the charging process starts come hours before and finished about the same hours before. This is an approximation that can lead to cumulated energetic requirements unbalances. Anyway, to have an idea, the sum of the energy (kWh) required by this input trucks' number over 24 hours amounts to 116.259 kWh, to be ideally distributed over these 24 hours, leading to 4844 kW of instant power to be constantly delivered each hour.

Going on, the second approximated estimation that I tried to carry out concerns the plug-in solution. Clearly, in this case we speak about fast charging stations in order to be able to charge the trucks' batteries in an acceptable time.

In order to do this, I tried two different approaches, the first based on a pure estimation and the second based on simulation's outputs. I took first the total number of trucks which should have reached the station during the 24 hours of simulation (i.e. 40*8 + 32*8 + 9*8 = 648) and split it according to the proportions previously explained (i.e. 66% - 34%). To obtain the average energy requirement of each truck I calculate the delta SoC (%) as the difference between the average entry SoC (%) and the average exit SoC (%) for both types of heavy-duty trucks.

This means for type 1 trucks:

$$Avg.\,\Delta\,SoC\ (\%) = 75.21\% - 15\% = 60.21\%$$

And for type 2 trucks:

$$Avg. \Delta\ SoC\ (\%) = 72.72\% - 35\% = 37.72\%$$

These “deltas”, converted into kWh, proportional to their relative batteries’ capacities, lead to an average requirement of 200.69 kWh for each type 1 truck and 209.56 kWh for each type 2 truck. Assuming that both types of batteries may be charged with a 150 kW (instant power) common fast charger, this means that, on average, a type 1 battery requires 1.34 hours to complete the charging process correspondent to the BSS output, in order for the two services to be comparable. A type 2 battery, instead, requires 1.4 hours to do the same. By instant power we mean the power required/provided at each time instant:

$$P(t) = V(t) * I(t)$$

In our case we consider it to be time-invariant, which means it is delivered at constant power over the whole time frame.

Considering possible further improvements in the long-term future and putting myself in the most unfavourable situation for BSS solution, I approximate the charging time to 1 hour in order to simplify calculations as well.

The second approach which instead consider the actual number of trucks which reached the station (i.e. 654) and the actual total energy demanded is just to further justify this approximation, because the total sum (i.e. 116.256 kWh) is less that the total sum that would come from the estimation described above. That value, in fact, would be obtained by multiplying the single truck energy requirement by truck type for the estimated number of trucks per type and then summing thse two results, obtaining 132.002 kWh of total energy demand over the 24 hours. Being the “actual” value lower (as so are both the type 1 and 2 contributions) then the time required to fill this SoC (%) gap through a fast charger would be a little lower than estimated times and, therefore, closer to the one hour value approximation.

Under this hypothesis, I can calculate the hourly power demanded to the grid considering that every truck occupy a single charging station for around 1 hour, allowing for the next customer to plug-in after this time. In this way, in each time slot the number of charging stations required amounts to the maximum hourly traffic flow value, which is 40 in the worst-case scenario, in order not to create queues. So, 40 charging stations should be installed to provide a comparable service to the one offered by the BSS solution in this scenario. For a matter of space, probably two parking and service areas are required one close to the other near Bologna, in order to split these 40 chargers (20 and 20), with a simple method to display to the drivers the availability of charging stations in the first or second area. Actually, the same exit SoC (%) is provided but with higher times in station since in this case every driver needs to stop his journey for more than one hour while in the case of BSS the average time in station is around 5 minutes. By multiplying the number of trucks (everyone associated to a fast charging station) with the instant power delivered by each charger (i.e. 150 kW) it is possible to determine the total average requirement estimated hour by hour, considering the traffic flows in the three time-slots of the day respectively equal to the already discussed values (i.e. 40-32-9). According to this, the power requirement is equal to 6.000 kw for the first time slot, 4.800 kW for the second one and 1.350 kW for the third one, considering the transition hours in the passage from one time slot to the following one.

In Figure 137. the energetic power demanded to the grid is plotted for the whole day, hour by hour. It is compared to the average value calculated before for the supply strategy.

The energy required/delivered is expressed in kWh as a unit of measure, while the instant power is expressed in kW.

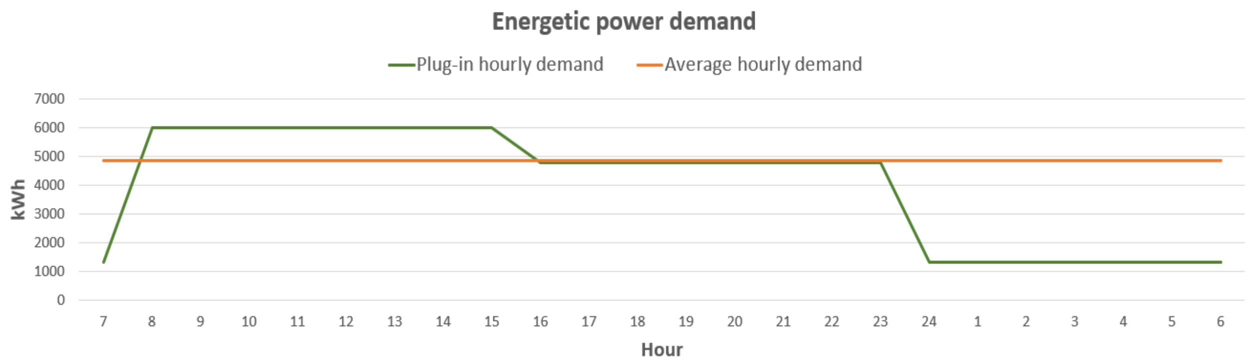



**Figure 137.** Energetic demand comparison (Plug-in and average). Source: personal elaboration

The average hourly demand turns out to be quite higher than expected, not allowing to match the total cumulated energy required by the two curves. This is due to some approximations made in terms of HDTs numbers, SoC (%) and, most of all, the time required to charge to the plug-in solution which, if not approximated by defect to one hour, would lead to different requirements and situations. In particular the energy balance could be faced in two ways, the first by keeping the same number of charging stations (not increasing the investment) but forming queues of HDTs, increasing waiting times and requiring the maximum total energy demand (i.e. 40 chargers contemporarily active) for a longer time. The second way consists in increasing proportionally the number of charging stations so as to keep the waiting times equal to zero the absolute peak value possible and the initial investment required.

If we compare the two curves, the main issue concerning a traditional plug-in fast charge solution is clearly pointed out. The curve is far away from being flat and shows a very high vertical amplitude if we consider the min-max range over the 24 hours. This implies instability of the energetic power demanded to the grid, leading to over stress during some time slots and under exploitation during others making the supply and pricing strategy less efficient as well. As we can see, during high traffic flow time slot, in which all the chargers are exploited, the curve rises far over the average hourly demand possibly used to set the energy acquisition strategy, even in this favourably approximated case.

To all this must be added the problems concerning the batteries' overheating and degradation.

Finally, to complete the energetic analysis and comparison section I tried to estimate the energy required by the 24 hours BSS simulation in the worst-case scenario. In this case I focused on the number of active chargers during the day, under the already stated assumption of the number of chargers corresponding to the rack (warehouse) dimension (i.e. 240 chargers in this case) and each charger providing a normal charging standard value of 22 kW of instant power. If I consider the simulation starting at 7:00 a.m. at steady state, then I note that after a specific hour (i.e. 13:00 p.m.), due to high traffic time slot, all the chargers are active for sure, since 240 trucks already came to the station and swapped their exhausted batteries. Looking at the simulation, this situation is going to last until the night time slot starts (i.e. 23:00 p.m.). So, during this time period the number of active chargers amounts to 240, which multiplied by the instant power delivered by each of them (i.e. 22 kW) we obtain a total instant energetic power demand of 5280 kW. At this point, I analytically tried to optimize the night charging distribution because the FlexSim model is programmed to charge each battery as soon as it comes to the warehouse and this is correct during high traffic time frames but it doesn't provide the possibility to distribute charging power over time during lower traffic time slots. For this reason, I stopped the simulation at 23:00 p.m. and I mapped all the 240 batteries' actual SoC (%) in the warehouse for both type 1 and type 2 batteries. In this way I obtained the Δ SoC (%) required to each battery to be fully charged to 90% SoC (%) in order to be ready for the peak management of the following day. Then, I converted these percentage results into kWh required to be filled for each battery and I summed them for both types, obtaining 24.939 kWh for type 1 trucks and 17.646 kW for type 2. So, the total capacity required amounts to 42.585 kWh and my maximum instant power available if all the chargers are active is 5280 kW, in this way the total average time estimated to charge all these batteries is 8.07 hours which, for sake of simplicity, I approximated to 8 hours. In this situation at 7.00 a.m. of the next day all the batteries should be more or less at full charge (90%) with an error due to the consideration of the 9*8 = 72 trucks arriving to the station during the night. However, the main concept is that I don't need all the batteries charged at 7:00 a.m., I just need the around 40 trucks/hour to be satisfied, meaning swapping the exhausted batteries with fully charged new ones. To accomplish this goal I keep just 75% of chargers active during the night (assumption for an ideal approximation), this means 180 chargers at 22 kW. In this way at 7:00 a.m. I will have around 11.000 kWh still missing to be charged. My requirement is to fill this gap by activating extra chargers compared to the ones strictly required in the morning, before all the chargers are forced to be active (i.e. 13.00 p.m.). After some trials, I opted for the activation of 200 chargers from 7:00 a.m. to 12:00 p.m. and I calculated the energetic power surplus that this solution provides (mathematically a triangle over the linearly growing curve of the minimum required chargers to be activated hour by hour). This extra charging amounts exactly to:

$$\frac{200*22kW*5h}{2} = 11.000\ kWh$$

Which is the amount to be recovered during the morning. To sum up, according to this configuration I will have the following energetic power requirement over 24 hours, 4400 kW from 8:00 a.m. to 12:00 p.m., 5280 kW from 13:00 p.m. to 23:00 p.m. and 3960 kW from 12:00 a.m. to 7:00 a.m., with the correspondent transition hours in the passage from a time frame to the other. This is clearly just a practical example, but many other combinations can be pointed out. The Figure 138. shows this curve over the 24 hours.

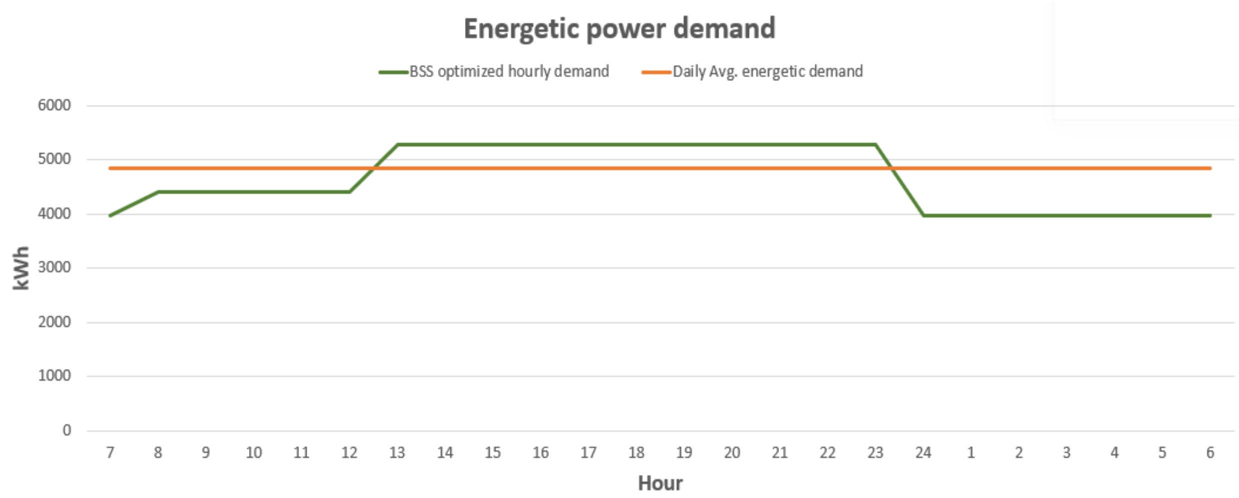



Figure 138. Energetic demand comparison (BSS and average). Source: personal elaboration

As we can see the curve is not flat but it gets closer to this result, by keeping always closer to the average curve with a reduced maximum amplitude range. Again, due to approximations, the average curve proves to be a little too high, making the whole balance unmatched. In order to better compare the results, the graph in Figure 139. plots both the plug-in and the BSS curves together.

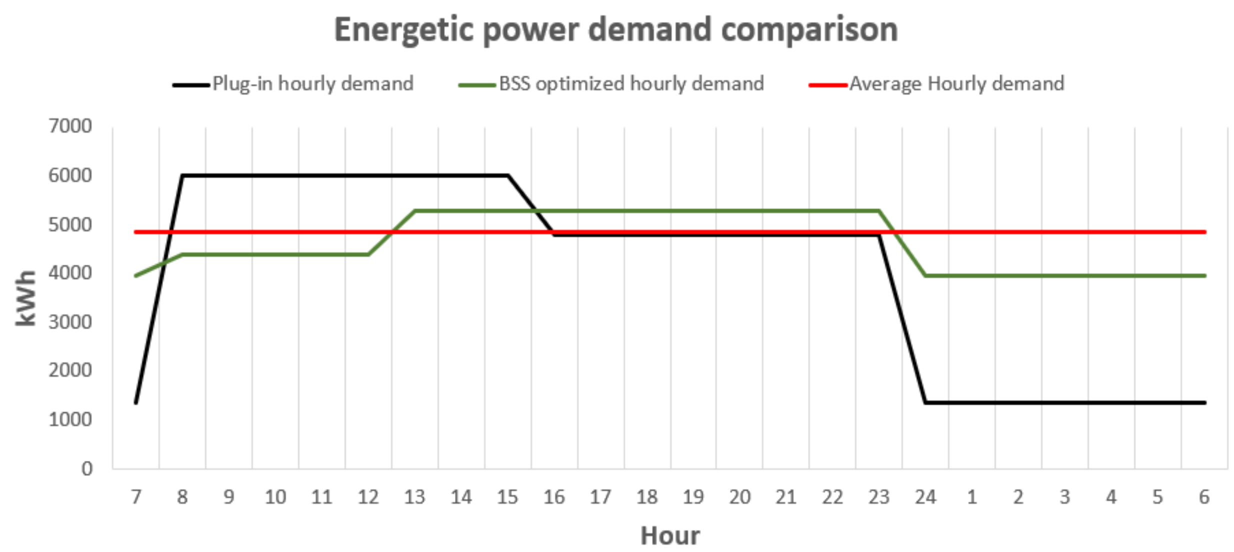



Figure 139. Energetic demand comparison (BSS, plug-in and average). Source: personal elaboration

The total energetic balance, obtained by summing the hourly values of kWh required, results to be a bit different if the plug-in and BSS curves are compared, this is mainly due to the plug-in big approximations that were made during calculations (already discussed).

Many considerations can be done looking at these curves, from the different stakeholders' point of view already considered in Chapter 5.3.

First of all, according to our assumptions and estimations, the BSS solution is able to ensure the same output to the clients (heavy-duty trucks drivers working for logistic/transport companies) compared to a more traditional plug-in solution. Looking carefully, in this scenario, the battery swapping is going to deliver the same average exit SoC (%) but providing a better time management, since waiting times are much lower. The major benefits I want to stress about this solution is that it is going to offer all this only exploiting normal "slow" charging. This choice has many positive implications for more than one player in the system. For example, from station owners' point of view (who manage the batteries in the BSS) overheating and battery earlier degradation with consequent reduction of useful life can be prevented and from energy providers point of view the BSS solution ensures better energy management, with curve flattening and peaks reduction by postponing or anticipating the hourly energy requirements.

Battery swapping stations must charge their battery packs - so they theoretically exert the same total demand on the grid as in charging stations, with the only difference that the demand can be controlled (even though in practical terms, it is essential for all battery packs to be charged as rapidly as possible, so that they are available for the next customer).

The main concept at the base is that this solution allows to decouple the customers' energetic demand from the supply of this energy delivered by the utility grid over the 24 hours of the day. Thus, the batteries assume a new role in the accumulation process which ideally allows an even bidirectional interaction of these energy accumulators for the flux optimization of the smart grids. This is perfectly in line with the idea of the global continuous connection and bidirectional movement of energy between every item able to store and release energy with the final aim of optimizing the energy management in its totality.

Using fast chargers in BSS would be senseless since it would lead to the same condition as plug-in charging, while trying normal charging in the plug-in solution would generate massive queues, solvable by increasing the number of available chargers but this would imply a lot of new chargers with consequent space issues, making even this solution impossible.

Looking at the energy supply (pricing) strategies the BSS solution allows for much better forecasts, management and agreement with the energy providers. I can analyse different supply and pricing choices. If the station owner decides to purchase energy by hourly time slot then, knowing that electric energy costs less during night compared to day prices, with a battery swap solution much more energy is required and purchase in the night compare to a plug-in solution, allowing for some money savings in the whole daily energy purchase. These savings may produce considerable impact on operating expenses in the income statement. If energy is purchased by station owner every 24 hours, then again the BS solution allows for a better curve management reducing risk of unexpected prolonged peak situations and requiring less energy to be stored before using it in the day. Again, if a contract between station owner and energy provider is signed to impose an instant power consumption ceiling value constant over the day and, as a consequence, a maximum daily total energy consumption, it is clearly easier for the BSS owner to control the demand in order not only to avoid exceeding that maximum level, but also to flatten the demand curve under that contract value already paid.

In case the final goal is to make the BS curve completely flat, which means a constant energetic power requirement over the day, it would be possible only by increasing the rack dimensions, allowing for more batteries to be charged during night and early morning in order to have more batteries ready to manage the peaks, allowing for less chargers to be in use during daytime (i.e. the same as during the other hours over the day). The model should be modified considering a limit to the maximum number of chargers active contemporarily. Quantifying the number of additional batteries required if not an easy stuff. An initial approximate calculation may come from the calculation of the energetic power surplus of the actual BSS curve compared to the actual average curve reducing the approximations, since the basic idea is to take this demand surplus and move it to the night/early morning in the same quantity and calculating how many 22 kW chargers would be required to fill this demand gap in a specific chosen time.

So, more batteries in the warehouse means even better energy management and exit SoC (%) of batteries delivered to drivers after the swap, but, on the other hand, it also implies a higher investment from the station owners' perspective and higher operating expenses and maintenance.

In the probabilistic scenario for example, the shape of the plug-in curve would remain the same even if with different absolute values, however the battery swapping solution would allow for an even easier, feasible and useful management of the demand curve.

In case of full charging (90%) requirement for all batteries even in the worst-case scenario, clearly the BSS would require a much higher number of batteries in the rack and, so, a higher investment. Anyway, this would happen in the plug-in solution as well since, keeping the instantaneous charging power fixed, higher charging times would be required and, as a consequence, longer queues would be created or, to avoid this, a much higher number of charging stations should be installed, requiring huge investments. A deeper analysis concerning this aspect is going to be provided in the next paragraphs.

Now I move to a more economic-oriented analysis both from the station owner perspective and the drivers (fleet managers). I tried to compare the operating model and the outputs of a single battery swapping station to a charging area composed by many charging stations but, in terms of investment, still remain doubts about which solution could more convenient.

Starting from the plug-in solution, I supposed that two specific charging areas, each one composed by 20 chargers, should be staged. According to [12], the cost of a fast charger (150 kW) is estimated to be around € 152.750 (€ 20.500 for civils, € 41.000 for the equipment, € 5.000 for the installation and € 86.250 for grid costs). Standard L2 charger (11-22kW), instead, may cost around €6.400 (€ 1.400 for the equipment, € 5.000 for the installation, and the grid connection). According to [77], a 100 kW charging station for BEVs would cost € 156.500 (€ 60.000 for equipment, € 10.250 for civils, € 5.000 for the installation, € 81.250 for grid costs).

Based on these values, 40 fast chargers installed would require an investment of around:

$$40 * € \, 152.750 = € \, 6.110.000 \quad \text{or} \quad 40 * € \, 156.500 = € \, 6.260.000$$

Considering some specificity issues for heavy-duty trucks, I suppose to approximate the total investment to € 7 Mln.

According to [77], the total costs for a fast charging infrastructure of this kind for battery electric trucks would be much higher due to other expenditures linked to civil macro works and additional professional fields, however these kind of expenditures would be incurred once for each charging area, would not be strictly dependent on the number of chargers and would be incurred even in the BSS case and, so, they are not determinant in the investment comparison.

On the other hand, the estimation for the BSS investment could be more difficult since less data are available. Anyway, as we mentioned in Chapter 5.3, a benchmarked reliable value of the investment for equipment (including structures, automation, warehouse, control and monitoring devices and chargers) and installation of a basic battery swapping station with a single swapping bay and a 50 batteries' warehouse amounts to € 500.000. To this value, however, a multiplying factor should be applied since I am dealing with heavy-duty battery electric trucks and not passenger cars (this implies higher dimensions and, as a consequence, higher spaces needed and bigger structures), our project requires two swapping bays and the warehouse is designed for 240 batteries. Considering all these aspects, I assumed this multiplying factor to be equal to 5, coming from the ratio between our warehouse's required dimension (and, therefore, number of chargers) and the benchmarked one. This leads to a € 2.500.000 investment. This value is not considering a big cost item which is the cost of batteries to initially fill the warehouse. For sake of simplicity, I didn't consider the cost of batteries to be provided to newly registered trucks, since this would imply considering the whole business model change described in Chapter 5.3. The warehouse should be filled, again, with 66% type 1 batteries (300 kWh capacity) and 34% type 2 batteries (500 kWh). As I mentioned in Chapter 5.3, it is possible to estimate a cost of batteries according to future forecasts and I assume a value equal to € 100/kWh, which is line with price ranges for heavy-duty trucks (100 – 200 k€), considering that the battery is the major cost item. So, it is possible to calculate the total investment required for the single station analysed as:

$$(160 * 300\, kWh + 80 * 500\, kWh) * 100 \frac{€}{kWh} = € \, 8.800.000$$

The total investment (capex), under these assumptions, would amount to € 11.300.000, which is more than € 4 Mln. higher than the plug-in solution (+ 66%).

From the drivers' (logistic/ transportation companies – fleet managers) perspective, it would be interesting to compare, after having focused of SoC (%) and timings, also the costs related to completing the full journey with a traditional truck and completing it with a battery electric truck. The pricing linked to the BSS solution, as we already mentioned in Chapter 5.3, is quite difficult to be estimated. Calculating the price per swap is a difficult job but according to the presented business model things are far more difficult, since the payment is based on a periodical fee. The estimation of the fee may be done starting from the cost of the plug-in charging and trying to make the two pricings comparable or, on the contrary, by using a fee allowing to ensure desired profits and then compare it with plug-in charging prices. For these reasons I decided to conduct just a more general comparison between electric and ICE trucks, declined on this scenario. Clearly the complete and correct comparison would imply an estimate of the TCO in both cases applied to this specific case study.

Qualitatively speaking, we already know that a battery electric truck, apart from infrastructure issues, requires an higher initial expenditure which should be diluted over time leveraging lower operating costs, maintenance costs (simpler vehicle), lower possession fees, higher incentives and providing to the company a much greener image coming from an environmentally-friendly solution (reduced CO2 emissions). Quantifying these discrepancies is a hard job but it is possible to focus on the main operating expense (apart from drivers' wages), the fuel consumption, which accounts for around 30% of the average opex. In our specific case each truck needs to drive for 1.453 km in case of route A and 1.204 in case of Route B to reach the destinations and the same kilometres to come back. Considering, for instance, the Route A, the total distance to be travelled amounts to 2.906 km. According to [84], the fuel consumption is strictly dependent on the dimensions, payload and type of road. However, on average, an heavy-duty truck with a payload higher than 25 tons, on Italian roads, would require 38 litres every 100 km driven. In this case, the truck would require an average estimated value of 1.104 litres to complete the journey.

According to [85], The reference value of the cost of diesel for transport services carried out in January is therefore equal to 1.003 euro / litre for vehicles with a total laden mass greater than 7.5 tons net of VAT and partial refund of excise duties. By computing a simple calculation, it comes out that the total cost of completing the full journey would be equal to € 1.108.

On the other hand, we have the case of BETs with direct ownership of the battery (DO) adopting a plug-in charging system to drive the full journey. Taking again the route A as a reference for the comparison and considering a depot and destination charging in Turing and Reggio Calabria during loading/unloading process with different payment forms and agreements, the truck needs to stop 10 times during the journey. Based on previously mentioned calculations about the average capacity required by every truck to reach a satisfying exit SoC (%) value, I take as an assumption that on average a truck requires around 200 kWh, delivered by a fast charging station (150 kW) in an hour and 20 minutes. Even in case of plug-in charging some energy providers like Enel are proposing new pricing models based on periodic (monthly/annual) fees for maximum energy consumptions, however I am going to consider a more traditional and diffused payment method based on €/kWh charged. According to [86], in Italy the price for a charge not at home is variable depending on the type of charging, charging power and who manages the service. The payment may be based on the pay as you use formula or, on the contrary may be flat with a monthly/annual fee. In this case we suppose the first option in order to be able to compute calculations in an easier way. On average, for such a fast charging, prices on the market are around 0,45 €/kWh. Based on these assumptions I can calculate the final cost of charging for this journey, which is equal to:

$$10 * 200\ kWh * 0{,}45 \frac{€}{kWh} = 1000\ €$$

So, according to these calculations, the difference is around 108 € for every truck completing the whole journey. This value is an approximation and seems to be too little, however, if we consider that a single transport/logistic company may manage dozens of trucks, this difference grows if summed for each truck and, after a certain number of HDTs complete the journey every week this may lead to some thousands euros saved every week.

Finally, since we spoke about timings, if we look at the whole system it is useful to remember that the total time for the journey is given by:

$$Driving + \sum Range\ extensions + \sum Forced\ rest$$

By forced rest we mean the resting time which drivers are force by Italian (and European) law to respect. Regulations are quite complex and variable about this, anyway every day a specific number of hours must be dedicated to resting and this time can be split according to different time slot combinations over 24 hours. Every week and every month, again a specific number of days must be devoted to full rest. Therefore, calculating total timings is not easy. An important consideration can be made about that, these forced breaks tend to favour the plug-in charging solution because often the drivers tend to exploit the waiting times while charging and count them as forced break hours, possibly compensating the benefit of very little waiting times linked to battery swap solution. However, this kind of practice is usually not allowed since more and more stringent regulations have been applied to clearly define how, when and where the break hours can and cannot be carried out. Furthermore, this strategy may give benefits when dealing with long journey as in this case study, but when dealing with shorter journey the situation is going to change. In particular, for commercial journeys requiring more than a single charging (range autonomy not sufficient to cover the whole distance scheduled) but requiring less than 6-8 hours of consecutive drive (which is the limit) the battery swap is much more convenient if compared to a plug-in solution which requires the driver to stop at least 30 – 60 minutes to charge the battery instead of swapping it in few minutes, go on with the journey and deliver the products on time.

Even if I preferred not to analyse the following stations, due to complex estimations required, I can say that exit times from the Bologna station are easily available and, so, the frequency of trucks entering the following station (only considering the trucks which continue the journey and not considering the ones stopping it or the new ones entering the route) may be estimated. The first station would behave as the bottleneck, setting the timing for the next ones since it has limited processing capacity so, in case of high traffic, the exit frequency of the first station (coinciding with the entry frequency of the second one for example) is shaped by the limit processing capacity of the swapping station. Therefore, in this case, the waiting times are going to reduce station by station, regulating the traffic flow and almost immediately reaching a distributed steady state of traffic allowing for zero waiting times.

# 6.6 Possible future developments

In this section I would like to provide some insights about how to deepen these concepts and how further research on this topic in the future may be developed, being this an innovative topic which could provide benefits to many stakeholders and play an important role in the transition to a more environmental-friendly world for future generations.

First of all, starting from the most practical parts, the model may be updated and improved by looking at it from a broader perspective with the aim to simulate the whole journey automatically. Moreover, most of all, the model could be modified in order to automatically manage a maximum ceiling of active chargers per time frame, which means a maximum number of batteries charged contemporary. This implies changing the “charge the battery as soon as it gets in the rack” principle, allowing for better energy demand optimization and curve flattening, starting from the graphs and the considerations of the Chapter 6.5.

Other tests and simulations may be conducted considering just single highway sections (i.e. shorter journeys) with different and more precise HDTs traffic flows’ estimates. Again, according to our assumptions, traffic flows are not constant over the day and stations as well are not all equal with exactly the same requirements. This implies the possibility, from one side, to build each battery swapping stations based on the specific traffic flows of that area in terms of number of swapping bays, warehouse dimensions and automation speed/accelerations required. On the other hand, this would also open the door to the possibility, once the design of the model has been chosen and realized, to activate just more or less swapping bays according to the specific time slot traffic requirements. This allows to be able to manage lower traffic flows by exploiting maybe just one swapping bay instead of keeping active both.

Finally, speaking about the simulation side, another possible test is related to the management of HDTs coming from both driving directions with a unique station.

Clearly, analysing the battery swapping technology applied to different scenarios and contexts would require very different considerations and analysis. For example, designing and analysing a battery swapping stations' network for passenger cars is completely different and differences are going to be amplified in case a urban context (instead of long hauls of highways) is chosen. My analysis is just exemplificative in order to try to apply some theoretical concepts and highlight the possible benefits and limits of the battery swap technology in a real context coherently with what I discussed in the previous chapters.

Another computation with a huge margin of improvement is the net present value (NPV) calculation for a hypothetical network of this type. This is a complex calculation which should take into consideration many values and factors and data should be extracted only from reliable sources, implying a lot of time required.

To conclude, a very relevant and innovative issue could be addressed and deepened starting from this case study and other academic papers available on the web. I am talking about renewable energy option which I already mentioned in Chapter 5.3, with particular attention to photovoltaic option. According to [71], the installation of solar panels over the roof of the battery swapping stations is an interesting possibility for a "green" investment, so as to accumulate renewable energy. The benefit of this kind of solution may be double, from the station owner's perspective first to become partially self-powered and self-sufficient as a station by capturing the solar generation variability, whereas from the power provider's (utility grid) point of view, this solution helps to host a higher penetration of solar generation stored. This kind of solution is clearly favoured by a BSS technology which is able to manage daily energy requirements by flattening the demand curves as much as possible because unpredictable peaks are difficult to be managed and endured by such a variable energy source, creating problems to the grid and often requiring traditional electricity sourcing. Moreover, BSS allow for the shifting of the charging power and energy delivered from a time slot to another during the day and this allows to make the most of solar energy when it abounds by shaping once again the charging and purchasing strategies. This means that in this case, besides the traffic flows and the energy price range varying according to the times in the day, another factor (renewable energy availability) needs to be considered when elaborating charging and purchasing strategies for the station.

# 7. Conclusions

In this last chapter the objective is to try to link all the sections of the paper, from the most general and theoretical ones to the practical simulations and considerations performed, so as to provide a sum up and a personal evaluation and advice related to the battery swapping technology.

What comes out starting from the beginning is that transport section needs to be revolutionized in the next years if we want to preserve our planet, since its impact on emissions is huge. Despite being the dominant paradigm in long term, the battery (full) electric vehicles will coexist with other solutions, first of all the hydrogen fuel cell vehicles. In this scenario, the high price tag as well as the range anxiety and charging times are the customers' main concerns. For this reason, strong government incentives are required (to be slowly reduced in the long term) to foster the electrification and massive investments in the charging infrastructure are required to solve the "chicken and egg" problem. Electrification of the transport sector is just a part of a broader plan to revise and optimize the energy management thanks to AI, ML, IoT and other technologies. The idea is to create huge networks of connected items and individual communicating with each other in order to manage in the smartest way possible the energy demand and supply. This implies continuous and efficient communication between the utility grid, electric vehicles, home automated appliances etc., in the evolution process toward smart communities.

Focusing on vehicles, the idea of car is changing a lot, with architectural innovation leading to the concept of a car as a modular object closer to a computer rather than the traditional car concept. In this rapidly evolving industry, possibilities for new business models are growing as well.

As I widely commented in the paper, each vehicle's typology and each scenario have different requirements and, therefore, when possible, specific tailored solutions should be implemented. Clearly, most of the times it is a matter of finding the best trade-off possible. The choice of the complementary technologies (i.e. charging infrastructure) is probably one of the most critical issues to be dealt with and the battery swapping seems to be one of the most innovative and controversial solutions. I analysed and studied this technology from many perspectives, highlighting all the great benefits it is able to provide as well as the serious obstacles which hindered its rise until now. There is not a univocal response about its superiority or not compared to other solutions like traditional plug-in charging or wireless induction charging, it depends on the lens under which it is analysed and to which scenario it is applied.

The aim of the second section in the paper has been to try to decline most of the previous theoretical considerations in a real life specific practical situation. In order to do this I introduced the heavy-duty trucks for long-hauls' case study and after a research on the market, estimates, simulations, analyses and comparisons some final objective and subjective considerations came out.

First of all, the adoption of BEVs for highways driving has many advantages from lower operating expenses, lower maintenance required, lower possession fees, higher incentives, greener image for the company etc., however, even assuming to be solved issues like the infrastructure and the dealers' problem, a big obstacle is still present: the initial price. Today it is still very high and the main driver is the battery costs whose price is expected to go on falling down during the next 20-30 years. What is certain it that, as we mentioned in Chapter 5.2, the TCO parity is much harder to be reached for HDTs compared to passenger cars or LDTs and this implies longer times before reaching profitability from different stakeholders' perspectives. This mainly comes from the impossibility for heavy-duty trucks, differently from LDTs and MDTs, to leverage infrastructure and exploit synergies with passenger cars on the highways, making the investment harder to become profitable in the short term since major technology upgrades will be necessary to charge HDTs efficiently.

However, important choices about infrastructure investments need to be addressed even in this sector and the simulation aimed at evaluating the feasibility of reaching specific outputs with battery swapping stations and to approximately compare them to more traditional plug-in fast charging solutions.

First of all a consideration about the battery swapping solution. Its introduction may completely revolutionize the business model, impacting all the players in the game, as I explained in Chapter 5.3. These massive changes may bring many benefits to all the stakeholders involved but are clearly not easy to the absorbed by the whole system in the short term, time is required and the coexistence of different infrastructure solutions may not be always feasible from both a technical and business point of view.

By taking the results of the simulated case study, I assume to generalize them so as to provide a personal evaluation and sum up about the battery swapping solution applied to heavy-duty trucks' market for long hauls.

What comes out is that a BSS is able to provide drivers (and fleet managers) a range extension service comparable to the one offered by the plug-in solution in terms of exit SoC (%) with much lower waiting times even in case of high traffic flows and lower battery degradation thanks to normal charging instead of fast charging. From the energy provider perspective (utility grid) it is going to provide the already discussed relevant benefits. In general, its ability to decouple the demand of energy by its supply is a key factor for the evolution of energy management in the future.

However, it is not the heaven and that's why it hasn't taken off yet. The practical case study analysis confirmed that the investment required to owners for a single swapping station is much higher that the investment required for a corresponding fast charging area. Moreover, despite the fact that even plug-in fast charging requires some degree of standardization, the effort in this sense required by battery swapping is much bigger to solve compatibility issues. Going on, as I said the HDTs require in any case specific infrastructure or a technology upgrade to provide efficient charging, however, for sure a BSS is designed only for heavy duty trucks due to dimensions and batteries' typologies and can never be exploited by any other kind of vehicle on the highway. On the contrary, however specific it may be, a plug-in charging area may be useful to other vehicles' typologies in case of emergency. This would clearly affect the traffic flows and, for this reason, cannot be considered a standard operation. Finally, a big difference between these two solutions is that in the BSS case the exit SoC (%) generally cannot be chosen by the driver (it depends on the warehouse availability in that moment) while in case of plug-in charging the driver can decide to charge its battery as much as he desires in accordance to its priorities (time, distance to be travelled…). This favours the plug-in solution from the driver's perspective but, on the other hand, make even harder and unforeseeable the energetic demand estimation for station owners and energy providers (utility grid). This BSS problem could be solved by a pre-booking system, as I mentioned in Chapter 5.3, but this would make things even harder to be managed and scheduled.

In light of all these insights and considerations, my personal opinion about battery swapping is that, despite many failures in the past, it may work in future applied to some specific sectors like this one but probably today it is not ready to be deployed and should be postponed to a moment in which stronger necessities and incentives will be present, so as to provide real value added. Meanwhile, for the next ten years let's say the mega charging technologies may be adopted. For sure they have many limitations but are easier to be designed and installed, less expensive, could provide the right incentives to start as soon as possible the electrification process and the waiting times may be used to take the forced stops (for example, according to European law, 45 minutes every 4-5 hours). However, in the meantime, two factors are going to shape the future in the long term, the first one is the development of dynamic charging (by wire or by induction) and second the autonomous driving introduction. Both technologies are probably going to be applied to heavy-duty trucks, being it a good fit thanks to the fixed long path to be scheduled and driven. These drivers are definitely going to change the game forever in favour of a battery swapping solution coupled with dynamic charging. Dynamic charging is under development and may solve many range anxiety problems overall in highways for commercial transport as in our case study. However, it requires very expensive investments and cannot be realized on every single highway section, for this reason this technology will always require a coupling with a static charging infrastructure (less charging areas required clearly). In this scenario, the advent of autonomous driving will definitely re-design the logistic processes with improved efficiencies and requirements. The main operating cost (i.e. the drivers' wages) will be cut off and no more breaks will be required since trucks will be automated, making the time losses even more critical factors. This will not only cut the benefit of exploiting the waiting times during charging as a forced break but will also require automatic forms of charging without human intervention since there is no driver who can plug-in the charger. What's more, without breaks the trucks journeys could be scheduled 24/7 without interruptions, thus leading to an even stronger impact of continuous fast charging on battery state of health. Finally, another factor playing an important role is that fast charging, in the striving to reduce charging times, is dramatically increasing charging waste and technology irritation, while, on the other hand, battery swapping is proposing an efficient, stable and safe physical process. It implies no need of continuous update of vehicles, poles and electrical systems to adapt to change of batteries since battery can back to the role of energy container. Therefore, battery swapping can reduce the waste of social investment brought by technology irritation in the long term, which may be more useful for the development of the EV industry in a sustainable way.

Therefore, this may be the strongest incentive to finally justify the investment for the adoption of a battery swapping stations' network. The number of stations required will be much less, being it a supportive infrastructure to the dynamic charging on the road, to be used in an emergency, when dynamic charging is not available, in case of high traffic flows or grid overload issues. The final solution may include the exploitation of some of the fast charging points installed during the years. This may happen by designing multi-functional charging areas with battery swapping stations and even the possibility to exploit some plug-in fast chargers for specific necessities and in case of problems. In this direction are proceeding some innovative companies like Flymovedianchè in Europe and NIO in China, providing both services in comprehensive stations with almost zero constructive and environmental impact. A unique pricing model would ideally be developed, with tiered period fees allowing to exploit every kind of dynamic and static charging mode.

Since I spoke about the combination of these three charging infrastructure types, I decided to report in Figure 140. an interesting sum up table comparing some of the most relevant aspects related to these technologies.

| EV Type | Charging Mode | Power Refill Rate * | Infrastructure Cost | Operation Cost | Usage Scenarios ** | Advantages | Disadvantages |
|---|---|---|---|---|---|---|---|
| PEV | Slow charging | 30–75 miles/h | L | L | Home/workplace | Cheap and safe | Long charging time |
| | Rapid charging | 180 miles/h | H | M | Public charging stations | Charge rapidly; not very expensive | Long charging time; powerful cooling systems required |
| WCEV | Dynamic charging | – | VH | VH | Designed to use on heavy load traffic corridor/ freeway | Charging while moving; without range anxiety | Extremely high investment cost |
| | Static charging | 20 to 100 miles/h | H | H | Public charging stations | Wireless | Long charging time |
| SCEV | Centralized battery charging | Swap time can be less than a minute | M | M | Public swap charging stations | Shorten charge time sharply; centralized charging | Battery ownership, purchase cost, standardization, and safety issues in the swap and charge process |

**Figure 140.** Charging infrastructure typologies comparison. Source: [76]

To conclude, the future is highly uncertain about the electrification process and its implications on charging technologies, however it will for sure revolutionize the whole transport sector  and, for this reason, every stakeholder possibly involved needs to be ready to take the most out of this process and to take care of our planet to preserve future generations.

# Table of figures

# List of acronyms

| | |
|---|---|
| **AC** | Alternate charging |
| **AI** | Artificial intelligence |
| **AV** | Autonomous vehicle |
| **B2G** | Battery-to-grid |
| **BEB** | Battery electric bus |
| **BECM** | Battery energy control module |
| **BET** | Battery electric truck |
| **BEV** | Battery electric vehicle |
| **BMS** | Battery management system |
| **BS** | Battery swapping system |
| **BShN** | Battery shared network (of stations) |
| **BShS** | Battery shared station |
| **DC** | Direct charging |
| **DES** | Discrete event simulation |
| **DoD** | Depth of discharge |
| **EDLCS** | Electric double-layer capacitors |
| **EOL** | End-of-Life |
| **EV** | Electric vehicles |
| **EVSE** | Electric vehicle supply equipment |
| **FC** | Fast charging |
| **FCV** | Fuel cell vehicle |
| **G2B** | Grid-to-battery |
| **GHG** | Greenhouse gases |
| **HDT** | Heavy-Duty Trucks |
| **HEV** | Hybrid electric vehicles |
| **ICE** | Internal combustion engines |
| **IoT** | Internet of things |
| **OEM** | Original equipment manufacturer |
| **PESTLE** | Political-economic-social-technological-legal-environmental analysis |
| **PHEV** | Plug-in electric vehicle |
| **PLM** | Product lifecycle management |
| **R&D** | Research and development |
| **RES** | Renewable energy system |
| **ROI** | Return on investment |
| **SAEV** | Shared automated electric vehicle |
| **SC** | Super charger |
| **SMP** | Smart mobility platform |
| **SoC** | State of charge |
| **SoH** | State of health |
| **SSCS** | Shared swapping charging station |
| **SWOT** | Strengths-weaknesses-opportunities-threats analysis |
| **TCO** | Total cost of ownership |
| **V2B** | Vehicle-to-building |
| **V2G** | Vehicle-to-grid |
| **WCS** | Wireless charging system |

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