HOW WILL THE DEVELOPMENT OF BATTERIES AFFECT ERS PROFITABILITY?

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INTRODUCTION

The transition to a fossil-free vehicle fleet in Sweden, the EU, and globally presents many challenges and uncertainties. The development of batteries is crucial for the contribution of electrification. The performance of batteries and the availability of raw materials required for their production pose a potential challenge to ensuring that the electrification of the transport sector progresses at a sufficient pace.

One of the most critical factors for the adoption of electric vehicles is how the cost of batteries will develop. Other challenges include how the vehicles will be charged and the load on the power grid. For heavy vehicles, the challenges are even larger as they are significantly heavier and often travel long distances and require high power charging. The expected development of batteries in terms of performance and costs will greatly influence the profitability of investing in electric road systems (ERS). Depending on these factors, ERS could be an alternative to stationary charging, especially for heavy vehicles. A critical question in understanding the potential profitability of ERS compared to stationary charging revolves around how battery capacity and costs will develop and the pace of this development. This report explores how and to what extent the expected battery development will affect the potential and demand for electric road systems.

Dynamic charging via ERS has potential to reduce the need for batteries with high energy capacity in the transport sector. By harnessing power directly from the electric road infrastructure, vehicles benefit from continuous energy supply. This approach offers several advantages, including efficient resource utilization, reduced emissions, and the potential for increased vehicle load capacity. Direct power to the drivetrain also provides higher efficiency, while charging the battery via an onboard charger costs a few percent. Notably, dynamic charging also minimizes downtime during recharging, which is particularly crucial for professional transport operations. Additionally, there is likely to be a great potential that geographically distributed power demand can alleviate strain on the electrical grid. Instead of experiencing sudden spikes in demand at specific charging stations, the grid handles a more consistent and dispersed load.

The flexibility of ERS vehicles depends largely on the proportion of the driving distance covered on electric roads and on battery range. In contrast, battery-powered vehicles are not tied to specific routes and can operate wherever charging facilities are available. Nevertheless, unlike ERS vehicles, they necessitate periodic stops for recharging. ERS is not likely to solve the entire charging issue on its own; a combination with stationary charging will be required, utilizing legally mandated rest periods for charging.

For investments in electric roads to be viable, it is essential that vehicles are profitable from a user perspective, which is necessary for vehicle manufacturers and logistics companies to generate demand for electric vehicles adapted to electric roads. For governments to make substantial investment decisions in building infrastructure for electric roads, the solution must also be economically viable in the long term. Therefore, the development of batteries is crucial to analyze from both perspectives.

When electric vehicles are charged on the move, smaller batteries are required. This benefits both the environment and the vehicle owners' finances. The question is how the costs and performance of batteries will develop and how the demand for electric roads will be shaped based on the expected development.

The purpose of this study is to track development projections for battery technology and empirically analyse the outlook of heavy battery electric vehicles (BEV) in a time perspective of 10-15 years, as well as their implications for ERS implementation.

The research questions of the report are as follows:

1) How are batteries expected to develop in the future in aspects relevant to the potential for ERS? Particularly:
   a) Battery performance (power, weights, range, time to charge)
   b) Costs
   c) Raw materials – is there a need for ERS with regards to this perspective?
2) What would the expected battery development imply for policies regarding the need and use of electric roads?

DISPOSITION

This report is part of the CollERS project. The idea behind this report came up in one of the previous studies within the CollERS project where WSP developed the system dynamics model to calculate how transports on electric road system will develop over time (WSP, 2024). Several of the assumptions in the model are related to batteries and their future costs, function and performance as this has an impact on the potential of the electric road system. That is why we saw a need to study battery development more deeply.

The report begins with an overview of the electric vehicle market. The aim is to provide an initial understanding of the current demand for electric vehicles and how it is expected to develop from a societal perspective. We describe the current market and global context, as well as outline the types of legislation that may influence the development and demand and the pace at what the development will occur.

In the following chapter 3, we describe the anticipated development of the battery market. We outline which types of batteries are most common on the market and how battery performance is expected to evolve, with a particular focus on volume, weight, range, and charging time. We also address the expected cost development.

The projected future battery costs are also discussed in the next chapter. There, we describe a research study that conducts a meta-analysis of approximately 200 sources regarding future battery costs.

Both the cost results of this study and the findings the projected battery development are then used as assumptions in our modified system dynamics model that we present in chapter 5.

Abbreviations

AC Alternating current	**IEA** International Energy Agency
AFIR The Alternative Fuels Infrastructure Regulation	**InduERS** Batteries with inductive charging
ASEK Analysmetod och samhällsekonomiska kalkylvärden	**IRA** Inflation Reduction Act
BESS Battery energy storage system	**LFP** Iron and phosphate
BEV Battery electric vehicles	**MCS** Megawatt charging systems
CCS Carbon capture and storage	**MNL** Multinomial logit
CondERS Batteries with conductive charging	**NCA** Nickel, cobalt and aluminum oxide
ERS Electric Road systems	**NMC** Nickel, manganese and cobalt
ERSV Electric road systems vehicle	**PHEV** Plug-in hybrid electric vehicles
EV Electric Vehicle	**RMI** Rocky Mountain Institute
FMCG Fast moving consumer goods	**SOC** State of charge
HDEV Heavy-duty electric vehicles	**TCO** Total cost of ownership
HDV Heavy-duty vehicles	**TEN-T** Trans-European Transport Network
ICEV Internal combustion engine vehicle	**ZET** zero emission truck

1. THE MARKET FOR ELECTRIC VEHICLES

In this section, we describe the recent developments in the market and demand for electric vehicles and batteries, and factors that have influenced or are expected to influence future battery demand.

Summary Chapter 1.

- The demand for electric vehicles in the global market has increased significantly over the past 5 years. However, we are still in the early stages of adopting to a fossil-free vehicle fleet worldwide.
- China currently accounts for a very large share of the global total demand for electric vehicles.
- Heavy electric vehicles still make up a very small part of the total heavy vehicle fleet, and their development is progressing much slower than that of passenger cars.
- In 2024, the upward trend for electric vehicles in Europe has paused, and demand has slightly declined. However, everything indicates that this is a temporary trend break.
- Regulation on the transition to fossil-free transportation has an impact on the demand for electric vehicles – it can potentially speed up the demand and use of electric vehicles depending on what policy decisions will be made in the future.
- Legislation and regulation through tariffs and trade barriers may also increasingly affect the costs of batteries and electric vehicles in the future.

DEVELOPMENT OF THE MARKET FOR ELECTRIC VEHICLES

The world market for electric vehicles has grown over the past years. In 2023, global sales of electric cars neared 14 million, reaching 18 percent of all cars sold. According to the International Energy Agency (IEA 2024), electric car sales keep rising and could reach around 17 million in 2024, accounting for more than one in five cars sold worldwide. (IEA, Global EV Outlook 2024, 2024) In the first quarter of 2024, electric car sales globally grew by around 25 percent compared with the first quarter of 2023. The increase in sales globally is led by demand in the Chinese market for BEV and plug-in hybrid electric vehicles (PHEV). China accounted for approximately 60 percent of all new electric car registrations globally (IEA, Global EV Outlook 2024, 2024)

In Europe, sales of electric (BEV and PHEV) passenger cars accounts for approximately 19,5 percent of all car sales in 2024 so far this year (EU, 2024). The share of newly registered electric cars in the EU has decreased by two percentage points compared to 2023.

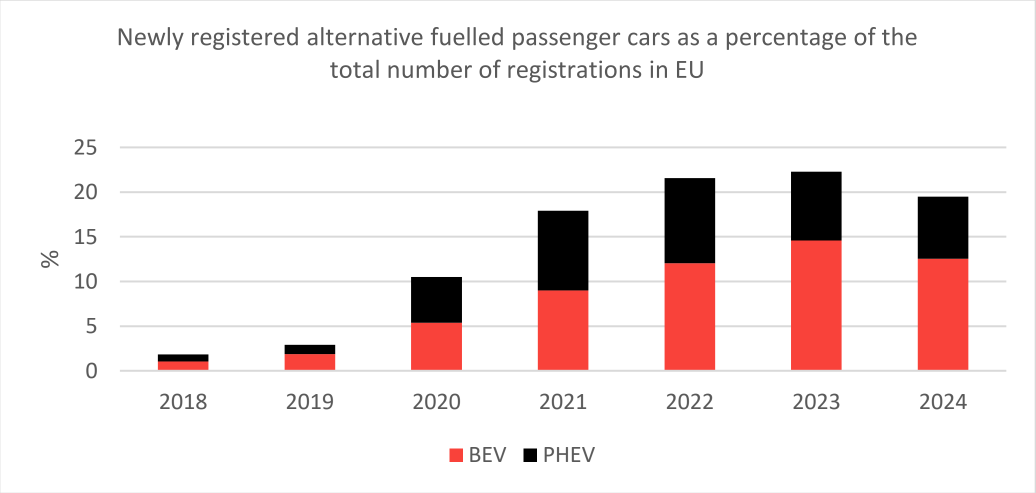


Figure 1. Newly registered alternative fuelled passenger cars as a percentage of the total number of registrations in EU

The market for heavy-duty electric vehicles (HDEV) is still behind that of passenger cars. In 2023, approximately 54 000 electric trucks were sold worldwide (IEA, Global EV Outlook 2024, 2024). As with passenger cars, China dominates both production and sales of HDEVs, accounting for approximately 70 percent of global electric bus and truck sales.

Sales of HDEVs remain low across most major markets, with the exception of China. In 2023, about 1,5 percent of the total sales of trucks in EU were elctric. However, while the trend is slightly decreasing for passenger cars in EU, in 2024, HDEVs accounts for 1,9 percent of the total sales of heavy duty vehicles in Europe. (EU, 2024)

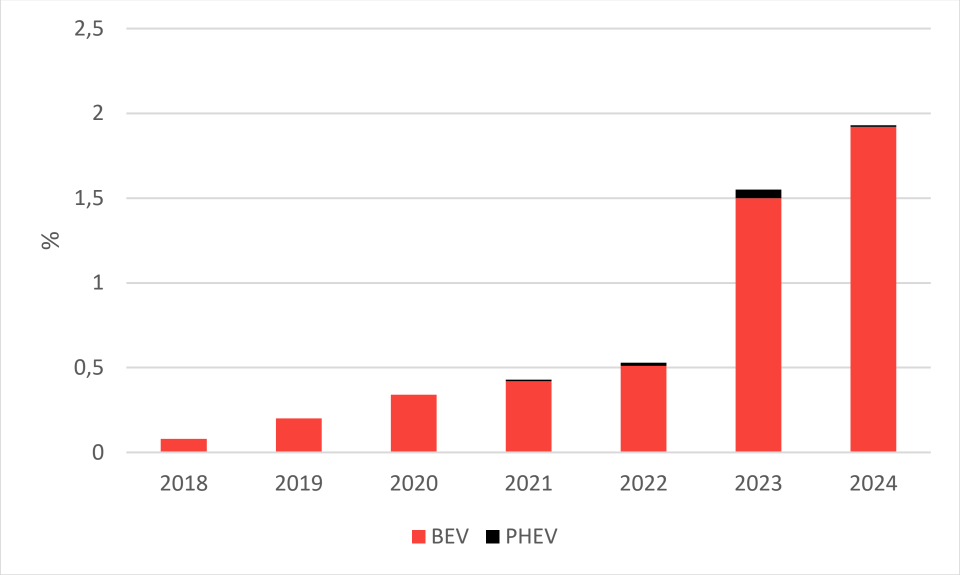


Figure 2. Newly registered alternative fuelled trucks as a percentage of the total number of registrations in EU

In Sweden, the share of HDEV in use is continually low relative to that of diesel-driven trucks, which remains the dominant fuel-type for heavy-duty vehicles (HDV) (Trafikanalys, 2024). According to vehicle statistics obtained from Transport Analysis (2024), the share of heavy electric or hybrid-electric trucks in use in Sweden was approximately 0,6 percent in 2023, whereas the share of diesel driven heavy trucks amounted to about 95 percent.

The growth in electric vehicle sales is pushing up demand for batteries, continuing the upward trend of recent years. Demand for electric batteries reached more than 750 GWh in 2023, up 40% relative to 2022. Electric cars account for 95% of this growth (IEA, Batteries and Secure Energy Transitions, 2024). In 2023, 92 percent of global sales of lithium-ion batteries went to electric vehicles (measured as GWh). Approximately 85 percent of these were sold to passenger cars. The rest was 7 percent for buses, 6 percent for two- and three-wheelers and 3 percent for heavy vehicles. (IEA, Batteries and Secure Energy Transitions, 2024)

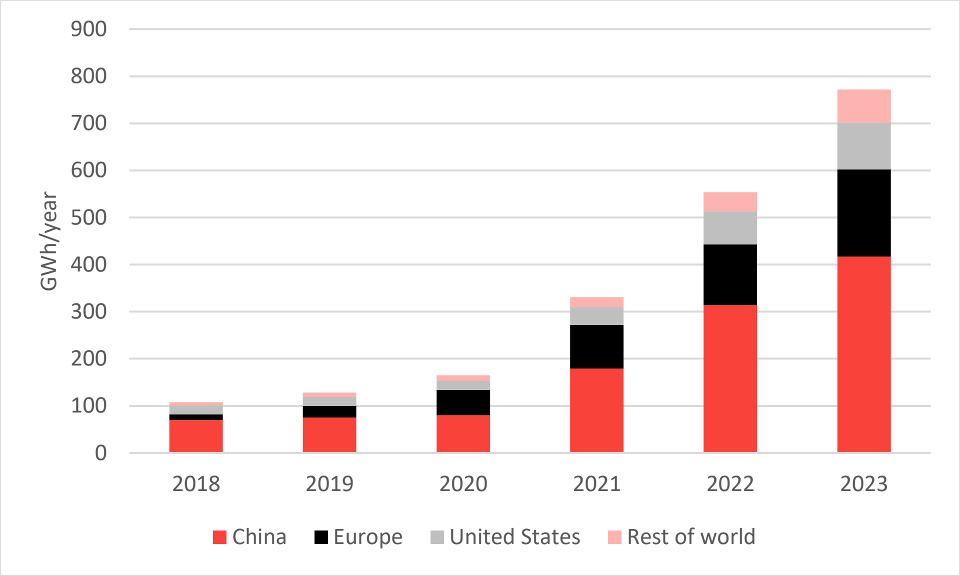


Figure 3. Electric vehicle battery demand by region

2.1 RECENT MOVEMENTS IN THE VEHICHLES MARKET

The European electric car market has grown significantly in recent years. However, 2024 marks a deceleration as the number of newly registered electric cars decreases for the first time. The global electric vehicle market is still growing rapidly due to continued strong growth in China, which has compensated for reduced sales in Europe. However, the increase globally was slower than in 2023.

Despite the fact that the cost of batteries for electric cars has decreased by 90 percent in 15 years, between the years 2008 and 2023, the purchase price of electric and plug-in hybrid cars remains higher than that of fossil-fueled cars. Countries have used policy instruments and incentive programs to varying extents to stimulate the purchase of electric cars, which has led to different developments in electric car adoption across countries. However, adjustments in incentive programs by many countries, together with a period of economic recession with high interest rates and inflation has affected the demand for electric vehicles. This development affects the profitability for users to buy an electric car, and hence, the demand for electric cars has been influenced by external factors over the past year. A positive development in battery prices and capacity will bring us closer to the tipping point where an electric car becomes more profitable than a combustion engine car. However, it is still uncertain when this will happen. The price development is depending on how the competition on the market will develop and at what phase. This breakeven point is discussed later in this report.

The trend in Sweden is the same as it is on EU-level (Mobility Sweden, 2024). The electrification goals among car manufacturers have varied in ambition, with some having to backtrack and revise their targets and plans. In September, Volvo Cars announced that they are also adjusting their electrification ambitions due to changing market conditions and customer demands (Volvo Cars, 2024).

The new ambition is that 90 to 100 percent of the global sales volume by 2030 to consist of electrified cars, both fully electric and plug-in hybrids. The remaining 0-10 percent allows for the sale of a limited number of mild hybrid models if needed, meaning gasoline cars supported by small electric motors to reduce fuel consumption.

Meanwhile, Volvo has announced that in 2025, they will launch a new long-range version of their FH Electric, capable of reaching up to 600 km on one charge (Volvo , 2024). The range is made possible by Volvo's new driveline technology, so-called e-axle, which creates space for significantly more battery capacity onboard.

The Swedish battery manufacturer Northvolt experienced economic turbulence during 2024. It is however not likely that financial difficulties of a single company will affect the world market of batteries, but it does illustrate the potential difficulties of being a battery manufacturer competing with China.

The current fluctuations in the demand for electric vehicles affect vehicle operators and battery manufacturers in the short term. However, there is not much to suggest that the temporary fluctuations currently affecting the market will seriously slow down the demand in the long term. Larger trends and regulations such as the CO2 requirements in EU, the Inflation Reduction Act in the US and the Chinese investments and incentives will likely have a large impact om the development in the longer run.

In May 2024, the United States increased tariffs on Chinese-made electric vehicles (EV) from 25% to 100%. In August 2024, Canada followed suit increasing its 6.1% import tariff on Chinese EVs to 100%. (Weihuan Zhou, 2024)

In october 2024, the European Commission concluded its anti-subsidy investigation by imposing definitive countervailing duties on imports of battery electric vehicles (BEVs) from China for a period of five years. The investigation previously found that the BEV value chain in China benefits from unfair subsidization which is causing threat of economic injury to EU producers of BEVs. As from the entry into force of the measures, sampled Chinese exporting producers will be subject to the following countervailing duties: BYD: 17.0%, Geely: 18.8%, SAIC: 35.3%. Other cooperating companies will be subject to a duty of 20.7% (European Commission, 2024).

Regulation on CO2 emissions for heavy duty vehicle sector

The development of the demand for electric heavy duty vehicles is expected to be affected by the EU regulation on the area. The develoment is required to speed up in order for european countries to meet the EU regulation on CO2 standards for heavy duty vehicle sector. The European Climate Law requires the EU to achieve climate neutrality by 2050. The transport sector is obligated to reduce its emissions by 90 percent by 2050 relative to 1990 to comply with this target. According to the Regulation on CO2 emission standards for HDVs, manufacturers will have to comply with targets for fleet-wide average CO2 emissions starting from 2025. These targets will apply to new HDVs registered in the reporting period of a given year, namely from 1 July of that year to 30 June of the following year. The CO2 standards were revised in 2024 and the CO2 reduction target of 15 percent for 2025 was maintained while the 2030 target was rised to 45 percent and another 65 percent reduction target for 2035 and a 90 percent target for 2040 was introduced. The standards include all heavy vehicles over 2,5 tonnes. The CO2 requirements do not specify the proportion of zero-emission vehicles but apply to a reduction from the 2021 level. This means that fuel efficiency improvements, such as through hybridization, also work to achieve the targets.

In US, the Inflation Reduction Act (IRA) includes several regulations and incentives specifically targeting heavy-duty vehicles. In California has effectively imposed the phase out of conventional combustion trucks by 2036, with other US states expected to follow. Moreover, the IRA provides significant tax credits for US lithium-ion batteries, making them competitive with Chinese alternatives. These credits include up to 30% of capital investment, $35 per kilowatt hour (kWh) for battery cells and $10/kWh for battery modules. By reducing production costs, these incentives encourage the adoption of heavy-duty electric vehicles, which can significantly reduce CO2 emissions in the heavy-duty sector by replacing diesel trucks with cleaner alternatives. However, the impact of the IRA on pricing is not yet clear.

Similarly, China is anticipated to tighten its tail-pipe emissions reduction targets soon to comply with its near-zero emissions target by 2060.

Charging infrastructure requirements

Given that this report focuses on battery development over the next 10 years, it is assumed that the Alternative Fuels Infrastructure Regulation (AFIR) has been achieved. The regulation, which is a part of EU:s “Fit for 55” package, entered into force in April 2024 and establishes legally binding national and EU-wide targets for the development of alternative fuel infrastructure. This means that member states are obligated to meet the specified requirements and deadlines to ensure adequate charging and refuelling infrastructure for both light-duty and heavy-duty vehicles.

Below is a concise description of the requirements regarding charging infrastructure.

By 2025 at the latest, charging facilities for light-duty electric vehicles must be available at intervals of no more than 60 kilometers along the Trans-European Transport Network (TEN-T) core road network (in Sweden consisting of E4, E6, E10, and parts of E18, E20 and Rv40). The power requirement increases by 2027, and from that year onward, corresponding requirements apply to the TEN-T comprehensive road network.

For heavy-duty electric vehicles, charging infrastructure must cover 15% of the TEN-T road network (core and comprehensive) by 2025 at the latest, with a minimum spacing of every 120 kilometers. By 2027, this coverage should extend to 50% of the roads. Finally, by 2030, charging stations must be available at intervals of at least 60 kilometers on the core road network and 100 kilometers on the comprehensive road network.

The charging stations must have a minimum output of 350 kW for heavy-duty electric vehicles and 150 kW for light-duty electric vehicles) (European Parliment, 2023).

The graph below shows the total number of recharging points by 2024 (in absolute numbers, not in relation to the size of the country). There are a few European countries that so far have begun their expansion on a larger scale.

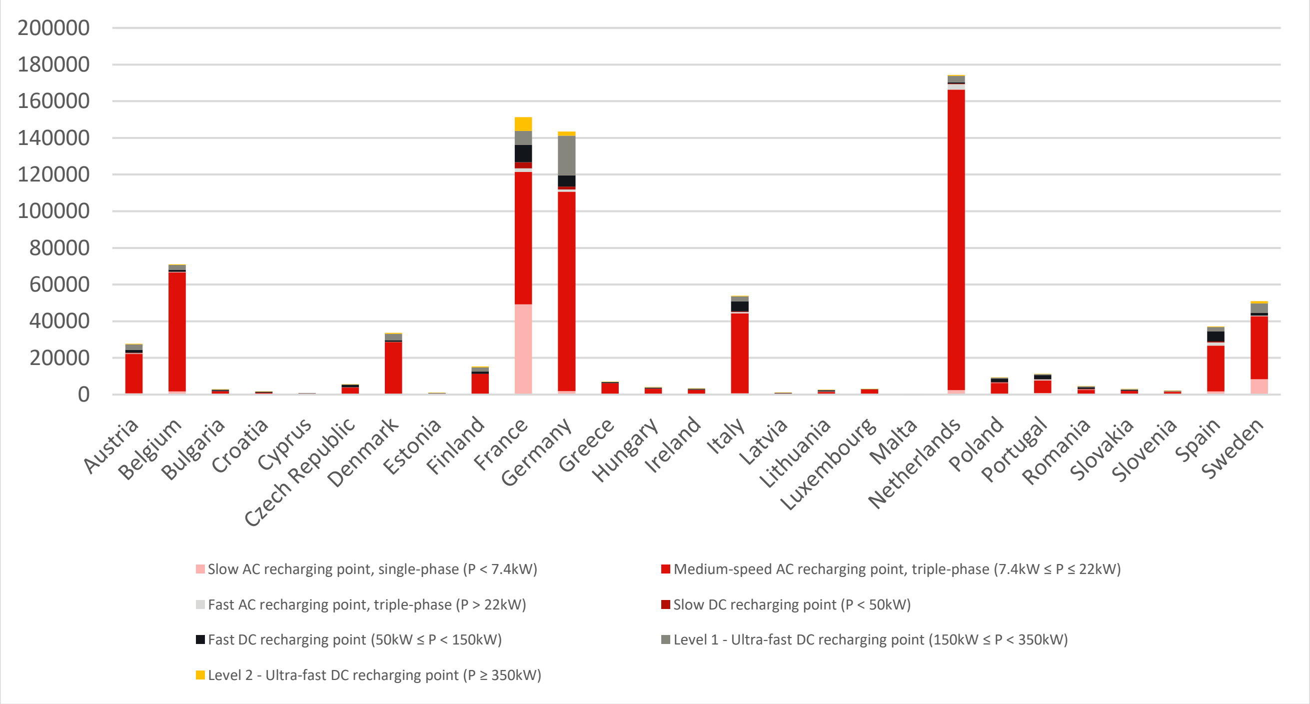


Figure 4. Total number of AC and DC recharging points, according to the AFIR categorization. (European Alternative Fuels Observatory, 2024)

3. THE MARKET FOR BATTERIES

Summary Chapter 3.

- The most common battery chemistries used in EVs are NMC, LFP and NCA, all of which are lithium-ion based. Sodium-ion batteries are one of the most promising alternatives to lithium-ion batteries. However, their lower energy density makes them less suitable for long-range trucks, as they take up more space and weight, which reduces the maximum range.
- Volume and weight no longer seem to be the main technological challenges for HDEV applications, but rather reducing charging time and increasing range. With legislation in Europe requiring drivers to rest for 45 minutes after 4.5 hours of driving, the end user's goal is to optimise operations to last for this time and recharge while resting.
- Recent developments in the efficiency and energy density of heavy-duty electric vehicles show that it is likely that the range will increase to 500-600 km by 2025. This corresponds to a battery capacity of around 600 kWh, which means that batteries are starting to reach a level where they can drive for 4.5 hours on a single charge, reducing the need for ERS.
- At existing fast-charging power levels, it can take up to 100 minutes to fully charge a 600 kWh truck. MW charging systems (MCS) are therefore needed to charge large batteries in 45 minutes. MCS is not yet established, nor is it currently included in the EU's AFIR legislation. But charging operators and vehicle manufacturers have big plans to develop MCS, and if their ambitions are realized, there could be many charging points in the future.
- Both ERS and MCS have the potential to further stress the distribution grid in an already increasingly electrified society. ERS allows multiple vehicles to be charged simultaneously, whereas MCS requires high power at a single point. This can lead to longer waiting times for grid connection and high electricity tariffs, especially in the case of MCS. Furthermore, some transport companies prefer to charge near cities, where grid challenges are prominent. This makes it more difficult for fleet hubs to secure connections, thereby increasing the uncertainty of future truck charging. WSP's analysis of current studies on ERS does not provide a clear assessment of whether ERS is significantly better than MCS in terms of power demand and its impact on the distribution grid. Therefore, in-depth studies in this area are needed to determine this trade-off.
- The future availability of raw materials for batteries is uncertain, but an important aspect of addressing this is increased recycling. At present, the value chains for this are not well developed.
- Over the past 30 years, the cost of batteries has fallen dramatically, while the energy density of high-quality cells has increased by a factor of five. This means that batteries have become cheaper, lighter and smaller. Although the rate of decline is now slowing, the price of batteries is approaching a level that will allow EVs to break even over the lifetime of the vehicle and reach price parity with internal combustion vehicles.

3.1 BATTERY DEVELOPMENT - TECHNICAL COMPOSITION OF BATTERIES

Battery development has seen major changes in both technical and market aspects. Historically, batteries have evolved to be more efficient, durable and able to hold more energy, although recent trends in new chemistries have different characteristics.

3.1.1 Technical composition of batteries

Technical composition of batteries conclusions

- The most common battery chemistries used in EVs are NMC, LFP and NCA, all of which are lithium-ion based.
- Sodium-ion batteries are one of the most promising alternatives to lithium-ion batteries. However, their lower energy density makes them less suitable for long-range trucks, as they take up more space and weight, which reduces the maximum range.

EVs are at the forefront of the automotive industry's shift towards sustainability, with their batteries playing a central role in this transformation. For some time, lithium-ion batteries have dominated the EV battery market. However, there has been a shift in the market share of the leading lithium-ion battery type and new chemistries have entered the market. All with different characteristics that affect range, especially for vehicles with a high number of batteries, such as heavy-duty trucks. Other developments that affect range include the way the batteries are mounted in the vehicle.

A lithium-ion battery is assembled with six parts:

- Anode
- Cathode
- Separator
- Electrolyte
- 2 x current collectors (positive/negative)

The operating principle is that charged lithium ions are carried by the electrolyte from the anode to the cathode or the other direction, depending on if the battery is charging or discharging. Considering the case where ions move from anode to cathode, free electrons are created in the anode when the lithium ions move through the electrolyte, which creates a charge at the positive current collector. Thus, current can then flow from the collector through the device needing power from the battery (Energy, 2023).

The boom in electric drivetrains for vehicles requires batteries to store energy that can later be used in the electric motor for propulsion. Electric vehicles can be divided into three categories:

- BEV – battery electric vehicle – Fully electric vehicles, powered by electricity only
- PHEV: Plug – in hybrid vehicle – Car with both an ICE and a battery, battery can be charged through cable
- HEV: Hybrid electric vehicle – Car with both ICE and a battery, battery charged only by ICE engine

Lithium-Ion Batteries

For batteries in cars, different options exist, but the arguably most used is lithium – ion batteries (sometimes called lithium – ion chemistries). Lithium-Ion batteries are today already commonly used in almost all consumer electronics applications, with examples ranging from laptops to phones. As li-ion batteries have relatively high energy density, and scores well on other metrics (ratio of power to weight, energy efficiency, temperature performance, lifecycle and low self-discharge) it is the most used battery chemistry. Also, li-ion batteries can largely be recycled, albeit cost of recycling are still relatively high. For batteries in electric vehicles, most use some form of li-ion chemistry, although the exact composition often varies from consumer applications (United States Department of Energy, u.d.).

The final composition of lithium – ion batteries might vary depending on application. The two primary chemistries for lithium-ion batteries are NMC (lithium, nickel, manganese, and cobalt oxide) and LFP (lithium, iron, and phosphate), with NCA (lithium, nickel, cobalt, and aluminum oxide) also being a notable addition. The general principle is that all of these are dependent on the input of lithium, cobalt, manganese and nickel, thus making those materials critical (Kinch, 2024).

While they are all lithium-based batteries, the difference is largely in the materials in the cathode, which impacts both performance and cost. The names thus often refer to the material in the cathode, even though they are all considered lithium – ion batteries. The most used chemistries in EV: s is:

- NMC: Nickel, manganese and cobalt
- LFP: Iron and phosphate
- NCA: Nickel, cobalt and aluminum oxide

Among these, they are sometimes referred to as “NMC811”, referring to the composition of minerals at the cathode, in this case 80% nickel, 10% manganese, 10% cobalt (Bhutada, 2023). For heavy vehicle manufacturers, the chemistries are certainly important. NMC batteries are common but may come at a higher price. There are also so-called low-cost chemistries, of which LFP is arguably the most common.

When referring to chemistries, the actual cells might be similar across many compositions, while the cathode material is different, thus giving the name to the specific chemistry. For NMC and LFP chemistries, the NMC is higher in price but has a higher performance, whereas the LFP has lower cost but slightly lower performance, as they have a lower voltage per battery cell. However, these batteries have a longer lifetime, and the lower price might be suitable for certain applications that are price sensitive.

In 2022, the most dominant battery chemistry was the NMC battery with a share of 60 percent, followed by LFP battery with a share of about 30 percent, and NCA with a share of about 8 percent (IEA, 2023). Compared to NCA and NCM batteries, the LFP-battery makes use of a chemistry composition of iron and phosphorus rather than nickel, manganese, and cobalt.

The supply of batteries is highly dependent on imports from China and thus can be seen as vulnerable to disruptions, given the large reliance on one export market. China currently controls – either directly or indirectly – around 80% of the NMC cathode materials and 92% of the LFP cathode materials, as the minerals used pass through China.

Alternatives to Lithium-Ion Batteries

Yet new emerging technologies have been evolving as alternatives to the lithium-ion batteries. The IEA (IEA, 2023) mentions that sodium-ion (Na-ion) is one such alternative. The Na-ion battery has the dual advantage of relying on lower cost materials and completely avoiding critical minerals, leading to lower cost batteries. Wood McKinsey made an overview of the different chemistry’s qualities, see figure 4.

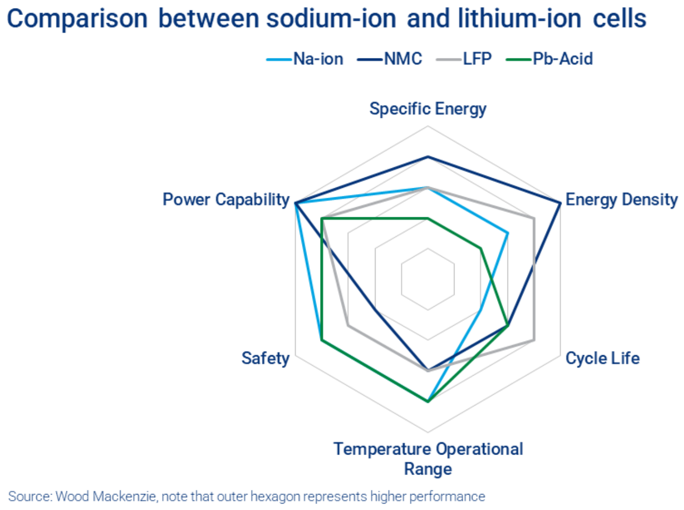


Figure 5. Comparison between sodium-ion and lithium-ion cells (Le Xu, 2021)

It is estimated that the Na-ion battery is about 30 percent cheaper than LFP-batteries but does not have the same energy density (about 75 - 160 Wh/kg compared to 120 – 260 Wh/kg for LFP). Hence, a lower energy density could make it more suitable for urban vehicles with low range and more challenging for vehicles that require long range with less accessible charging (IEA, 2023). As of today, there are nearly 30 Na-ion battery manufacturing plants operating, planned, or under construction for a combined capacity of about 100 GWh, almost all in China (IEA, 2023). Comparing that to the manufacturing capacity of Lithium-ion batteries, which is about 1 500 GWh, it is still relatively low. Nevertheless, car manufacturers such as BYD and Volkswagen-JAC have announced Na-ion batteries in future EVs. Na-ion batteries can potentially reduce the total cost of ownership for future EVs and possible even HDEV assuming there are frequent charging stations and ERS sections along major road networks. However, the scale or size of such possible potential is not yet known. A possible implication of this is that Na-Ion batteries are more suitable for urban use cases for vehicles, or stationary battery storages where weight is not a similar issue as in transport. Therefore, in markets where range is a higher priority or chargers less accessible, it is Na-Ion batteries might be less popular.

As mentioned, the choice of cathode material in the battery is crucial as those also make up over 50% of the cost of a battery cell, as well as determining important characteristics, such as possible charging speed and energy density. The anode – often graphite – and the electrolytes – often solutions based on lithium salt – are critical as well, but the possible options for those parts are more limited (Anthony L. Cheng, 2024).

Although certain chemistries, such as sodium-ion, may be more attractive for passenger cars and short-range applications, there is likely to be a continued need for long-range solutions and therefore demand for lithium-ion batteries. This is particularly relevant for HDEVs, which require extended range and higher energy density to meet the demands of long-distance transport.

All in all, the difference in performance and cost across chemistries highlights the trade-offs and choices manufacturers must make when choosing batteries, as the most suitable one depends on the application where it is used (TRATON, 2023).

3.1.2 Energy density and battery size optimization

Energy density and battery size optimization conclusions

- Studies shows that the required batteries size is reduced up to 50-80% with ERS.
- There have been many developments to minimise the space required for batteries. Volume and weight no longer seem to be the main issue for HDEV applications, but rather reducing charging time and increasing range.

Optimizing the weight and energy density of batteries is critical to the efficiency and performance of electric vehicles. Higher energy density allows batteries to store more energy without increasing their size or weight, which is essential for extending the range of EVs. If batteries become sufficiently advanced to allow vehicles to drive longer distances on a single charge, the need for ERS could be reduced.

There are possible improvements that could be done on the batteries to improve the challenge with energy density. One example is changing the anode material from graphite to silicon, thus making it lighter with higher energy density as a result. There are already ongoing efforts to infuse silicon in the graphite used today, which is used in 30% on anodes today. A research topic that is not yet commercially available is to use lithium metal anodes that has great potential if available on the market (IEA, 2023).

Moreover, when designing a battery configuration, composition is critical. The cells themselves are important, but so are the packs they make up and the modules into which they are assembled. Starting from a structure that historically placed battery cells in modules that were packed into battery packs, energy density has been increased by skipping the module part. The latest trend is also to remove the pack and integrate the cells directly into the chassis frame, reducing the number of components by 40% (Gongquan Wang a, 2024). An overview of the different configurations is shown in Figure 5.

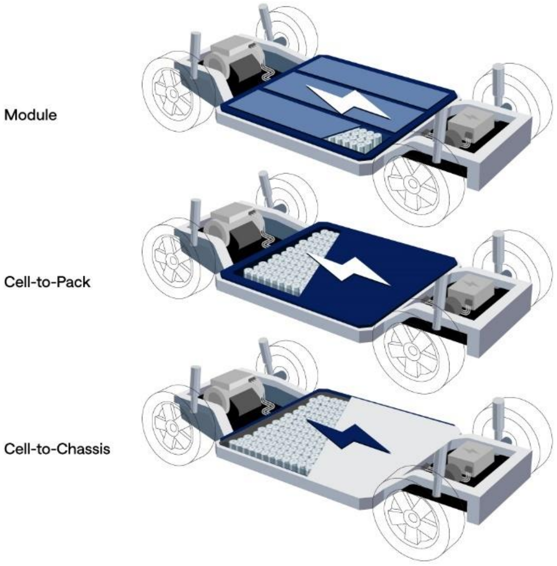


Figure. 6 An overview of the different battery configurations in EVs

This is one of the reasons why we have seen an increase in energy density in recent years. However, it could be argued that there is a limit to the extent to which further optimization can be achieved in this way.

Rocky Mountain Institute (RMI) (Daan Walter, 2024) notes that the efficiency of top – tier batteries has increased historically, from 250 Wh/kg in 2015 to 300-350 Wh/kg in 2020, with some of the best performing packs reaching 500 Wh/kg in 2023. While it is unclear from their analysis if the top tier packs are readily available for the market, it suggests that available energy density on the battery market for EV-manufacturers is increasing steadily. However, as mentioned above, there may be different requirements for range, and therefore energy density, depending on the application, e.g. different geographies.

Mats Alaküla, a professor from Lund University who has been studying electric roads for over 14 years, states that the environmental impact from mining all metals for batteries can be significant but reduced with ERS as the batteries needed for ERS is smaller. With ERS, the required battery size can be reduced by 50-80%, meaning that the environmental impact will be reduced and mitigated as the battery sizes are smaller (Bjerg, 2023). Furthermore, a study from Chalmers has demonstrated that battery size can be reduced by up to 70% in the most favorable scenario, while simultaneously distributing the load on the power grid throughout the day. This study focused on personal EVs, rather than trucks (Wasim Shoman, 2022). However, the charging power used in the study was limited to 72 kW, which is considerably lower than the latest ERS developments.

While the literature emphasises advances in battery configuration and energy density for passenger cars, these improvements are equally important to the development of HDEVs. Historically, the HDEV sector has leveraged design improvements from the passenger car industry, resulting in large technological advances. By incorporating the latest innovations in battery technology, HDEVs can achieve extended range, improved efficiency and reduced operating costs. Together, these benefits support a sustainable and economically viable future for heavy-duty electric vehicles.

Even To understand how much weight and space batteries for HDEV would require, we can assume an energy density in weight and volume of 200Wh/kg and 500Wh/l respectively. This would give a battery with a range of 500 km and an installed capacity of 621 kWh (Mercedes eActros 500) a weight of 3100 kg and a space requirement of 1.2 m^3. As the cells are currently packed in the chassis, they are highly space-efficient and may not be a critical concern. However, a heavier battery will always reduce efficiency, as the vehicle requires more energy to move itself around. Although larger and therefore heavier batteries will be required in the future, reducing charging time and increasing vehicle range appear to be the main challenges for truck manufacturers today.

3.1.3 Impact on range on EV adoption

Impact on range on EV adoption conclusions

- There are different trends in range depending on geography, with Europe and the US tending to have longer ranges while China seems to have shorter ranges, especially seen in the EV sector.
- Legislation in Europe requires drivers to rest for 45 minutes after 4.5 hours of driving, therefore the target for end users is that the battery capacity will last for this time and can be recharged during the rest period. If batteries can support 4.5 hours of driving at 80-90 km/h, the need for ERS is reduced.
- Recent developments in the HDEV industry show that the market will soon reach a level where such trucks can drive for 4.5 hours without stopping to recharge.

The range of EVs is critical to their practicality and adoption, especially for HDEVs with high daily mileage. With legislation in Europe requiring drivers to rest for 45 minutes after 4.5 hours of driving, the aim for end users to optimize operations is to last for this time and recharge while resting. If batteries can support 4.5 hours of driving at 80-90 km/h, the need for ERS is reduced, as vehicles can recharge during mandatory breaks.

The battery supply chain is currently under pressure since the average range of EV:s is increasing. While the average size of battery packs have increased 10% p.a. in the last five years – from 40kWh to 60kWh, the average range of EV:s have increased from 230km to 337 km (47% increase). This is largely to meet consumer demand for longer range, which still is higher than most offered models. As this pushes car manufacturers to offer longer range models, there is room for improvement in both battery technology and powertrain construction to limit range anxiety. Also, improved charging speed and density of charging networks can help in this regard (Bloomberg NEF, 2023).

A notable change in the market recently has been a general shift from NMC to LFP chemistries, particularly in the Chinese market where LFP has increased from 20% of the EV battery market to 80 % over a three-year span. One possible explanation for this shift could be supply chain reasons – some manufacturers point out that China can produce some of the critical raw materials of iron titanium from residues in other industries. Also, LFP batteries are suitable in China, where the demand for range is lower than in many western geographies (IEA, Global EV Outlook 2024, 2024). Thus, the popularity of LFP batteries might remain lower in the western hemisphere, but the low cost of LFP batteries might be attractive to some consumers. However, in the American market – arguably one of those with the most demand for longer range – the number of long-range models has increased drastically during the last few years. Long range is typically defined as 300 miles or more on a charge, and there were 30 models with this performance in the US in 2024, a five-time increase over three years. For comparison, there wasn't even one option for long range a decade ago, highlighting a relatively quick development in range for cars. In addition, the latest trends in HDEV in Europe are the launches of new electric trucks with a range of 500-600 km. This is being driven by companies such as Volvo (Volvo trucks, 2024), Mercedes-Benz (Mercedes-Benz, u.d.) and Scania (Scania, u.d.), indicating the future demand for range in Europe.

3.1.4 Charging and charging time

Charging and charging time conclusions

- With current technology, the charging time is around 100 minutes, but the new MCS would reduce this to under 45 minutes, allowing HDEV to be fully charged during the mandatory 45-minute break.
- MCS is not yet commercially established, nor has it been included in the EU's AFIR legislation for the time being. However, both truck manufacturers and charging operators have plans to build many charging points over the next 5 years.
- Some transport companies prefer to charge near cities, where grid challenges are prominent. This makes it more difficult for fleet hubs to secure connections, thereby increasing the uncertainty of future truck charging.
- High power demands from charging HDEV can lead to strains in the electricity network. Current studies on ERS do not provide a clear assessment of whether ERS is clearly better than MCS in terms of its impact on the distribution network. Therefore, in-depth studies in this area are needed to determine this trade-off.

The ability to quickly recharge HDEV is a crucial element in making them a competitive alternative to diesel trucks while simultaneously reducing the necessity for extensive ERS development. This implies the capacity to recharge the HDEV during the mandatory 45-minute break.

For a battery with a capacity of 600 kWh, the charging time today while using a fast charger with 350 kW can be up to 100 minutes. However, the heavy truck industry is currently anticipating the megawatt (MW) – charging standard, which would allow for significantly higher charging speeds. The new megawatt charging standard is designed to handle from 700 kW up to 3,75 MW which can enable full charging within 45 minutes. However, there is no likely demand of a charger powers close to 3,75 as a truck with a 1,2 MWh sized battery would be able to charge 10% to 90% state of charge (SOC) during 45 minutes with a 1,3 MW charger (Daniel Speth, Depot slow charging is sufficient for most electric trucks in Germany, 2024). To date, megawatt charging systems (MCS) is still under development and has not been commercialized. ABB installed the first MW charger prototype in

Germany in 2024 and demonstrated charging higher than 700 kW. As described in section 2.1, EU AFIR legislation sets the minimum HDV charging power at 350kW, without mentioning higher power requirements (ABB, 2024). However, the CEO of MAN Truck & Bus stated “The goal is to have 30,000 MCS charging points in Europe by 2030, of which around 4,000 will be in Germany” (Colaluce, 2024). Truck manufacturers are also investing in MCS, with Volvo Group, Traton Group and Daimler Trucks setting up Milence to build and operate 1700 high-capacity (mixed MCS and carbon capture and storage (CCS)) charging points in Europe by 2027 (milence, u.d.).

Moreover, many trucks do not recharge at public charging stations, but at their fleet hubs. A fleet hub is a central location where a company's fleet of vehicles is charged and maintained. This may be a distribution centre, for example, rather than a public charging station. By 2030, it is estimated that 50% of long-haul trucks will charge at public fast chargers, 10% at public overnight chargers and 40% at fleet hubs. For regional and urban trucks, 10% will charge overnight at public stations and 90% at fleet hubs (ACEA, 2022). This places significant demands on the charging infrastructure at fleet hubs.

CLOSER, a collaboration platform for increased transport efficiency, points out that the growing use of electric heavy-duty trucks increases the importance and challenges of energy supply. Charging often takes place when the trucks are stationary, such as during loading and unloading, leading to higher energy demand at terminals and potential power peaks. This requires more grid capacity and increases grid connection costs and tariffs (CLOSER, 2024). As cities are shifting from centralized to local energy production, the stress on grids in densely populated areas is becoming increasingly apparent. In some urban areas, delayed grid connections, congestion issues, and limitations to infrastructure expansion are already limiting residential and commercial activities (E.DSO, 2024). This makes it particularly challenging for the charging infrastructure at distribution centres, which are often located near large cities and are highly dependent on the availability of grid connections due to their fixed locations. This contributes to greater uncertainty about the future of truck charging availability.

Dr Patrick Plötz (Volvotrucks, 2024), coordinator of the energy business unit at the Fraunhofer Institute for Systems and Innovation Research ISI in Germany, believes that MCS will be commercially available in late 2024 or early 2025. He also highlights the potential issues with MCS, with some sites requiring up to 12MW of grid capacity to support up to 20 MCS outlets, which will put a strain on grid infrastructure (Mobility Portal, 2024). Furthermore, one of the most important parts of planning a charging point is getting electricity to a specific location, as the timeframe for large electrical installation projects can be very long (i.e. 2 to 5 years) (CHARIN, 2022). Another possible concern with such high charging speeds could be stress on the battery, the general size of heavy-duty truck batteries is so large that the C – rate – indicating the stress – will not become so high anyway (TRATON, 2023). However, it will still stress the battery more with these chargers than with lower capacity chargers.

A concentration of charging activity in specific regions could have a negative impact on power grids, placing strain on the system while other areas remain relatively inactive. In addition, as electricity prices for a 500-kWh battery can vary by up to 40 EUR per charge in different countries (Poland or Germany) (Julia Hildermeier, 2024), this could further increase local electricity demand and lead to overloading of the local grid. With ERS, the power used to charge the battery is much lower, today we see charging power between 180-300kW, but with alternating current (AC) potential up to 800kW. The charge is distributed over a larger geographical area and not in a single point as with MCS. Evias, the manufacturer of the conductive ERS, has sections of 50 meters that are activated one after the other (Power Circle, 2021). Since ERS allows battery sizes to be reduced, this also means less capacity to be charged. However, as ERS allows more vehicles to be charged at the same time, it could potentially lead to even more electricity being consumed from the grid. As both MCS and ERS are new innovative technologies, there is less research on them and therefore it is difficult to say with certainty which would have the biggest impact on the electric grid.

3.1.5 Battery recycling and raw material impact

Battery recycling and raw material impact conclusions

- Battery recycling is essential to reduce dependence on raw materials and to address environmental concerns. Reports show that recycling LFP batteries is currently less profitable than recycling NMC and NCA batteries.
- Although lithium is the main component, studies indicate that demand can be met until 2026, and with new recycling capacity and projects, demand could be met beyond 2030.
- It should be noted that the infrastructure also requires raw materials. A study that includes the infrastructure shows that BEVs have the highest demand for aluminium, while ERS with induction has the highest demand for copper.
- The development of sodium-ion batteries has the potential to reduce reliance on critical raw materials, as they have the possibility to increase market shares in segments where cost is more crucial than energy density, like the battery energy storage systems (BESS) industry. This could have a positive impact on market dynamics by reducing the need to rely solely on LFP and NMC batteries.
- The increasing number of second-life applications for EV batteries that do not meet EV standards but can instead be used in the energy storage industry presents an opportunity to reduce the charging time, range and cost (TCO) through an extended lifespan of 7-10 years. However, this may result in delays to recycling lithium batteries.

According to the IEA (IEA, 2023), the overall supply and demand of battery metals have increased significantly between 2016 – 2022. As seen in Figure 6 below, the global EV-market demand (light blue) for Lithium, Nickel and Cobalt has grown since 2016, where the demand for lithium has seen the largest increase. This is primarily due to demand for lithium-ion batteries in the EV market.

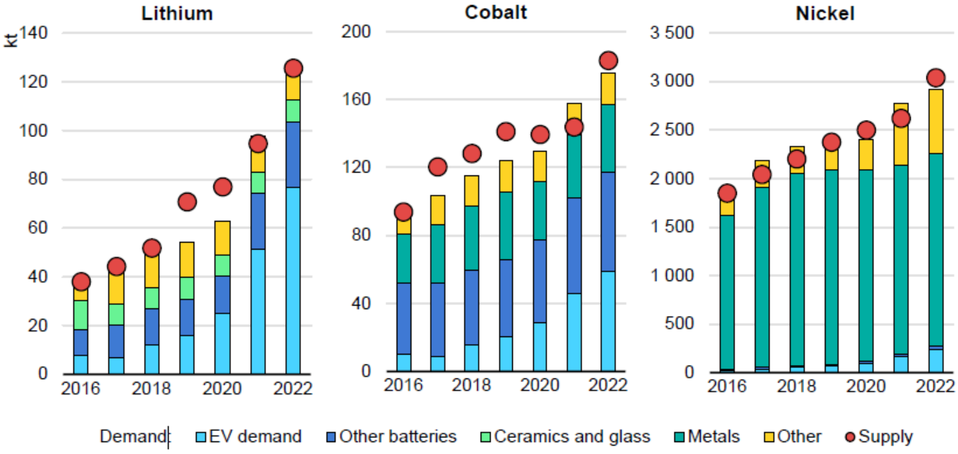


Figure 7. The supply (red dot) and demand (coloured bars) for different battery chemistries grouped by sector between 2016 – 2022 (IEA, 2023).

A recent article from McKinsey (Jakob Fleischmann, 2024) shows that the lithium demand will be met until 2026. With new recycling capabilities and further projects expected, the demand could be satisfied beyond 2030. In addition, sodium-ion batteries, which do not require critical raw materials, could increase their market share and thus reduce the demand for LFP and NMC batteries and their materials.

The critical materials needed for batteries might also influence choices for battery chemistries among auto manufacturers. From a historical standpoint, NMC batteries with a balanced ratio of nickel, manganese, and cobalt were popular until 2015. After an increase in cobalt prices and media scrutiny regarding mining of cobalt, manufacturing of batteries switched to chemistries with lower degrees of cobalt. In the last years, as nickel prices have increased, LFP chemistries have become more popular, highlighting how increases in material prices reflect choices of batteries downstream in the value chain.

The properties, benefits and drawbacks of different battery chemistries also depends largely on different use cases as mentioned. For long haulage, TRATON (TRATON, 2023) noted in a conversation that for long haulage, trucks usually drive 130 – 160 000km per annum, which translates to 520km per day, with operations on 250 days per year.

Recycling and reusing batteries are crucial for reducing dependency on raw material imports and addressing environmental concerns. As of today, recycling LFP batteries is less profitable compared to NMC and NCA batteries. As more batteries reach the end of their life, recovery rates will become increasingly important. The increasing market share of LFP could therefore have a negative impact on future overall recycling rates. This could change if demand for lithium-ion batteries outstrips supply, as the value of recycling LFP batteries is highly dependent on the price of lithium (Jakob Fleischmann, 2024). This means that when lithium demand is high, most end-of-life batteries will be recycled, and the materials will be returned to the value chain.

Sodium-ion batteries, which do not require critical raw materials, could also influence the market. If sodium-ion batteries gain a larger market share, the demand for LFP and NMC batteries may decrease, reducing the need for critical materials and affecting future recycling needs. In addition, it is not uncommon for EV batteries that do not meet EV standards to be used as second-life batteries in the energy storage industry, where energy density is not as critical. This extends their battery life by 7-10 years (European Commission, 2023). However, this also means that these batteries cannot be recycled for an even longer period, which may have an influence on the future number of batteries recycled.

However, even though that the larger batteries by default mean higher demand for mined metals than for smaller batteries, the infrastructure of ERS charging also requires mined metals. In one report, Seshadri Srinivasa Raghavan (Seshadri Srinivasa Raghavan, 2023) investigated this. They have comparted the demand for metals for vehicles including the infrastructure it requires comparing ICE, battery stationary charging (BEV), batteries with inductive charging (InduERS) and batteries with conductive charging (CondERS). Their results show that the demand for aluminium for BEVs is the highest (1600 kilo ton (kt)), followed by InduERS (1400 kt) and CondERS (1150 kt). However, when it comes to copper, InduERS have the highest demand (660 kt), followed closely by BEV (645 kt) while CondERS only needs 400 kt where the infrastructure accounts for about 30% of the copper in the different scenarios.

3.1.6 Future heavy vehicle battery expectations

Future heavy vehicle battery expectations conclusions

Various factors will influence the necessity for an ERS, depending on developments in battery technology. Three key considerations are cost (TCO), charging time and range. The batteries represent a significant portion of the trucks overall cost, and therefore their affordability is a crucial factor. Additionally, the charging time must align with the mandatory 45-minute break, and the range must be sufficient for the vehicle to operate without requiring additional charging. WSP's assessment is that break-even for ICE vs HDEV will be reached in terms of TCO in 2030, given that charging is available and assuming there are no political obstacles to the utilisation of the relevant materials.

The future of heavy-duty vehicles is increasingly looking beyond the ICE thanks to advances in battery technology. Until now, the combination of long charging times, high costs and insufficient range has made electric alternatives impractical. Modern batteries are approaching enough energy density to provide sufficient range, which is critical for heavy-duty vehicles that require high battery capacity. In addition, the recent drop in lithium prices has made electric heavy-duty vehicles a more viable option, although they are still more expensive in terms of both purchase price and lifetime costs. However, with these technological and economic improvements, electric heavy-duty vehicles are starting to become a viable and attractive option. The question is when the break-even point will be reached, in terms of lifetime costs, but also in terms of range and charging time.

In contrast to electric heavy-duty trucks, the future retail price of diesel heavy-duty trucks is estimated to increase until 2030 due to future compliance with emission targets. Not by much, but about 9% by 2030 and stable until 2040. Moreover, when comparing the retail prices of battery-powered and diesel-powered heavy-duty trucks driving 800 km per day, battery-powered trucks are 2.6 times more expensive (EUR 457,000 vs. EUR 176,000) (Hussein Basma, 2023). This aligns with Mercedez electric truck with a range of 500 km, which is 2.5 times more expensive than its diesel equivalent (Reuters, 2023) and an analysis from McKinsey shows that it would be 2 times more expensive, see Figure 8

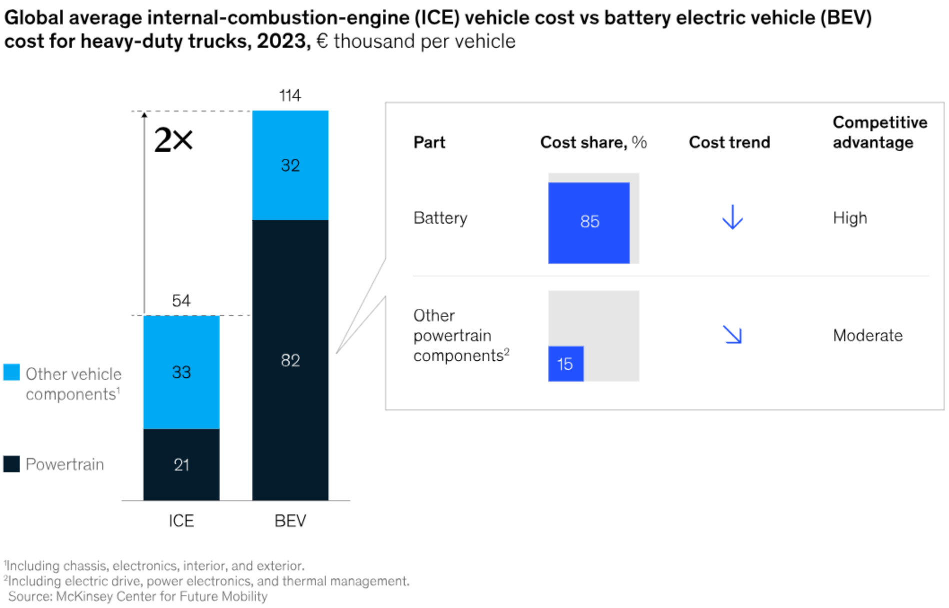


Figure 8. ICE vs BEV costs (Jakob Fleischmann, 2024)

However, if there is a change in tax or regulation, the retail price of EVs could potentially change, and it could shift in both directions. For example, as described in section 2.1, the IRA has introduced tax breaks for domestic battery manufacturing. If we see more similar tax breaks and subsidies and they are large enough, this could lead to lower retail costs for HDEVs. In addition, the purchase price of ICE trucks could increase as they comply with CO2 reduction targets, leading to compliance costs and potential penalties. On the other hand, as the Western world sees China's subsidies for battery production as unfair, more regions seem to be introducing higher tariffs for electric vehicles (EU recently for example, increasing tariffs on EVs from 10% up to 35%) (Blenkinsop, 2024). Apart from the tariffs themselves, this could also lead to higher prices as trade tensions lead to an imbalance between supply and demand and lower global growth. There are many possible outcomes from new regulations and taxes. But it is difficult to say with certainty what will happen.

Currently, batteries constitute the major expense in HDEVs, accounting for 85% of the powertrain costs and which make up for about 60% of the total vehicle cost (Jakob Fleischmann, 2024). However, it should be noted that this is an evolving innovation, not a mature market competing on price alone. As battery prices fall, EVs may become cheaper, but there is no indication that they will become significantly cheaper. Furthermore, it is not uncommon for new products to have higher development costs, which we believe can be reflected in the pricing and could potentially result in lower future prices. Moreover, even if battery prices do not fall significantly, there may be changes in the value chain in the battery sector that also could contribute to lower HDEV prices in the future, in addition to cell prices and development costs. One example of this is Volvo Group, which utilizes second-life batteries from buses, trucks and other machines for its battery energy storage systems. This approach not only prolongs the lifetime of the batteries but also minimizes the total cost of ownership of the batteries used in HDEV. Furthermore, recent data indicates that more affordable electric vehicles are on the horizon. One year ago, Citroen introduced their e-C3 car with a price of 23.3 thousand EUR. At the same time, Renault showed their 25 thousand EUR car, and Volkswagen expects to have models in the same pricing category. Furthermore, Tesla seems to be developing a smaller model that will revolutionize the manufacturing process for EVs. Tesla is already utilizing gigacasting, a process whereby large components of the vehicle are cast in a single piece. This is a technique that will also be employed by Volvo and Toyota. According to a study by Gartner, battery costs will be a factor in reducing EV prices, but the most significant impact will be the result of advances in manufacturing. Gigacasting, for example, has the potential to reduce manufacturing costs by 20% (Undéhn, 2024). It is unclear whether HDEVs will be priced low enough to match the retail cost of ICE trucks. However, they are expected to reach a point of total cost parity over time. McKinsey conducted an analysis to determine when this potential break-even point with ICE heavy-duty trucks might be reached, as illustrated in Figure 9.

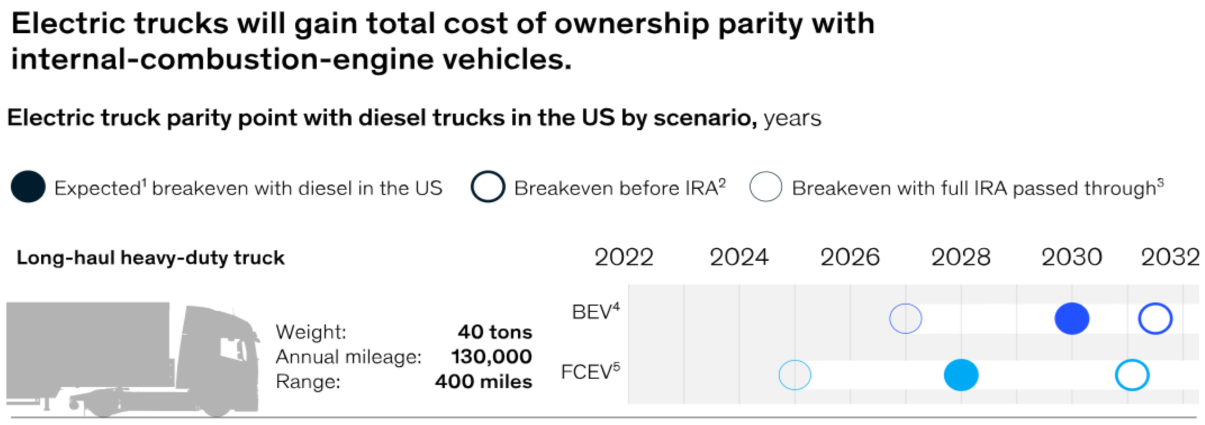


Figure 9. TCO break even ICE vs BEV (Saral Chauhan, 2023)

They estimate that the break-even point in the US will be around 2030. As the break-even point for lifetime costs is around 5 years, other considerations include the time it will take to recharge and the range the trucks will have in that time. As mentioned earlier, several manufacturers have announced their developments for 2025, and these can reach up to 600 km in one charge. This is an important achievement as they can drive for 4.5 hours without recharging. By 2030, therefore, the range does not seem to be an issue and the time it takes to recharge is the last important factor. Today, the charging time for these new heavy trucks would be around 100 minutes. However, with the new MCS it would be possible to charge in less than 45 minutes. As of today, there are not many of these chargers in use, but if things go as planned, there will be a lot more of them by 2030. Nevertheless, considering the rapid advancements in charging technology, we believe that the MCS charging challenge will be overcome. Barring any political obstacles to the utilization of the relevant materials, we anticipate that there will be a point of equilibrium in terms of total cost of ownership (TCO) in 2030 for ICE and HDEV.

3.2 COST DEVELOPMENT OF BATTERIES

Conclusion - Cost development of batteries

- Over the past decade, lithium-ion batteries have become the primary choice due to their high performance, energy density, and significant cost reductions.
- The break-even point for price parity with internal combustion vehicles is around 92 EUR/kWh, which is expected to be reached by 2030.
- There is a cost discrepancy between heavy and light commercial vehicle segments, with HDEV projected to be priced 10% above the industry average by 2030 due to the use of tailored, engineered battery designs.
- Future battery prices are uncertain, but many projections indicate continued cost reductions as manufacturers improve efficiency across the battery value chain.

Among different battery chemistries, lithium-ion has been the main choice for the last ten years. Thanks to high technical performance, comparatively high energy density and lifetime and with drastic cost reductions (~90% since 2010) it is currently the dominating battery alternative in the market. This chapter will explore the current and future costs of battery cells and battery packs. The next chapters, 3.2.1 and 3.2.2, looks at learning curve and forecasts of the future costs of the entire battery system, which includes other components, e.g. thermal management systems, etc.

Figure 10 is taken from EIA and shows the development of average electric vehicle battery price since 2010. In 2010, battery prices were 1300 EUR/kWh, compared to just 130 EUR/kWh, in 2023. However, towards 2030 the prices are estimated to reach a level of below 100 EUR/kWh.

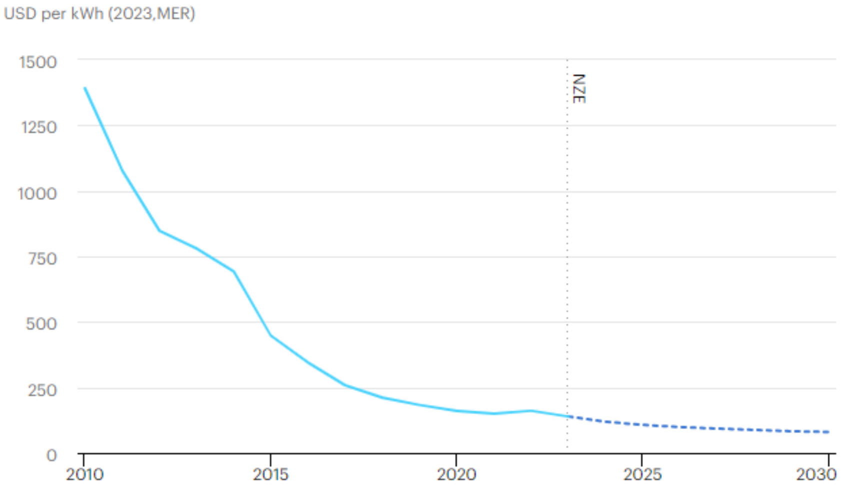


Figure 10. Trend and projection for average EV battery prices (IEA, 2023)

The trend for the battery packs in which the cells are mounted has also declined over the past 10 years, according to another analysis by BNEF. Figure 11 below illustrates the general development of prices for both battery packs and cells between 2013 and 2023. However, 2022 saw an increase in prices – largely fueled by increased prices of components and raw materials, which was in turn driven by increased production capacity in all stages of battery manufacturing. Also, demand was lower in 2022 than expected (BloombergNEF, 2023).

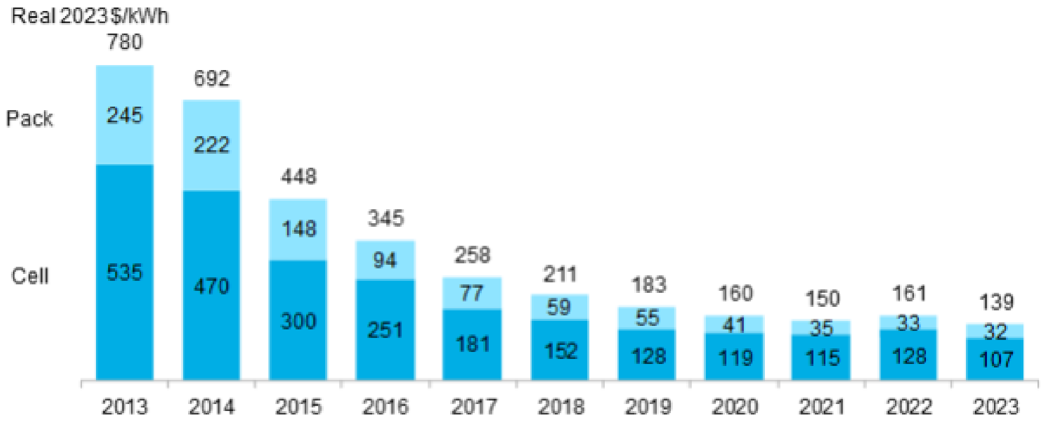


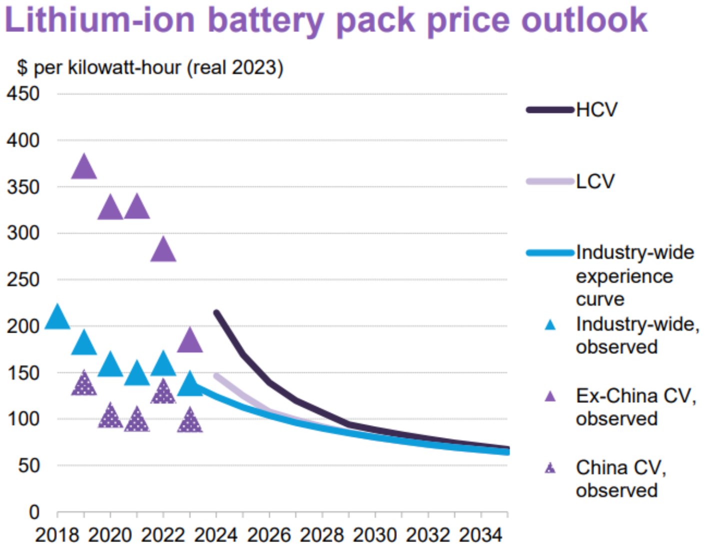
Figure 11. Battery cells and packs cost development (BloombergNEF, 2023)

Bloomberg NEF does project that battery prices will fall to 74 EUR/kWh by 2030. Investment bank Goldman Sachs have a similar view, projecting prices for battery packs to reach 83 EUR/kWh by 2025 and 63 EUR/kWh by 2030, largely driven by their projection that EV:s share of light vehicle sales will continue to increase, supported by programs such as the inflation reduction act in the US (Goldman Sachs, 2024).

Nonprofit Institute RMI also concurs in this view, with projections below 91 EUR/kWh by 2030. They also note that the efficiency (among top-tier battery packs) has increased at a similar pace as prices have decreased, and projects these patterns to continue until 2030, albeit the pace of the development depends on projection scenario (Daan Walter, 2024). The break-even point for achieving price parity over lifetime with internal combustion vehicles is widely recognized as being 92 EUR/kWh (cicenergigune, 2024). Given the numerous analyses that have projected future prices to be around 92 EUR or below, it is possible that we will reach this break-even point even if the decline in cost is not as rapid as it has been historically.

The demand for lithium-ion batteries in the automotive industry increased by roughly 65% between 2021 and 2022, corresponding to 550 GWh of battery capacity. The largest demand for LFP batteries comes from China, where 95% of LFP batteries in electric vehicles also were produced. As of 2022, the NMC chemistries made up a majority of the battery supply, corresponding to 60% market share, with LFP batteries making up 30%. NCA batteries are less used and had a market share of 8%.

The manufacturing cost of the cells into packs for batteries was estimated at 20% of total battery cost in 2022, a decrease from 30% over the decade. This has occurred while the cost of cell manufacturing saw a slight increase in 2022, with costs being level with 2019 prices, largely due to increased material costs. Furthermore, Bloomberg has highlighted a cost discrepancy between heavy and light commercial vehicle segments. This is attributed to the necessity of additional engineering resources to tailor batteries for specific use cases. By 2030, it is projected that HDEV will be priced at 10% above the industry average, with a further narrowing of the gap in the subsequent decade (Nikolas Soulopoulos, 2024). This trend is illustrated in Figure 12.



Source: BloombergNEF. Note: 'CV' is commercial vehicle; 'LCV' is light-duty commercial vehicle; 'HCV' is heavy-duty commercial vehicle.

Figure 12. Trend and projection for HCV and LCV battery pack prices (Nikolas Soulopoulos, 2024)

Indications of future prices for batteries are of course uncertain, but there are several projections indicating a continuing pattern of lower prices as manufacturers become more efficient across the battery value chain. While above figures highlight an exponential decrease in battery cost, many analysts expect this pattern to continue.

3.2.1 Future battery systems costs – learning curve of batteries

Conclusion – Learning curve of batteries

- Learning curves predict future cost reductions as technology matures.
- A scientific article from 2024, based on over 200 forecasts, concludes that battery costs for heavy trucks are expected to decline much faster than expected.
- The cost of battery systems for heavy trucks is projected to decrease by 64–75 percent until 2050, potentially falling below €150 per kWh^{-1} by 2035 (from around €225 per kWh^{-1} in 2024) and approaching €100 kWh^{-1} towards 2050.
- We use these findings as new input for our system dynamics model to estimate how the projected battery costs will affect the demand for ERS.

As battery costs are considered a critical factor in the adoption of not least electric vehicles, researchers have shown increasing interest in forecasting battery costs. One way to analyse the predicted development of battery costs is to use a so-called learning curve. In this chapter, the analysed costs refer to the battery system (including the thermal management system, connectors, etc.), while the costs presented in chapter 3.2 refer to the costs for battery cells and pack.

This report does not aim to develop its own learning curve but instead uses the results from Link et al. (2024). In this section, the theory is first briefly explained, followed by a presentation of the results from the article by Link et al. We then use the results from the article in our self-developed system dynamic model to estimate how the projected battery costs will affect the demand for ERS.

Technological learning, also known as the learning curve or experience curve analysis, highlights our understanding of cost dynamics. It assumes a fundamental relationship between technology costs and learning parameters. By analyzing historical data, technological learning aims to estimate future cost reductions as technology matures.

Various methodologies can be used for forecasting battery costs through technological learning. The predominant method is the 1-factor approach, which correlates forecasted values to the future development of a single learning factor. For instance, it associates predictions of battery costs with factors such as cumulative battery production or sales volume (Lukas Mauler, 2021). An alternative approach is the multi-factor approach, where cost or price reductions are derived based on the future development of multiple learning factors. This method considers various aspects simultaneously to provide a more precise estimation of battery costs. Furthermore, there is the 2-stage approach, which conducts technological learning in two sequential stages. Different cost components exhibit specific learning rates.

However, comparing outcomes from diverse methodologies presents challenges. Even when utilizing the same dataset, factor-specific rates tend to become lower with the 2-factor approach, as cost reductions are partially allocated to other factors.

The time period selected for calculating the learning rate significantly influences its magnitude. Since learning rates stem from historical correlations between learning factors (often the battery market) and the forecasted item (battery cost or price), outcomes may fluctuate across years due to shifting market dynamics.

3.2.1 Cost projections

Link et al (2024) conducted a meta-analysis of over 200 sources, including peer-reviewed papers, industry announcements, and analyst reports, to forecast cost trends for zero emission truck (ZET) components. They found that the cost of battery systems for trucks is projected to decrease by 64 to 75 percent until 2050, and potentially falling below €150 per kWh by 2035 and approach €100 per kWh towards 2050. In contrast, fuel cell costs are likely to reach €150 per kW in the late 2030s, although with greater uncertainty due to lower commercial maturity and doubts about realizing floor costs.

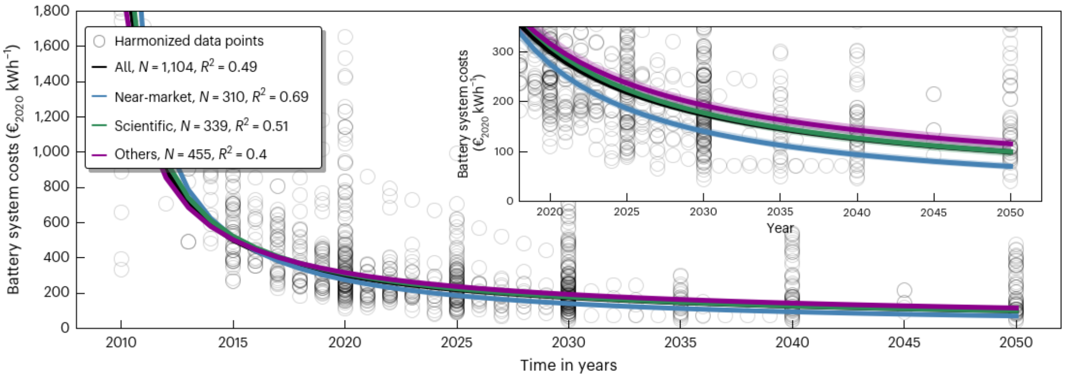


Figure 13. Projections for heavy ZET battery system costs (Link et at, 2024)

Figure 13 illustrates the projected cost decline of battery systems for trucks categorized into three main groups[1]: near-market, scientific, and others. The graph shows system-level costs per kWh of total gross battery capacity. These include, among others, battery and thermal management systems, cell modules, housing, connectors, wiring and assembly. Black circle markers represent the original harmonized data. Solid lines represent the regression results, with the shaded areas in the zoom-level plot (period 2020–2050) as 95% confidence intervals.

The results show that battery costs are primed to decline much faster than expected and are showing a significant reduction over time, but with differences between groups of estimates. The article finds cost reductions of around 5% yearly (scientific and others) to 6.5% yearly (near market) until 2030 and 3.3–4.5% yearly over an extended 2020–2050 period. Hence, there are significant differences between scientific and near-market estimates. Near-market estimates generally forecast the fastest cost reductions, reflecting industry confidence in rapid advancements. This consolidates into expected cost estimates, where near-market estimates project a decrease from around €275 per kWh in 2020 to €140 per kWh by 2030 and around €70 per kWh by 2050. In contrast, scientific estimates suggest a more gradual decline and indicate a drop from roughly €310 per kWh in 2020 to €180 per kWh by 2030 and around €100 per kWh by 2050. The “others” category provides additional context, highlighting the range of possible outcomes based on different assumptions and data sources and project more conservative progress, cutting €200 per kWh by 2030 and approximating €115 per kWh by 2050.

The steep decline in the graph, up until around 2030, indicates significant cost reductions, primarily driven by technological advancements. After 2030, the curves level off, and the cost reductions become considerably slower towards 2050, even though reductions are still occuring. Since the most impactful innovations are likely already implemented by then, ach further sharp cost reductions becomes more challenging.

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[1] Near-market estimates refer to projections made by industry stakeholders, such as manufacturers and market analysts. These estimates are typically based on current market trends, technological advancements, and production scaling, which is why they tend to be more optimistic. Scientific estimates, on the other hand, are derived from academic research and studies are based on rigorous scientific methodologies and peer-reviewed data. The “others” category includes projections from various sources that do not fit into the near-market or scientific categories, such as non-peer-reviewed academic publications

4. RAW MATERIALS - UPSTREAM UNCERTAINTIES

The upstream uncertainties linked to environmental/sustainability aspects (the largest environmental impacts come from the mining of critical minerals and metals for batteries) and the supply-chain risks (geo-politic) may be reduced by using smaller batteries and ERS. One of the largest supply risks are for the materials copper, cobalt and lithium. Copper is highlighted as a metal with supply risks in the long term. This is based on current and known manufacturing techniques and materials for batteries. The following aspects related to raw materials are discussed in this section:

- Supply-chain resilience
- A focus on environmental and sustainability effects
- Creation of a circular value chain

Summary Chapter 4.

- The largest supply-chain risks and uncertainties involve the raw materials copper, cobalt and lithium. The major upstream supply-chain for cobalt involves both Africa and Asia.
- The mining and processing of the raw material today gives rise to large emissions and environmental problems. Most of the world's production takes place in Asia and in countries with lower environmental legislation than, for example, the EU
- If a serious shortage situation arises, it can in the long run also affect the price of the input material for batteries.
- In summary, these supply-chain risks and uncertainties may be reduced by using smaller vehicle batteries/ERS.

4.1 THE EV BATTERY SUPPLY CHAIN

The term ***supply chain*** describes the process by which a product is made and delivered to a consumer (Carreon, 2023).

The steps involved in producing and using an EV battery fall into four general categories:

Upstream: Mines extract raw materials; for batteries, these raw materials typically contain lithium, cobalt, manganese, nickel, and graphite (The Economist Intelligence Unit, 2023). Lithium and cobalt are two critical minerals on EU's list of Critical Raw Materials (Gian Andrea Blengini, 2020). Asia dominates mineral processing. The potential for geographical shift in the midstream battery supply chain is greater. In 2022 China accounted for a major share of the processing of key battery materials: about 65% of the world's lithium, 74% of cobalt, 100% of graphite and 42% of copper processing. The processing of these materials is critical for China to meet its own demand for lithium-ion batteries. In 2022 China accounted for about 57% share of global demand for lithium-ion batteries, as it leads global EV production. Many different types of studies show a risk of long-term scarcity for copper. In addition, copper is used in all types of electrification (as well as other strategic sectors). The most high-grade ore deposits are becoming depleted, requiring more extraction at greater depths and from deposits with lower copper content (Seshadri Srinivasa Raghavan, 2023).

The upstream supply chain when it comes to mining the raw materials cobalt is illustrated in figure 14.

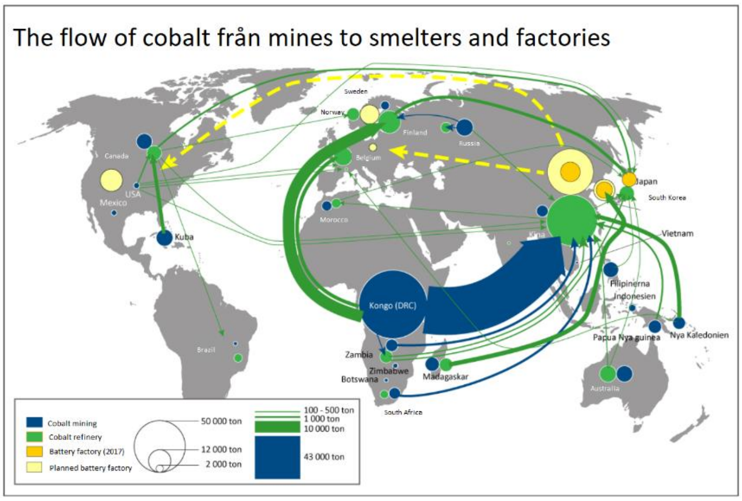
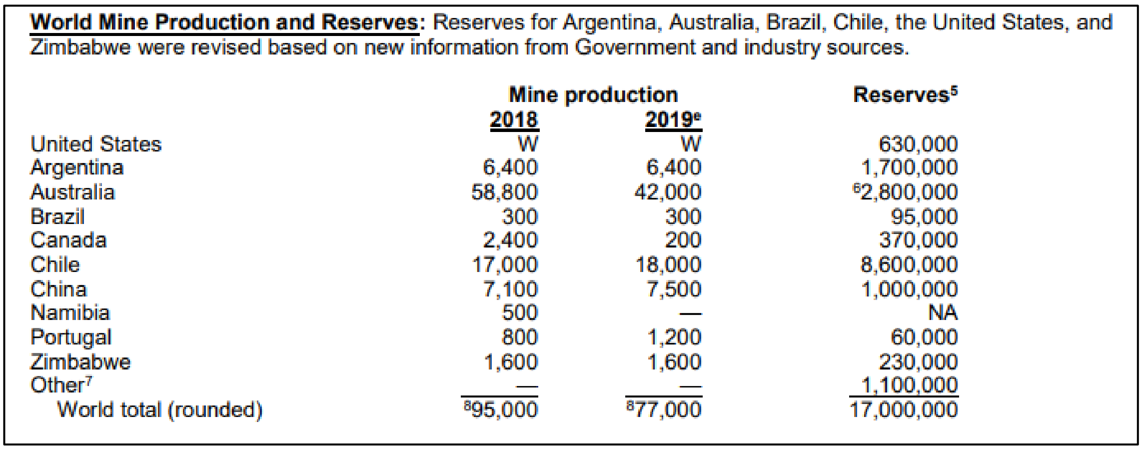


Figure 14. Upstream supply chain Cobalt (Sveriges geologiska undersökning, 2021)

On a global level, mining is concentrated in Congo and the availability of cobalt is good on a global level and is expected to be able to meet future needs, even though a small amount of cobalt is currently possible to recycle from lithium-ion batteries.

The World mine production and reserves of Lithium are listed in table 1. Although China has great control over the processing of lithium, there are large reserves and mining elsewhere in the world.



World Mine Production and Reserves: Reserves for Argentina, Australia, Brazil, Chile, the United States, and Zimbabwe were revised based on new information from Government and industry sources.

	Mine production		Reserves[5]
	2018	2019[e]	
United States	W	W	630,000
Argentina	6,400	6,400	1,700,000
Australia	58,800	42,000	[6]2,800,000
Brazil	300	300	95,000
Canada	2,400	200	370,000
Chile	17,000	18,000	8,600,000
China	7,100	7,500	1,000,000
Namibia	500	—	NA
Portugal	800	1,200	60,000
Zimbabwe	1,600	1,600	230,000
Other[7]	—	—	1,100,000
World total (rounded)	[8]95,000	[8]77,000	17,000,000

Table 1. World Mine Production and Reserves, Lithium (Jaskula, 2020)

Concerning the raw material Nickel, the assessment is that it is not critical for European production, but strategical. The EU assesses that Nickel has relatively low economic importance and supply risk, compared to Lithium and Cobalt (Gian Andrea Blengini, 2020).

Midstream: Processors and refiners purify the raw materials, then use them to create cathode and anode active battery materials; commodities traders buy and sell raw materials to firms that produce battery cells.

Downstream: Battery manufacturers assemble the battery cells into modules and then pack and sell them to automakers, who place the finished batteries in EVs. Some automakers like Ford and Stellantis have formed partnerships with battery manufacturers to produce their own batteries for the vehicles they sell. China will continue to lead battery downstream activities. Western policymakers also have their eyes set on the downstream battery supply chain, which is also firmly in the hands of China at present. The country accounted for about 73.3% of global lithium battery manufacturing capacity as of May 2023, according to S&P Global, a market research company. The US, Germany and Poland accounted for about 6.7%, 5.4% and 3.2% of the market, respectively. Investment is still pouring into China, which faces a risk of overcapacity in 2024.

End of Life: When batteries no longer serve their original purpose, they can be reused or recycled (IEA, 2022)(Read more about recycling in 3.5.1).

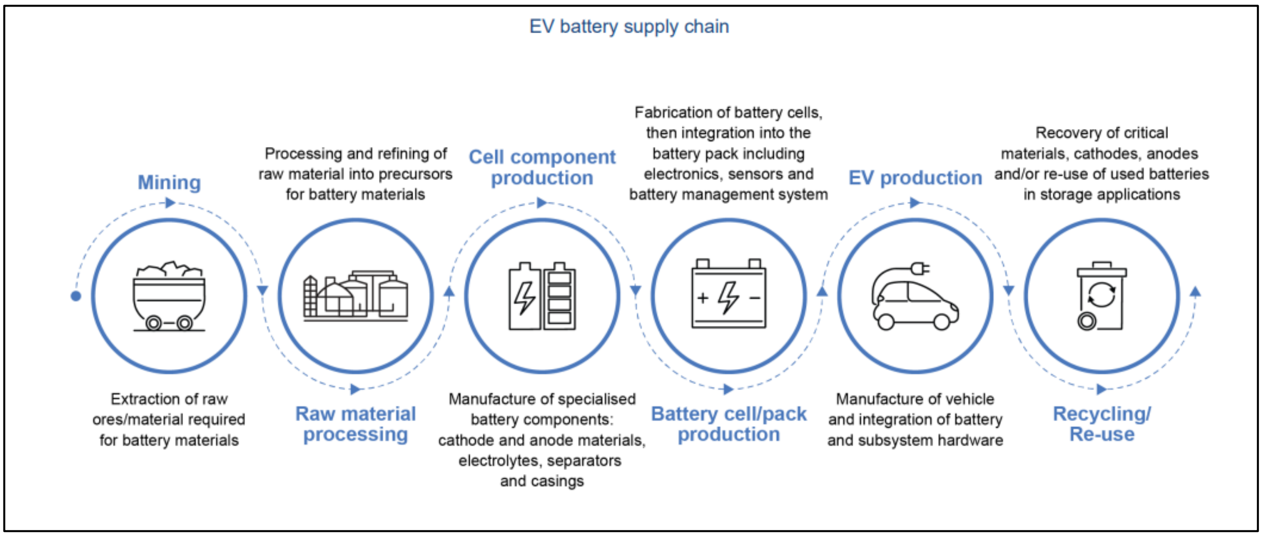


Figure 15. EV battery supply chain (IEA, 2022)

IS THERE A POLITICAL RISK INVOLVED IN BATTERY PRODUCTION?

Crisis, conflict, climate, politics can mean difficulties with access of certain raw materials from time to time. For example, we have had longer lead times for deliveries from parts of the world, which has led to a greater need for foresight in planning/ordering projects. There are assessments that there is access to critical raw material for future needs on a global level, the challenge is to complement existing raw material suppliers with European and American ones, to be able to handle shortages and risks.

Increasing the resilience of the global EV battery supply chain

The EV battery supply chain is dispersed around the world — battery minerals travel an average of 50,000 miles from extraction to battery cell production. At the same time, much of the mineral supply is concentrated in just a few countries. This dispersion and concentration make the global supply chain vulnerable to disruptions, including:

- Extreme weather (e.g., hurricanes, tornadoes and earthquakes that impact energy inputs and disrupt infrastructure like pipelines and shipping routes)
- Geopolitics (e.g., the war between Russia and Ukraine)
- Changing trade alliances between countries or regions
- Corporate consolidation: Today, when one of the many companies involved in the battery supply chain experiences a disruption, others are affected. As EV demand rises, it's likely that there will be a few big players that will oversee more parts of the process. If one (or more) of these companies experience disruptions, the effects will be greater.
- A change in materials needed due to new technologies: Battery chemistries and designs are changing quickly; many of them use alternative and more abundant materials. These changes will affect the supply chain network, and the countries and companies involved.

These disruptions can result in bottlenecks and negatively affect the rest of the battery supply chain; they can also impact economies, cause delays for suppliers, increase transportation costs, force employers to cut jobs, discourage investment, and hinder transportation decarbonization.

ENVIRONMENTAL IMPACT IN THE PRODUCTION OF VEHICLE BATTERIES

The production of battery cells is energy-intensive as it must take place in environments with very low humidity. The size of the greenhouse gas emissions depends on the energy mix used in manufacturing and the utilization rate or capacity that the battery factory is working with. The environmental impact from the battery value chain is assessed be relatively larger in many other active countries compared to if it were established in Sweden. In a study from IVL Swedish Environmental Research Institute on battery production for passenger cars, a calculation example is made to describe the climate impact of battery production in today's large-scale factories where waste route is not included. Mining and mineral processing are energy-intensive and account for about half of the climate impact that occurs in the production of an average lithium-ion battery for a passenger car. The greenhouse gas emissions that occur during the actual extraction of raw materials and the processing of the materials to produce the batteries are estimated at approximately 60 kg of carbon dioxide equivalents per kWh of energy storage capacity in a finished battery. The demand for batteries for vehicles increased globally from just over 0.15 terawatt-hour (TWh)/year in 2021 to about 0.35 TWh/year in 2022. By 2030, the need is expected to increase to between 2–3.5 TWh/year, depending on the scenario assumptions.

ERS implies that the vehicles can be equipped with smaller batteries, require less raw materials and are thus better from a sustainability perspective. The largest environmental impacts, in addition to the reduction of greenhouse gas emissions, come from the mining of critical minerals and metals for batteries (Fabien Perdua, 2023). Mining activities cause serious environmental problems and based on an exponentially increasing need for these critical minerals and metals and the fact that new mining is increasingly proposed to take place in remote and ecologically sensitive areas, the risks of significant environmental consequences may increase (Naturvårdsverket, 2023). The ERS batteries requires approximately 15 percent less metals than BEV, so the difference is not that big, but still significant (VTI, 2024).

WHAT ARE THE PROSPECTS FOR THE FUTURE?

The EU's strategic plan (2030) supporting significant increased mining of critical raw materials within the Union is progressing slowly with challenges concerning costly, long and complicated permit processes for increased mining. There are different ways to tackle the challenge of supplying raw materials. In addition to an increased element of self-sufficiency within the EU, consideration should be given to securing more suppliers from different regions, increased elements of different inventory strategies and supplier strategies that enable increased flexibility and support continuity in production. Examples include encouraging certain steps in the supply chain to be carried out in or closer to the EU, duplication of suppliers for certain materials, etc. For example, we see vehicle manufacturers increasing vertical integration through the acquisition of battery factories. Further, when it comes to the EU and joint work on circular economy and dependence on electricity/vehicles, the importance of systematic work with resilience. Finally, it can be mentioned that several studies show that the common assessment is that there are resources in the form of critical raw materials to meet the climate transition.

5. PROJECTED BATTERY DEVELOPMENT EFFECT ON ERS

Summary Chapter 5.

- The system dynamics model is developed by WSP (in 2023/2024) to predict the expected proportion of each type of truck (ICEV, BEV and ERSV) in the vehicle fleet for the years 2030-2050.
- In this report, further investigation on battery development has challenged some assumptions from the previous model of the system dynamics model. Some of the assumptions in the base model has now been updated according to research from work with this report.
- Battery capacity is increased (from 500 in the previous model) to 600 kWh in 2025 following market development. Battery capacity is set at 750 kWh in 2040. Compared to the previous project, this means that the purchase cost is initially higher in 2025 but lower by 2040.
- In the new model, we have assumed that it is possible to charge during the driver's break time without costing more than the static charging cost. During the previous project, it was assumed that it would not be possible. Research followed by discussions in this project shows that it is likely to occur. Having the ability to charging during the break makes BEV more attractive and even cheaper than electric road systems vehicles (ERSV) in the beginning of the studied period.
- We have performed eight new sensitivity analyses to analyse the results of findings regarding battery development in this report.
- Results for the base scenario and most sensitivity analysis show that ERSV is marginally cheaper than BEV. The difference is small.
- The largest difference between the new model and the previous model is the faster decrease in battery cost and the possibility to charge during the 45-minute rest pause.
- The sensitivity analysis where it is assumed not to be possible to charge during the driver's break time shows that ERSV is still cheaper than BEV. However, assuming that battery capacity might increase to follow the need of driving for nine hours straight in another sensitivity analysis, BEV ends up being cheaper

5.2 THE SYSTEM DYNAMICS MODEL – AN UPDATED VERSION

The system dynamics model is developed by WSP (in 2023/2024) to predict the expected proportion of each type of truck (ICEV, BEV and ERSV) in the vehicle fleet for the years 2030-2050.

In this report, further investigation on battery development has challenged some assumptions from the previous model of the system dynamics model (WSP, 2024). Some of the assumptions in the base model has now been updated according to research results from work with this report. The assumptions that have been updated in the base model are:

- The battery capacity
- The battery cost (according to the assumptions discussed in Chapter 3.2.1.)
- The assumption regarding the ability to charge the vehicle during the mandatory break.

In addition to the updates in the base model, we have also performed **eight** sensitivity analyses, based on findings from research in the work with this report.

The model, illustrated in Figure 16 below, aims to calculate the proportion of each type of truck in the fleet: fuel-powered trucks (ICEV), pure battery electric trucks (BEV), and battery electric trucks that can also be charged via electric road systems (ERSV).

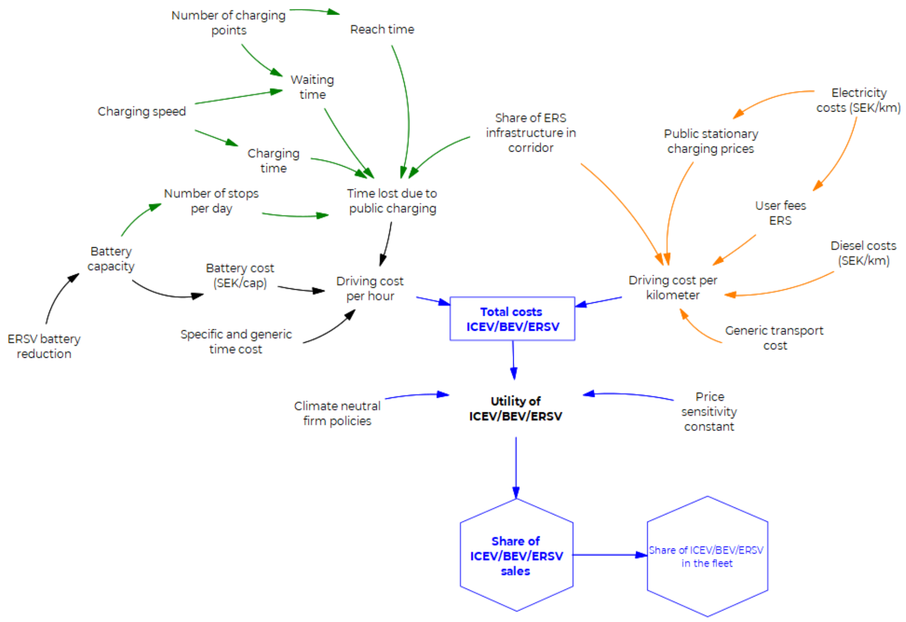


Figure 16. Simplified version of the system dynamics model. Time loss due to public charging is shown in green, driving cost per hour is shown in black, driving cost per kilometer is shown in orange, and the truck share component is shown in blue.

To be able to calculate the respective shares, a comparable component is needed that can be calculated for all three types of vehicles, such as the total costs for each vehicle type. Total annual costs are calculated by combining driving costs per hour and driving costs per kilometre. These two costs are scaled to an annual level using annual operating hours and annual vehicle kilometres, as per *Analysmetod och samhällsekonomiska kalkylvärden* (ASEK). The model also accounts for the time spent on charging for BEVs and ERSVs. This time loss is factored into the driving cost per hour as additional driving time to maintain the same production rate as internal combustion engine vehicles (ICEV). It is assumed that ERSVs will need stationary charging during the development of electric roads, as charging via electric roads will not be sufficient.

Below, dependencies of the model are explained.

5.2.1 Time loss due to public charging

Time loss due to public stationary charging is calculated for both BEV and ERSV. The time loss for ERSV is assumed to decrease as the electric road network expands, which means that the more charging done via the electric road, the less time needs to be spent on stationary charging. In the model, we assume that public stationary charging will approach zero for ERSV once the electric road is fully developed along the route, even though this will probably not be the case; public charging will still be needed in certain situations and parts of the route.

Three components are combined to calculate the time loss: access time, waiting time, and the actual charging time.

- **Access time** refers to the time required to drive to and from a specific charging point, i.e., slowing down and turning off the road to a charging station. This is influenced by the pace of the charging infrastructure development, meaning the more charging points available, the shorter the access time.
- **Waiting time** is the time a truck spends waiting for an available charging spot and is affected by the charging speed and the number of charging points along the route. The assumption is that higher charging speeds and a larger number of charging points reduce waiting time.

- **Charging time** refers to the time it takes to charge a truck, which is directly impacted by the charging speed.

5.2.2 Time-dependent cost

In addition to time loss due to public charging, the driving cost per hour is also influenced by battery costs and other specific and generic costs.

- **Battery costs** are affected by battery capacity and other production-related expenses such as raw materials. The cost is assumed to be lower for ERSV compared to BEV due to the smaller battery pack in the vehicle.
- **Specific and generic costs** include interest, insurance, and depreciation costs per hour, as well as taxes and driver costs.

5.2.3 Distance-dependent cost

Driving cost per kilometre is affected by fuel costs (electricity prices or diesel prices) and generic costs. Generic costs include depreciation per kilometre, tire wear, and service and repair. Depending on the type of truck, the respective fuel cost is added to the driving cost per kilometre, i.e., fuel costs for ICEVs and electricity costs for BEVs and ERSVs.

For electric vehicles, the cost is affected by the method of charging. A fee is added for stationary charging and ERS. The truck can also be charged at the depot, where no additional fee is assumed beyond the electricity price.

5.2.4 Multinomial logit model

Since actual sales figures (for ERSV) are lacking, which could be used to identify preferences and estimate the utility of each truck type, a multinomial logit (MNL) model has been developed.

The MNL model is a widely used model in choice modelling to estimate the probability of choosing a specific alternative from a set of mutually exclusive options. The choice probability in the MNL model uses the concept of utility. In a multinomial logit model, how different independent variables (such as battery cost and electricity cost) affect the probability that the dependent variable (such as total costs) falls into each specific category is examined.

In our model, TCO is the dependent variable, and all variables used to estimate it are independent. In the model, independent variables are grouped into two main variables: Driving Cost per hour and Driving Cost per kilometre.

$$Total\ cost = Driving\ Cost\ per\ hour + Driving\ Cost\ per\ kilometer$$

In our model, the utility for each alternative is based on the inverse of the annual ownership cost. For the battery-powered options, the price is reduced by 20 percent to capture the higher willingness to pay that is assumed to exist for choosing a more environmentally friendly option. The argument for this is that BEVs are already being purchased/leased even though they are not yet cost-competitive. This may be because carriers want to be early adopters in establishing a system (charging stations, etc.) for electric drive as the technology scales up.

Additionally, a price sensitivity factor is included to adjust the relationship between the utility of each alternative. The factor ranges from 0 to 1 and is set to 0.2 in the model. The lower the factor, the more sensitive the sales are to price differences. The truck market is considered relatively homogeneous, so price is assumed to be significant in the purchasing decision.

This factor results in the difference in utility between alternatives being greater than the actual difference in price.

$$Utility = \frac{1}{Price\ sensitivity\ constant * Climate\ neutral\ firm\ policy * Total\ Cost}$$

In calibrated multinomial logit models, an alternative-specific constant is defined. This constant helps account for variations in choice that cannot be explained by the observed (independent) variables and affects the utility of a specific alternative. It is defined and calibrated based on real data. Unfortunately, actual sales figures (for ERSV) are lacking to explain these unobserved variations and define such a constant. Thus, no alternative-specific constants exist in the utility.

Theoretically, the probability P_j that alternative j is chosen is obtained using the multinomial logit function. $\sum_k e^{U_k}$ is the sum of the exponential utilities for all alternatives.

$$P_j = \frac{e^{U_j}}{\sum_k e^{U_k}}$$

Since the two battery-powered options cannot be assumed to be independent of each other, the logit model has been constructed as nested. A nested logit model allows for multiple choice situations to be considered. In this case, there are two choice situations: in the first, they choose between a battery-powered engine and an internal combustion engine. If they choose battery-powered, they then have a separate logit model to decide whether it should be ERS-compatible or not.

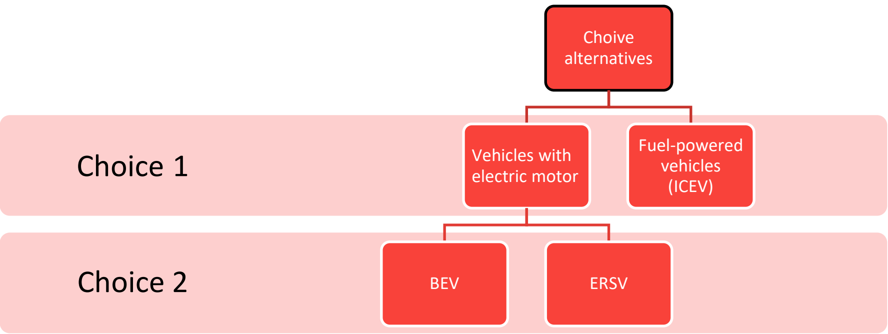


Figure 17. Choice model

The probability for each alternative can be interpreted as the share of sales for each type of truck.

By assuming a seven-year lifecycle for each truck, the sales share for all three types of vehicles can be converted into their share in the fleet over the time period. That means that every year, one seventh of the fleet is replaced by new vehicles. The share of each type of vehicle (ERSV, BEV or ICEV) is applied to these new vehicles entering the fleet. Over time, the share of each type of vehicle will change depending on the calculated share based on the TCO of each type of vehicle for each specific year.

5.3 ASSUMPTIONS FOR THE ANALYSIS

The table below shows the assumptions made in this study, based on literature reviews and interviews. Most of these assumptions have been made for a preview study but the highlighted variables have been changed to reflect the new findings that have been published since then. The base model has been updated with the actual predictions of battery costs according to the assumptions discussed in Chapter 3.

Category	**Variable**	**2025**	**2040**	**Unit**	**Source**
General	Depreciation	27.33	27.33	kr/h	ASEK 7.1
General	Insurance/Damage	31.16	31.16	kr/h	ASEK 7.1
General	Interest	19.07	19.07	kr/h	ASEK 7.1
General	Vehicle Tax	7.95	7.95	kr/h	ASEK 7.1
General	Driver Salary	245	245	kr/h	ASEK 7.1
General	Vehicle Lifespan	7	7	Years	ASEK 7.1
BEV & ERSV	Battery Cost	0.044	0.018	kr/kWh	Link et al (2024), same ASEK 7.1 method for ICEV applied

ERSV	Battery Reduction Factor	40	40	%	Scania, Volvo Trucks
BEV & ERSV	Battery Lifespan	7	7	Years	Estimated based on information from Scania
BEV & ERSV	Battery Wear	10%	10%	Share of initial capacity	Scania
BEV & ERSV	Government Support	20	0	%	Regulation (SFS (2020:750)) on state support for certain environmental vehicles
ICEV	Diesel Price	17.55	29.98	kr/l	Diesel price 2021 from Drivkraft Sverige, Projection to 2040 from Rogstadius (2022)
ICEV	Diesel Consumption	0.27	0.27	l/fkm	ASEK 7.1 but without efficiency improvements
BEV & ERSV	Electricity Price	1.35	1.75	kr/kWh	ASEK 7.1
BEV & ERSV	Electricity Consumption	1.5	1	kWh/fkm	Vehicle Manufacturer
BEV	Battery Capacity	600	750	kWh	Scania, Volvo Trucks and own assessment
ERSV	Battery Capacity	360	450	kWh	Scania, Volvo Trucks and own assessment
BEV	Load Factor	90	90	%	Own assessment, based on the entire fleet and primarily long-distance transport
BEV & ERSV	Net Capacity (percentage of the battery used)	90	90	%	Own assessment of a reserve similar to a reserve tank
BEV & ERSV	Percentage of Battery Charged Per Stop	70	70	%	Own assessment based on Volvo Trucks (2023) and Swedish Energy Agency (2020)
BEV & ERSV	Extra Time	20	10	minutes	Assumption of extra time related to driving off the road to the charging station and back
ERSV	Usage Fee (excluding electricity cost), Base Scenario	0.6	0.6	kr/fkm	Based on own assessment and calculation according to the method in Börjesson et al (2021). Operation and maintenance cost is not included, it is assumed to be internalized.
BEV & ERSV	Charging Infrastructure Fee (excluding electricity cost)	6	2.5	kr/kWh	Own assessment based on current price and potential price development with higher utilization rates
BEV & ERSV	Average Power in Public Charging Infrastructure	130	600	kW	Swedish Transport Administration (2021c), ACEA (2021), Scania (2022)
BEV & ERSV	Possibility to charge during 45-minute break	Yes	Yes	-	Power Cirle[2], Daniel Speth, Patrick Plötz[3]

Table 2. Assumption and variables for the model, highlighted variables have been added or updated

The following four assumptions, also highlighted above, are shown in the table below with their respective old assumptions.

		New assumptions		**Old assumptions**		**Unit**	**Comment**
Category	**Variable**	**2025**	**2040**	**2025**	**2040**		
BEV & ERSV	Battery Cost	0.044	0.018	200%	112%	kr/kWh	Previously, battery cost was calculated as a function the purchase cost of an ICEV.
BEV	Battery Capacity	600	750	500	800	kWh	Capacities are already at 600 kWh as of 2024. Capacities will need to satisfy up to one work shift without stopping to charge. This is reached already with 750 kWh.
ERSV	Battery Capacity	360	450	300	480	kWh	Idem.
BEV & ERSV	Possibility to charge during 45-minute break	Yes	Yes	No	No	-	During the previous project, it was assumed that charging during breaks would not be possible. Research followed by discussions in this project shows that it is likely to occur

Table 3. Updates in the base model compared to the last model

In the model, the electric road is assumed to be **constructed over five years** starting in 2030, while the model simulates results up to 2040. Thus, the electric road is assumed to be fully built out by **2035**. Similarly, charging infrastructure is assumed to be available where needed.

This means that the analysis and model are based on an even distribution and utilization across the electrified road network, regardless of technology. In other words, we assume that those who can utilize either the electric road or charging infrastructure will do so proportionally to the share of transport on that part of the road network.

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[2] (Power Circle , 2021)

[3] (Daniel Speth, Depot slow charging is sufficient for most electric trucks in Germany, 2024)

This is in line with how previous studies have addressed the issue. The implication is that whether a truck is fully electric, hybrid, or conventional (diesel-powered) does not affect which road segment is used. Additionally, regardless of distance or type of cargo being transported, the proportion remains the same across the entire road network. There are no decisive differences between, for example, the routes Stockholm – Gothenburg or Stockholm – Malmö that would make one route more interesting or advantageous to use with an electric road.

What we mean by decisive differences is that the traffic on these roads, such as parcel goods and scheduled services, is similar and is served by the same type of vehicles. From an electric road perspective, the type of goods transported is not of interest. What matters is the type of truck, with the majority being either truck with trailer or semi-trailer. The only truck type that would have a clear advantage with electric roads is refrigerated transport, but it constitutes a negligible portion of all transport. Otherwise, we refer to the previously presented transport setups in the report, where we discuss the suitability of each setup for electric roads.

Given the relatively large uncertainties regarding costs such as diesel prices and electricity prices, which have been particularly evident in recent years, a review of the variable costs that form the basis for the modeling has been conducted. This has resulted in a combination of established values from ASEK's recommendations, and our own assumptions based on experience, expert interviews, and logical reasoning. A categorization has also been made to clarify the type of cost in question and its source.

The current and future development of batteries is a factor that affects several assumptions: the difference in purchase cost for BEV and ERSV compared to ICEV is largely due to the batteries; battery capacity (i.e., the vehicle's range) affects how often they need to be charged; and electricity consumption affects the range for a given battery size. Assumptions about the proportion of the battery charged per fast charge also depend on battery technology. It is assumed that batteries should not be fast charged to 100 percent and that charging from 80 to 100 percent takes disproportionately long (based on information from Volvo Trucks (Volvo Lastvagnar, 2023)) and the Swedish Energy Agency (Energimyndigheten, 2020)). We assume (Maria Börjesson, 2021) that batteries have 80 percent of their capacity when scrapped (information from Scania), meaning they have an average of 90 percent during their operational life.

The assumption for **battery capacity in 2025 is 600 kWh** based on information from Scania and Volvo Trucks (Scania, 2023; Volvo Trucks, 2023; Trafikverket, 2020). **For 2040, a battery capacity of 750 kWh is assumed** for BEVs due to technological advancements. Even though technological advancement permits a higher battery capacity, it is assumed that trucks will be equipped with the capacity necessary for a nine-hour drive, before the end of the workday. In fact, battery capacity is likely to be a variable determined and optimized based on user needs and availability of charging infrastructure. In this analysis, **the battery size for ERSV is assumed to be 40 percent smaller than for BEV**, based on interviews with Scania indicating a range of 30 to 50 percent smaller batteries for ERSV. However, this assumption has a high uncertainty.

The charging power at public stationary fast chargers depends on the charging point and the vehicle's battery. Today (as of 2025 in Table 5), it is assumed that vehicles can charge publicly at a power of 130 kW, and by 2040, the power is assumed to be 600 kW. By 2040, it is likely that the vehicle's batteries will be the limiting factor since MCS are expected to deliver up to 3.75 MW (Scania, 2022), but batteries will likely not be able to utilize all of that power. The figure of 600 kW is mentioned by Trafikverket (Trafikverket, 2021c), and ACEA (ACEA, 2021) states that a large number of charging points will need to offer over 500 kW by 2030.

According to what was discussed in chapter 3.2.1 above, **battery cells will cost around EUR 300 in 2025** and will **decrease to around EUR 100 by 2050**. With an assumed capacity of 600 kW per battery, the price of the battery is around the price of an internal combustion engine vehicle. According to the interviews conducted with Scania and Volvo Lastvagnar, battery electric vehicles are, in 2025, twice as expensive compared to internal combustion engines vehicles. This implies that the assumptions about battery price and capacity is in accordance with Scania's and Volvo Lastvagnar's statements.

Charging fees for electric roads are assumed in the base scenario to be internalized, i.e., in accordance with Swedish transport policy principles. This assessment follows the method applied by Börjesson et al. (2021) and is presented in a CollERS report (Andersson, Johansson, Jöhrens, & Mottschall, 2023).

Charging is allowed during the drivers' 45-minutes breaks. This means that the cost of static charging is the only cost during this time. When charging takes more than 45 minutes, the salary cost of drivers is added to the cost of static charging. Drivers rest after four and half hours of driving.

The development of battery cost and capacity are important components in the model. The graphs below show the development of battery cost and capacity.

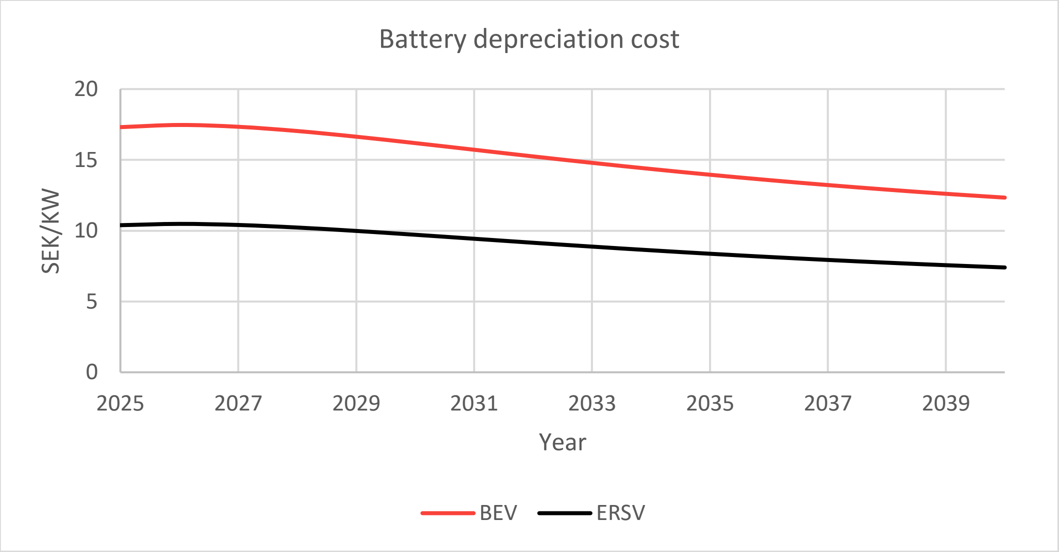

Figure 18. Battery depreciation cost over time

Figure 18 shows that the cost of batteries decreases the most initially. After 2030, this decrease continues but somewhat slower. The difference in cost between BEV and ERSV assumes that the battery of an ERSV is 60 percent of the size of a battery in a BEV.

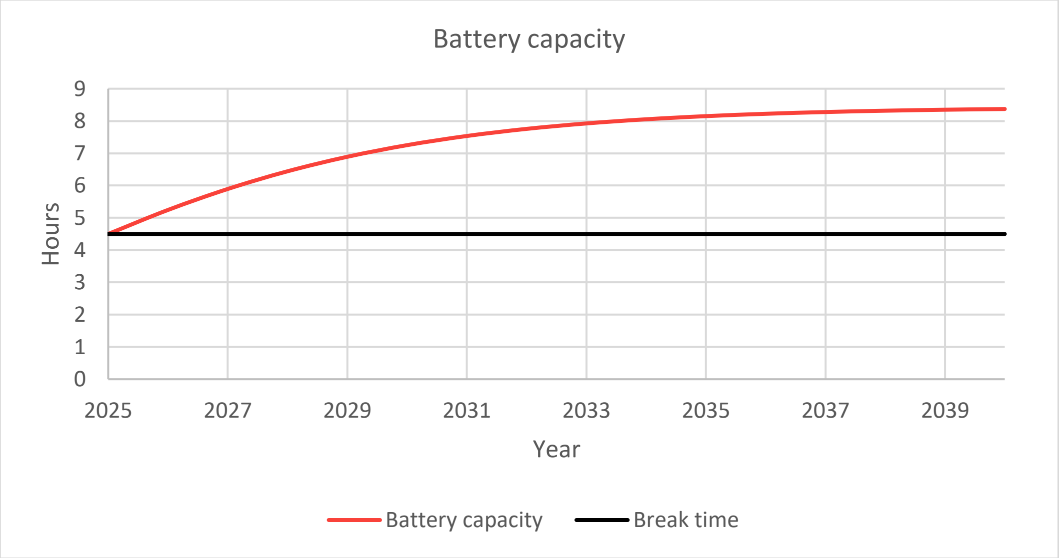

Figure 19. Battery capacity over time

Already in 2025, a truck can drive more than four and half hours before needing to stop. By 2030, this driving possibility is higher than seven hours and increasing to almost reach nine hours.

5.4 RESULTS

Below are the results from the system dynamics model, focusing on the total cost of ownership per year and the share of the vehicle fleet for the three simulated vehicle types: ICEV, BEV and ERSV. Based on the assumptions mentioned above, a base scenario has been constructed. Since there are uncertainties in the assumptions that underpin the base scenario, sensitivity analyses are presented.

The results presented are TCO (total cost of ownership) estimates, which are used to estimate the share of users choosing electric roads on a corridor where electric roads are installed (i.e. not the total road system in Sweden). As discussed earlier in the report, this share is higher than the share for the entire network (i.e., including sections without electric roads), which is presented in some reports (given that electric roads are not assumed to be built everywhere, as assumed in some reports, in which case the share for the corridor and the share for the network would be the same). The graphs below start in 2025; however, one must be cautious with the TCO of ERSV before 2030 as ERS itself is assumed to start operating (partly) by 2030. The TCO is shown to give a theoretical insight in what cost the model estimates and with these estimates, cost parity between ICEV and BEV is expected around the year 2028.

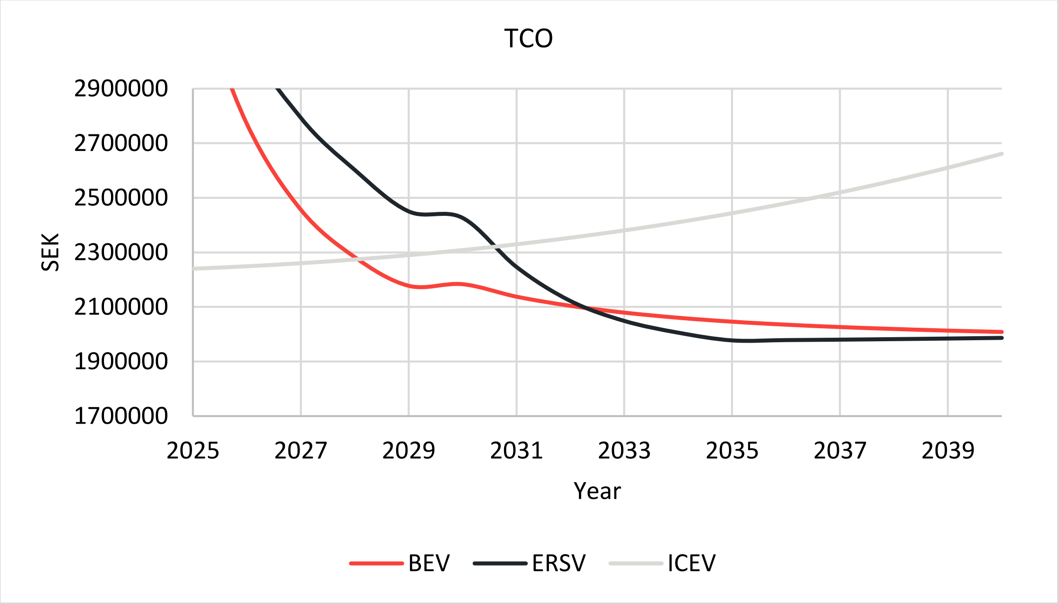

Figure 20. TCO over time

The total cost of ownership of battery-powered trucks is initially (before 2030) high in the base scenario. This is affected by the assumption that it costs around twice to purchase a BEV compared to an ICEV and the fact that the time required to charge during a normal trip is very long (due to low battery capacity and low charging capacity in the public charging infrastructure). As battery capacity and charging capacity are assumed to improve, the total cost of battery-powered trucks decreases. By 2030, battery capacity is assumed to be high enough for a truck to make a long trip of up to four and a half hours without needing to stop for charging. With the charging speed assumed in the system, charging time is lower than 45 minutes and can be done during the driver’s mandatory break. This fact will have a large impact on the total cost of electric vehicles from that time and forward.

Since ERS-compatible trucks are assumed to be built with smaller batteries than BEVs, the total cost is initially higher than pure battery-powered trucks due to the longer downtime for charging. The assumption of lower investment costs does not compensate for this in terms of total costs. By 2035, the ERS infrastructure in the corridor is assumed to be fully developed, which means that ERS-compatible trucks are also expected to be able to operate without stopping for charging.

The graph below (figure 21) shows the results for the development of the three types of trucks over time. Initially, a sharp increase in BEVs is observed before 2030. With the opening of the ERS in 2030, ERSVs begin to enter the truck fleet and compete with BEVs (and ICEV), causing the growth rate for BEV to stagnate around 35%. The share of ICEVs decrease steadily over the period. By 2040, more than two-thirds of the trucks in the fleet are expected to be electric.

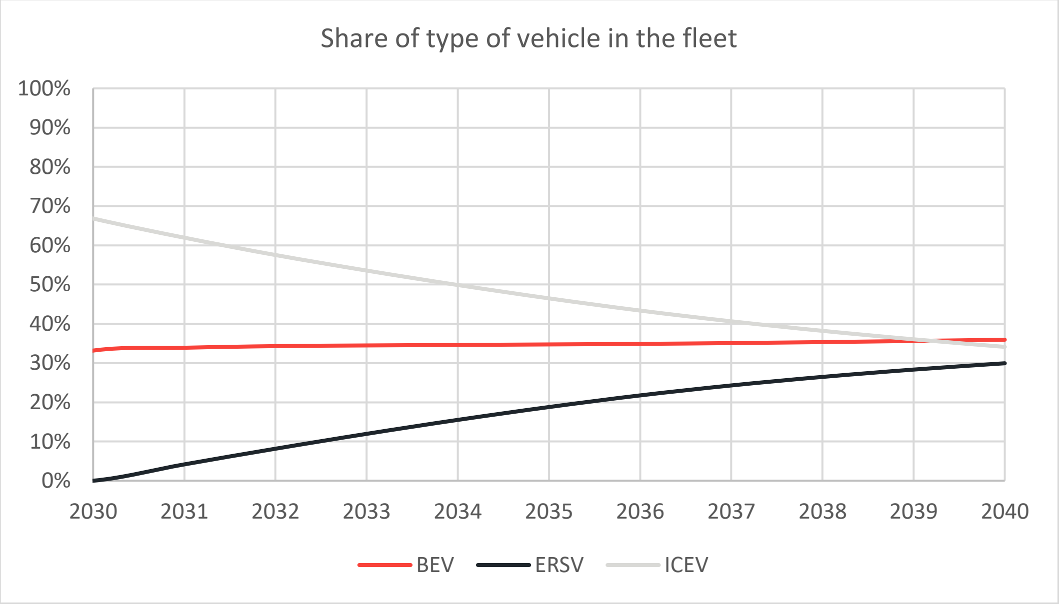

Figure 21. Share of the different types of trucks in the fleet over time

In the previous study by WSP (2024), a slower decrease of prices for batteries was assumed. In the previous study, the price of batteries was assumed to decrease by 44%, while it assumed to decrease by 59% in this new study. A sensitivity analysis has been done in this report with the previous assumption.

Figure 22 shows the TCO by year 2040 for both BEV and ERSV. With the new assumption for battery price depreciation, TCO for BEV is lower by 0.7%. In both sensitivity analysis, BEV is more expensive than ERSV. However, with the old assumption ERSV is even cheaper than BEV by 1.4% compared to 1.1% with the new assumption. The difference is however small and not very significant. This shows that even though the battery prices are expected to drop even faster, this fact will not change the results of the TCO for BEV and ERSV to a large extent.

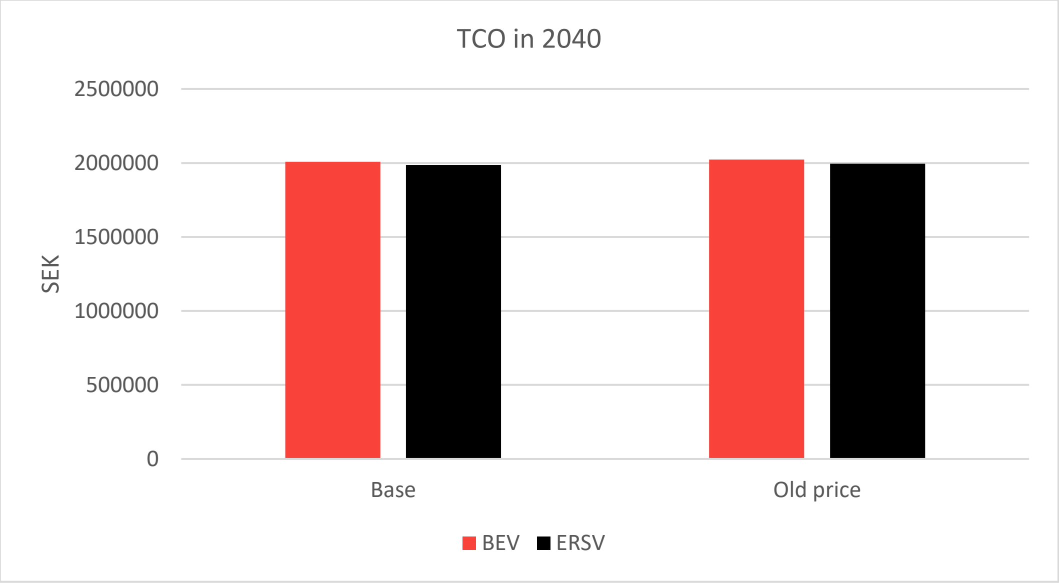

Figure 22. TCO in 2040

5.5 SENSITIVITY ANALYSIS

ICEVs are more expensive than both types of electric trucks for most sensitivity analysis and will thus not be discussed.

The results of all sensitivity analysis show very small differences in the aggregated level, and as many of the assumptions (and the underlying indata) are rather insecure, we do not want to draw too far-fetched conclusions of the results. The main cost for both BEV and ERSV (at least in the early phases of construction) is the loss time for static charging. However, the battery capacity observed today allows for a 4.5-hour drive with no stopping, meaning that no additional stops are needed for BEV compared to ERSV. In addition to an increase in capacity and charging speeds, an important increase in battery efficiency will lead to lower time for static charging (if any is even needed), well-within the 45-minute rest pause for drivers. This means that the biggest cost is very similar between BEV and ERSV.

However, we will still present what the analysis shows and to what extent the results change in our theoretical model.

5.5.1 Sensitivity analysis 1: Reduction factor for ERSV batteries

During interviews with manufacturers, the reduction factor was still uncertain. It is important to understand how significant this factor affects the total cost of ERSV. The reduction factor in the base model is 40%.

Two sensitivity analysis with respectively a lower and higher factor has been analyzed.

Category	**Variable**	**2025**	**2040**
ERSV	Reduction factor 1	20	20
ERSV	Reduction factor 2	60	60

Table 4. Assumptions regarding reduction factor

Figure 23 shows the TCO by year 2040 for both BEV and ERSV. In both sensitivity analysis, BEV is still more expensive than ERSV. However, with a lower reduction factor, the TCO is 0.7% smaller than in the base model, and with a higher reduction factor, the TCO is 1.4% higher. The difference is however small and not very significant.

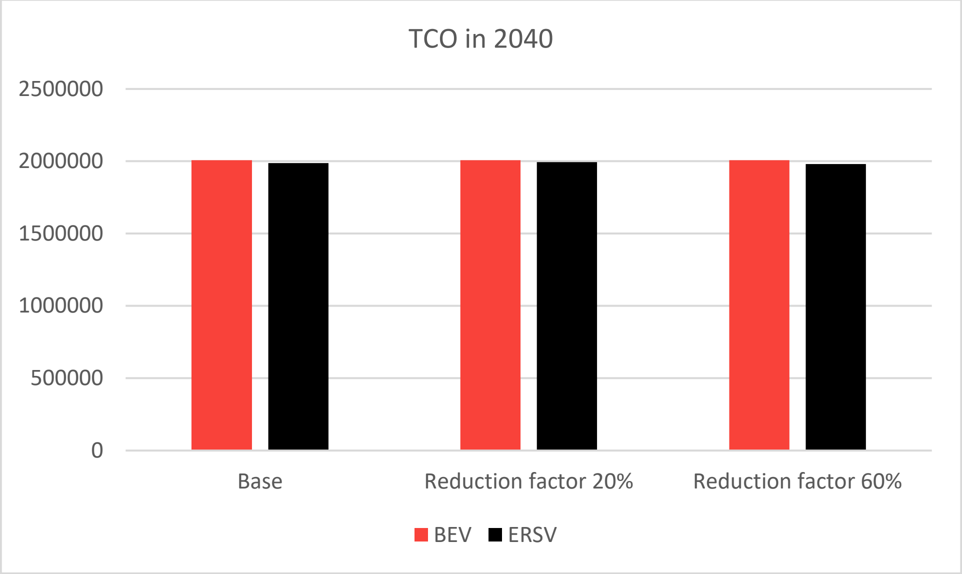

Figure 23. TCO in 2040

5.5.3 Sensitivity analysis 3: Tax on Chinese batteries shifts to EU/US battery production (-more expensive battery production)

Most batteries are made in China at this date and are then imported to the EU. Economical protectionism is growing in both the USA and the EU. And we have seen introduction of taxes on Chinese electric cars. Equivalent measures are likely to be taken regarding batteries.

Manufacturing batteries in Europe and the US remains more expensive than in China. For example, assuming that material costs do not vary regionally, it is almost 20% more expensive to produce a battery cell in the US than in China. In reality, the manufacturing cost gap could be even wider, as Chinese manufacturers are likely to benefit from preferential prices from local material producers and a more integrated supply chain within China. In addition, unlike the US and Europe, most Chinese batteries are LFP, which is more than 20% cheaper to produce than NMC.

However, local policies such as the $45/kWh production tax credit for cells and packs under the Inflation Reduction Act in the US may offset some of the costs, although the impact of the IRA on pricing is not yet clear.

In this sensitivity analysis we make the assumption that the taxes and trade duties on Chinese batteries will lead to that no batteries and electric vehicles are imported from China ang hence the production will be in the US or in Europe, where the production cost is 20 percent higher.

Category	Variable	2025	2040	Unit	Comments
BEV & ERSV	Chinese tax on batteries – EU and US battery production	0	20	%	Introduction in 2030

Table 5. Assumption regarding higher tax on batteries

Figure 24 shows the difference in development of battery costs for both the base scenario and this sensitivity analysis.

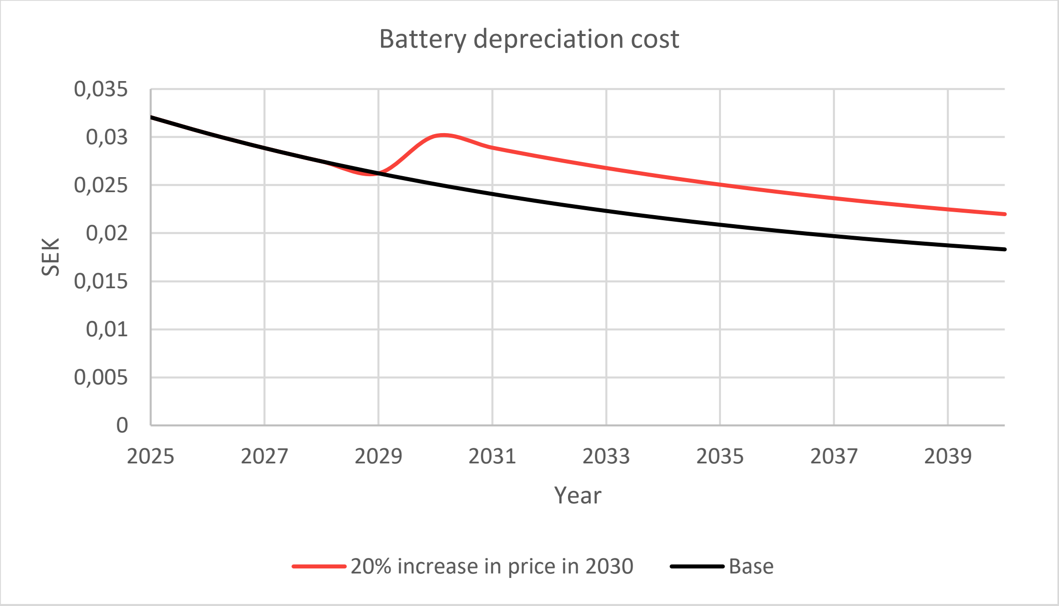

Figure 24. Battery depreciation cost in the base scenario and sensitivity analysis. Increase in price in 2030

Figure 25 shows the TCO by year 2040 for both BEV and ERSV. Even if both types of trucks are more expensive, the increase is marginal. However, it is worth noting that the difference in price between ERSV and BEV decreases when the tax is introduced, even though this difference is insignificant. In the base scenario, the difference is around 1.1%. After the introduction of the tax, the difference deceases to 1.3%.

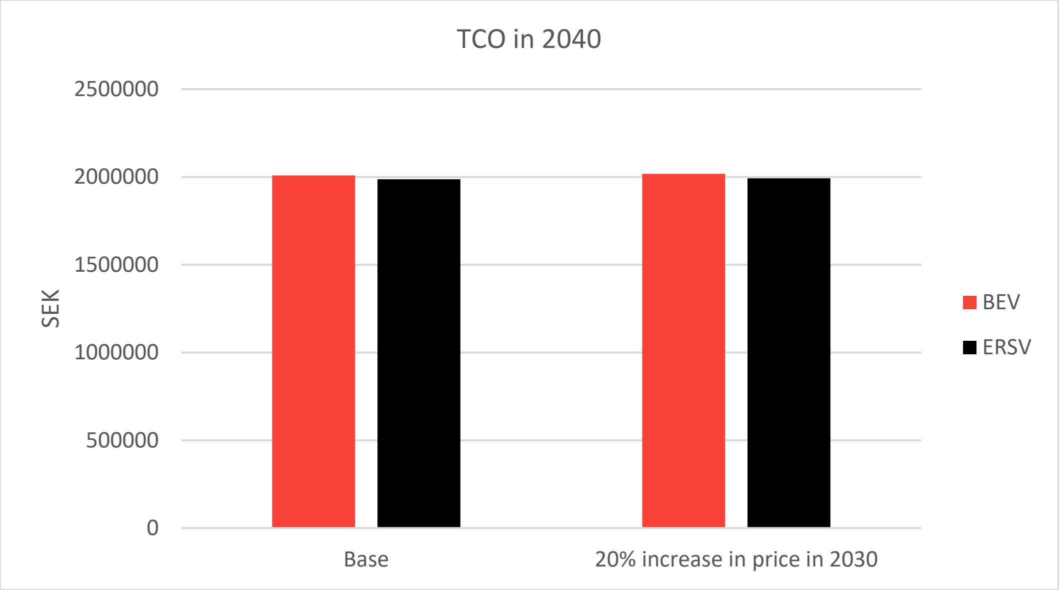

Figure 25. TCO in 2040

5.5.4 Sensitivity analysis 4: Slower charging

In our base scenario, it is possible to charge the additional needed energy during the 45 minutes break of the driver. This is partly because of the assumption that fast chargers will be rolled out by 2040. However, this roll-out might not happen and the speed of charging does not increase as assumed. This might lead to the need of additional charging time after the 45-minutes of break. The EU parliament has established a minimum of charging requirements of 350 kW for heavy-duty vehicles in 2023, meaning that charger cannot be less powerful than this requirement.

Category	Variable	2025	2040	Unit	Comments
BEV & ERSV	Average power in public charging infrastructure	130	350	kW	Swedish Transport Administration (2021c), ACEA (2021), Scania (2022), EU parlement (2023)

Table 6. Assumption regarding power in public charging infrastructure

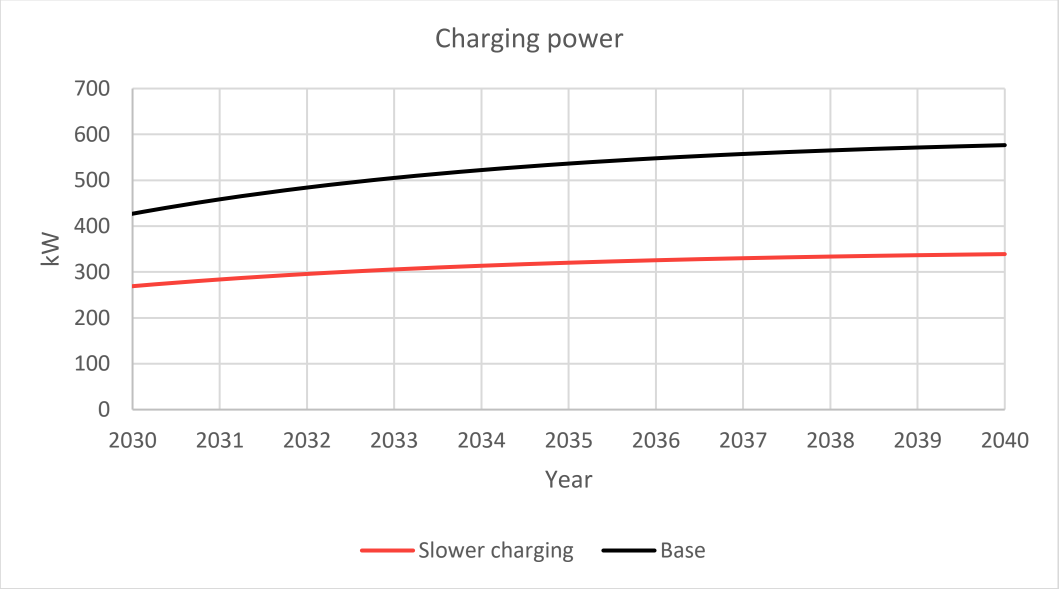

Figure 26. Development of charging power for both scenarios

The figures 27 and 28 below shows the development of TCO over time in this scenario and the TCO by 2040, for both the base scenario and this sensitivity analysis. The development over time is very similar to the development for the base scenario, with ERSV being more expensive in this sensitivity analysis than in the base scenario in 2030.

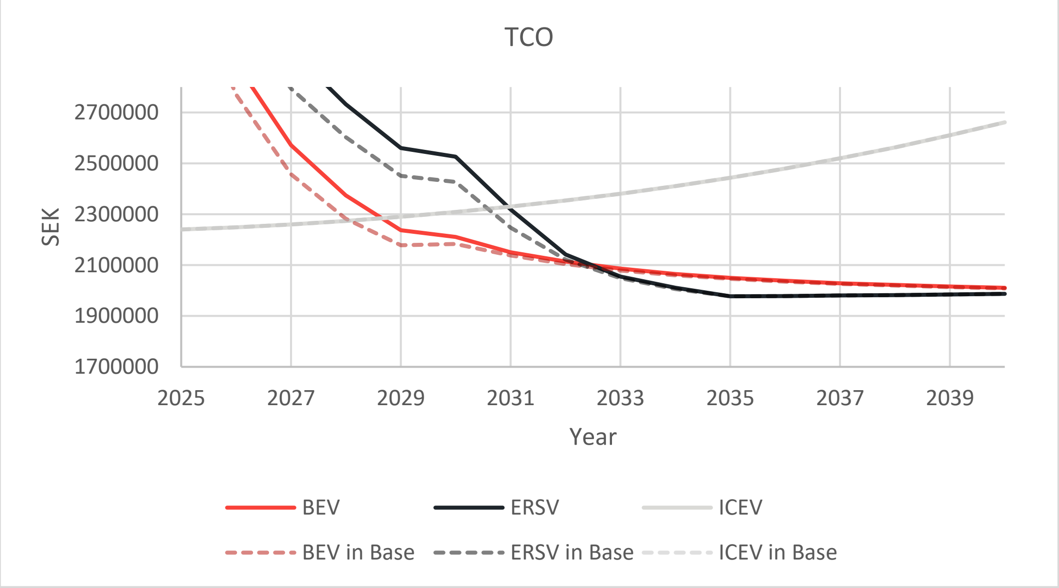

Figure 27. By 2040, the difference in TCO is very similar to the base scenario with a difference of 1.2% by 2040

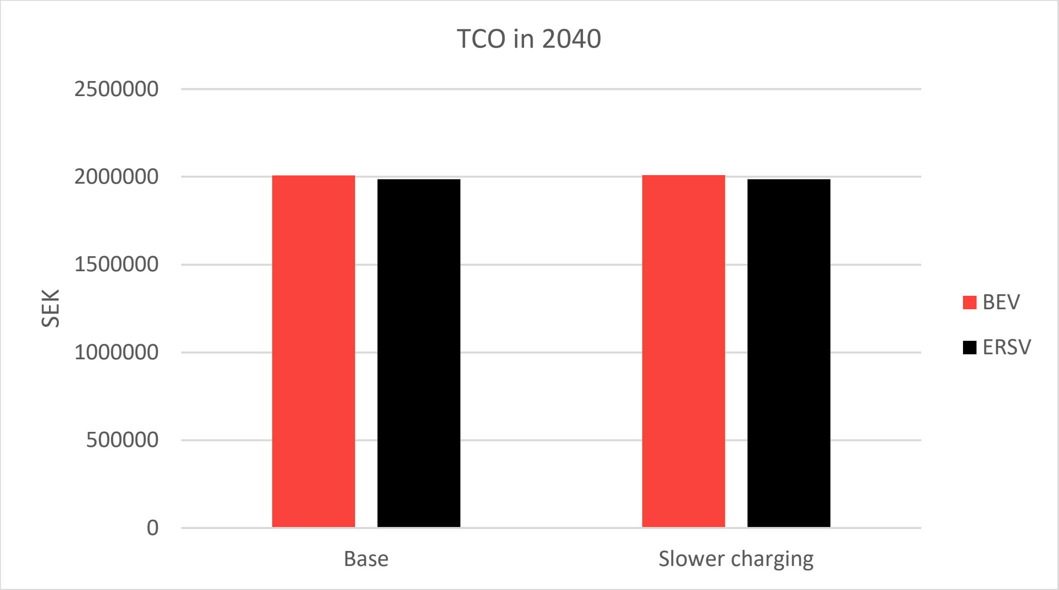

Figure 28. TCO in 2040

The difference between the two scenarios is marginal. This is since all charging occurs during the 45-minute rest pause. The little difference seen is the increased time trucks must wait to find an available charger.

5.5.5 Sensitivity analysis 5: Unchanged capacity

In the same reasoning, a sensitivity analysis where the battery capacity is not changed and remains at the 2025 level, at 600 kW.

Category	**Variable**	**2025**	**2040**	**Unit**	**Comments**
BEV	Battery Capacity	600	600	kWh	-

Table 7. Assumption regarding battery capacity for BEV

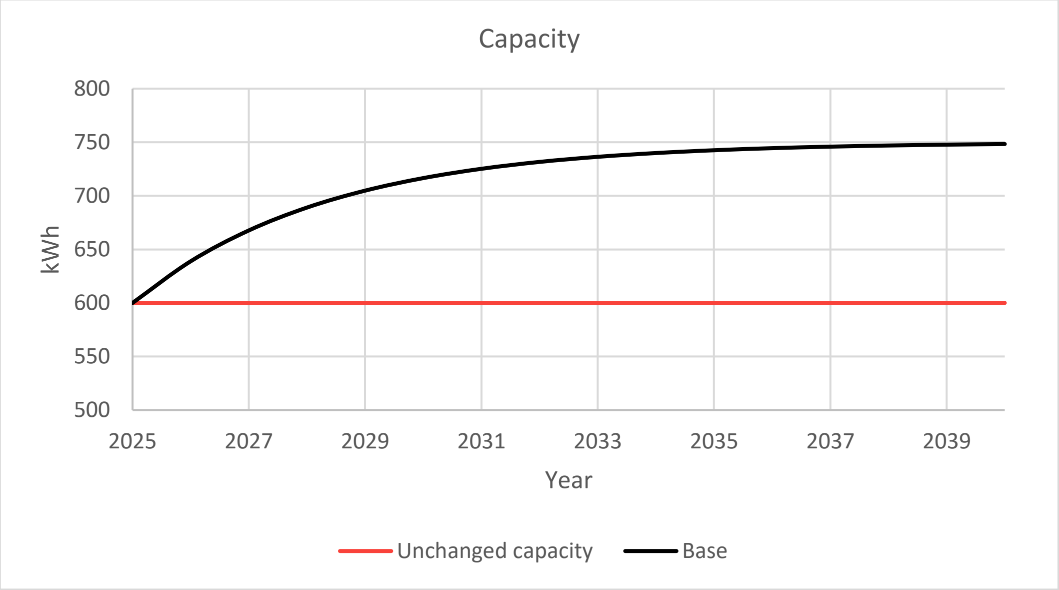

Figure 29. The development of capacity in both the base scenario and this sensitivity analysis

Figure 30 shows the development of TCO over time in this sensitivity analysis. The development is like the base scenario with a slower decrease for BEV.

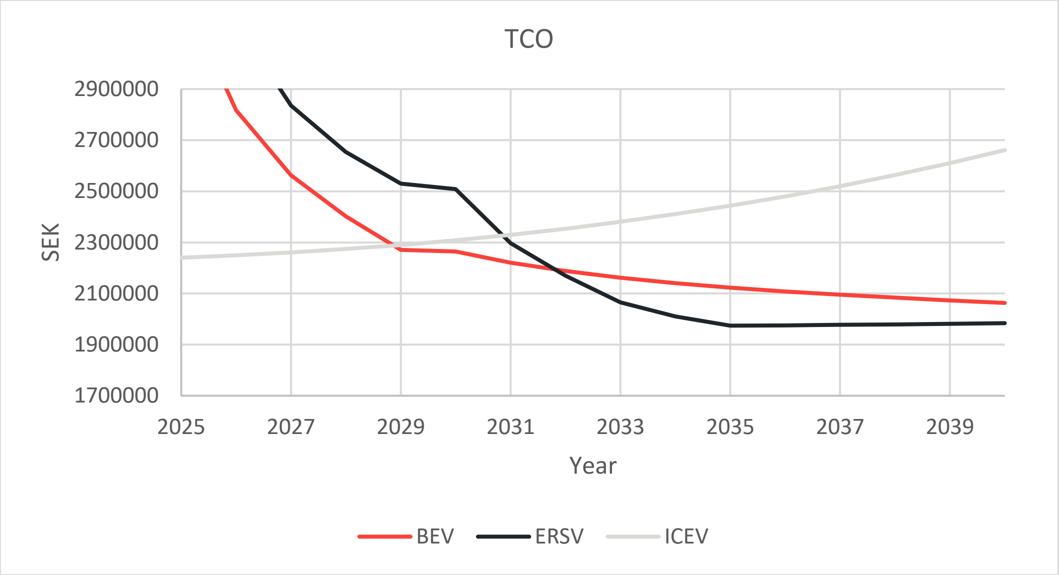

Figure 30. TCO over time

By 2040, the difference in price is more significant than in the base scenario, standing at 4%. This is mainly since, by 2040, more stops must be done for charging compared to the base scenario.

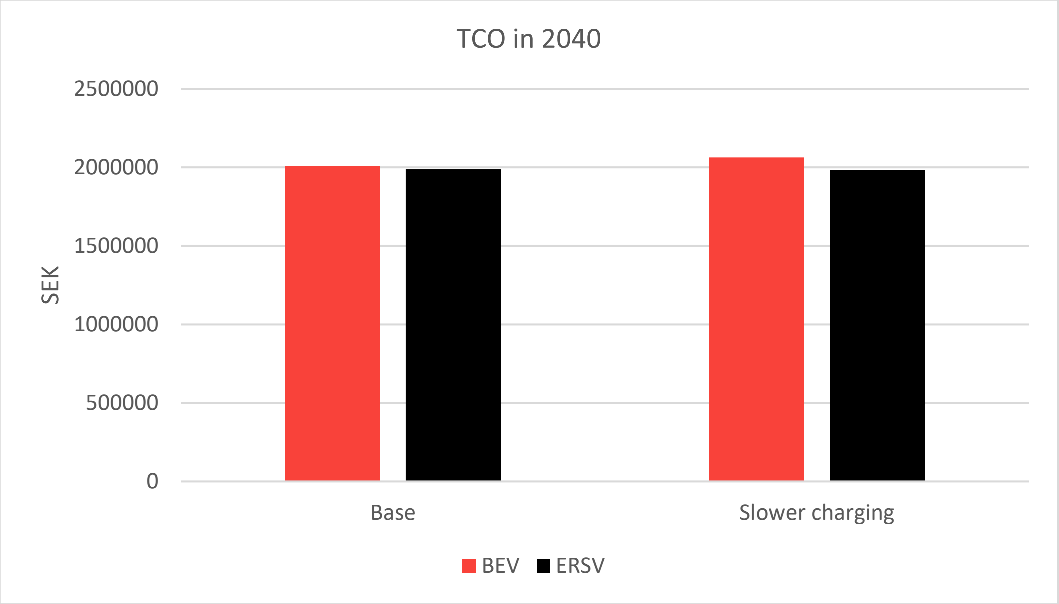

Figure 31. TCO in 2040

5.5.6 Sensitivity analysis 6: No possibilty to charger during breaks

The fact that charging can happen during breaks is an assumption that makes it cheaper for BEV users. However, even though this is a very plausible assumption, this is not yet established at this stage. The possibility of charging during breaks is not guaranteed and can thus cost the BEV user, labor cost additionally to static charging cost.

Category	Variable	2025	2040	Unit
BEV & ERSV	Possibility to charge during 45-minute break	No	No	-

Table 8. Assumption regarding possibility to charge during 45-minute break

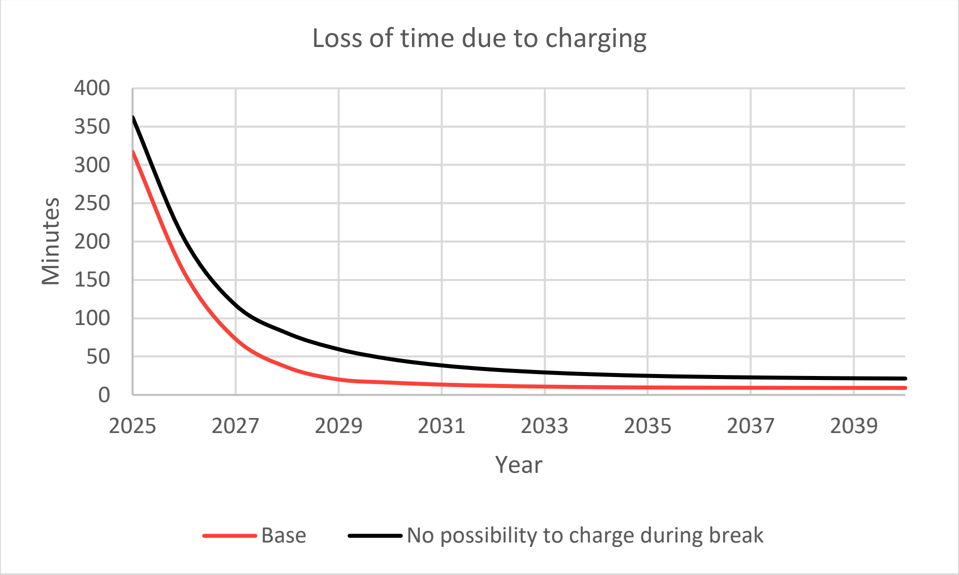

Figure 32. Loss of time due to charging

Figure 33 shows the development of TCO over time. Even though BEV is cheaper than ERSV in the beginning of the period, ERSV's TCO decreases and ends up being lower than BEV's TCO by 2040. The taking over occurs in 2032.

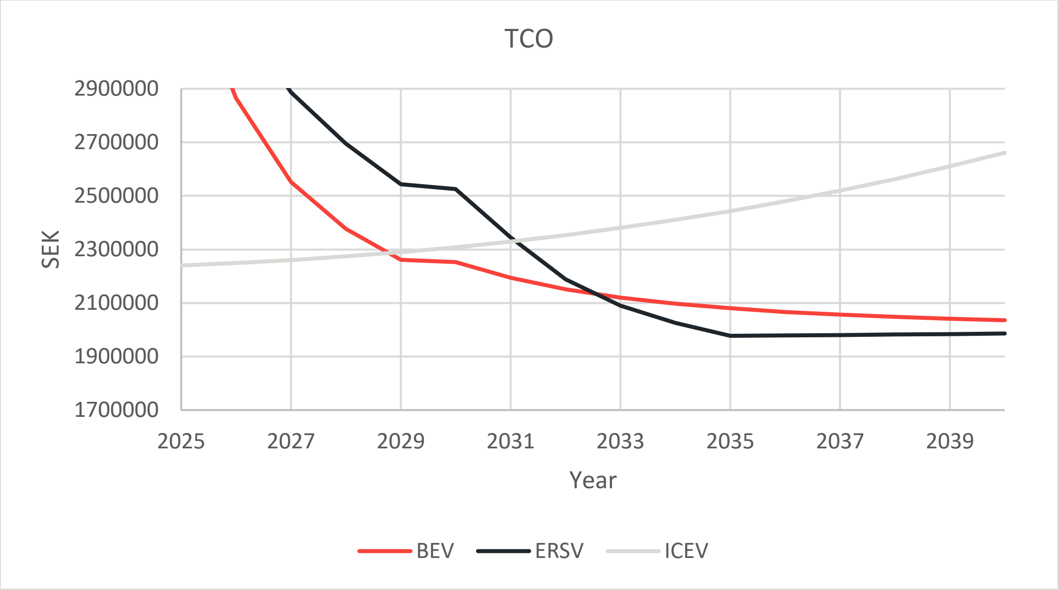

Figure 33. TCO over time

Figure 34 shows the TCO by 2040 for both the base scenario and this sensitivity analysis. The difference in TCO increases to 2.5% compared to 1.1% in the base scenario.

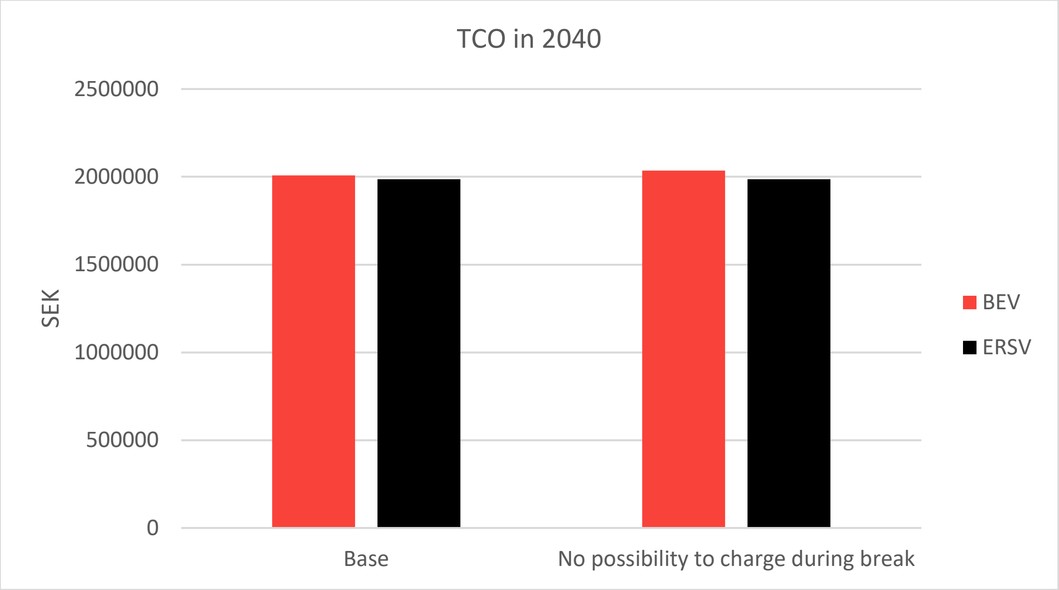

Figure 34. TCO in 2040

5.5.7 Sensitivity analysis 7: No possibilty to charge during breaks and higher capacity

Without the possibility of charging during the break, the TCO for BEV is higher than the TCO for ERSV. However, in the previous sensitivity analysis, the capacity is assumed to be the same as in the base scenario where it is, then, enough to not require an additional time for charging. Battery capacity can then be increased in order to reach the point where charging is not required before the end of the working day, i.e. nine hours of driving. In the following sensitivity analysis, the capacity is increased to satisfy that need.

Figure 35 shows the loss of time due to charging. In the base scenario, it is still required to stop to charge. Even if the charging itself can be done during the rest time, reaching a charging point and the waiting time for an available charger does cost money. In this scenario, the increased capacity dispenses the driver from charging and waiting for an available charger but, as resting is mandatory, the driving time to access a resting area is not free.

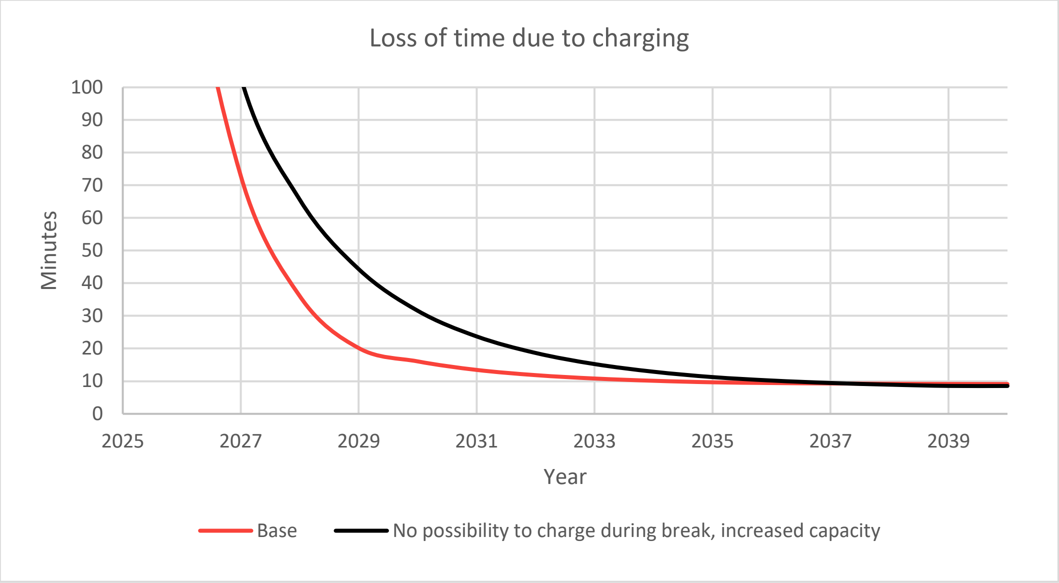

Figure 35. Loss of time due to charging

Category	Variable	2025	2040	Unit
BEV & ERSV	Possibility to charge during 45-minute break	No	No	-
BEV	Battery Capacity	600	900	kWh

Table 9. Assumptions regarding possibility to charge during 45-minute break and battery capacity

Figure 36 shows the TCO over time. Even with a higher purchase cost, the TCO for BEV is lower than the one for ERSV and this, since the beginning of the studied period.

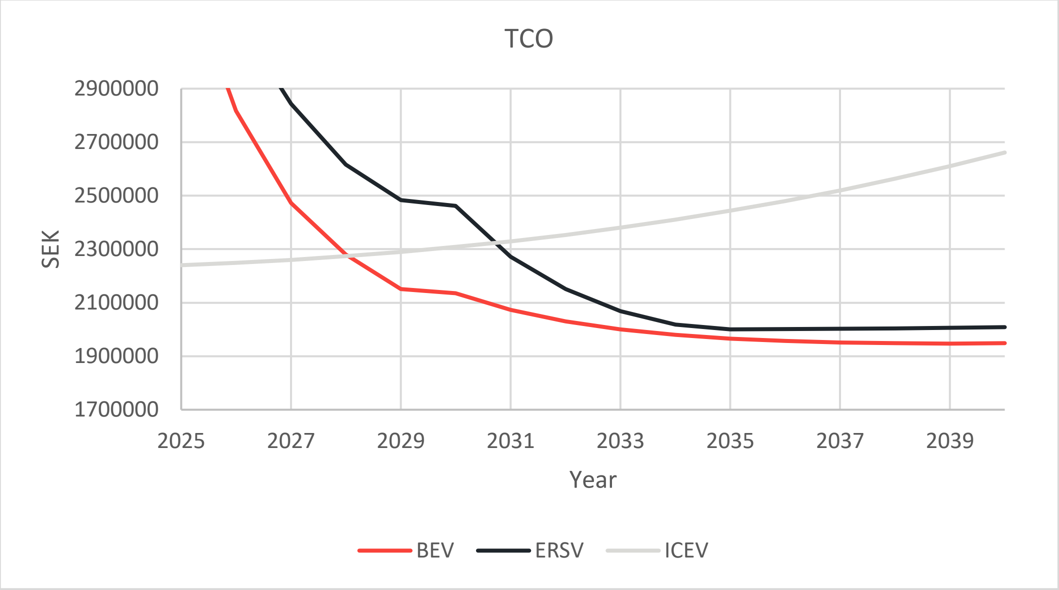

Figure 36. TCO over time

By 2040, the TCO for BEV is still lower than the one for ERSV. This is the only scenario where BEV is 3% cheaper than ERSV by 2040.

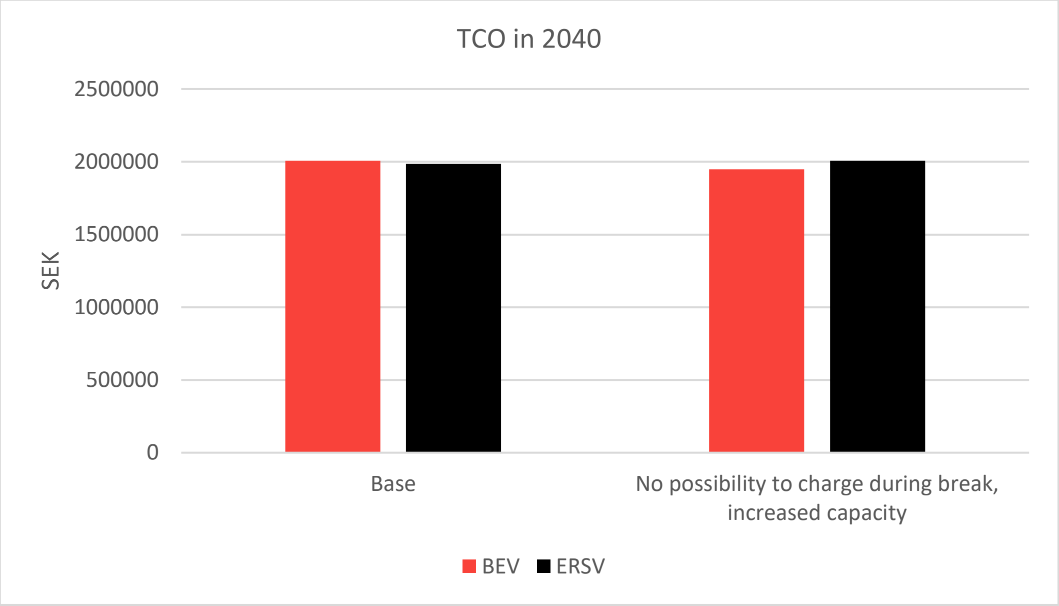

Figure 37. TCO in 2040.

It is worth noting that the market might accommodate for higher battery capacity to avoid stopping even in a scenario where charging is permitted during the breaktime, avoiding the extra cost of waiting and charging publicly which is more expensive.

5.5.8 Sensitivity analysis 8: Autonomous trucks

Autonomous vehicles are expected to enter vehicle fleets in the coming years. With these vehicles, drivers will not be needed, and operators will thus avoid costs related to them, like salaries. Additionally, trucks will be able to theoretically drive non-stop, without needing to stop for breaks. ERS might then be cheaper in this situation when charging is done dynamically while driving with no need to stop while BEVs will need to stop and loose time and thus money, charging. Figure 38 shows that ERSV will be around 16% cheaper to drive than BEV cars compared to only 1.1% cheaper in the base scenario.

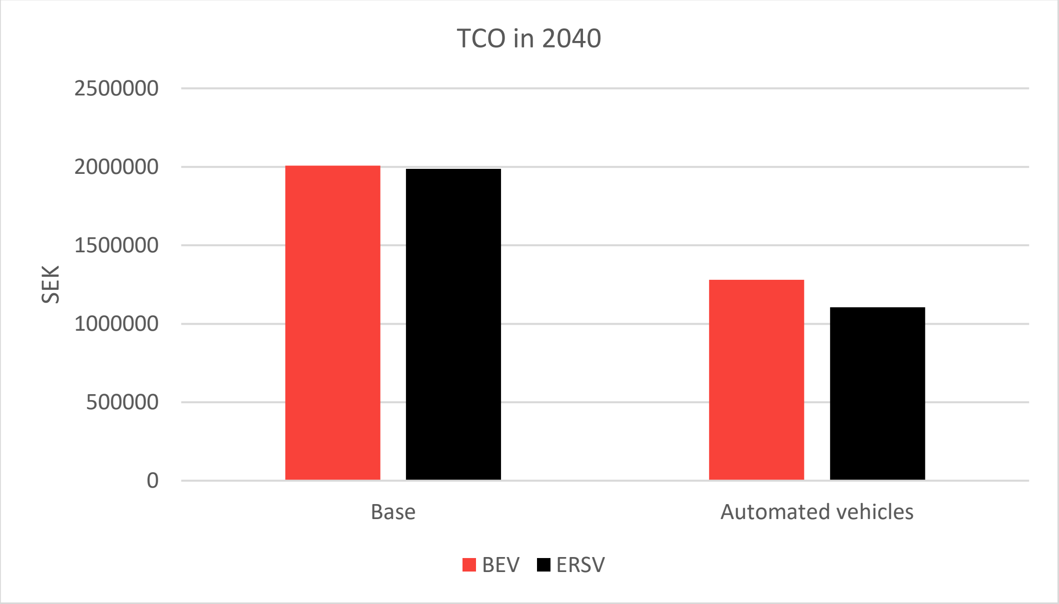

Figure 38. TCO in 2040

5.6 CONCLUSION

In conclusion, even though ERSV is more expensive than BEV in the beginning of the studied period, its TCO decreases constantly over time, following the development of the ERS in the network, avoiding the need to stop for static charging. It is worth noting though that the difference in cost is marginal. Additionally, the fact that ERSV is more profitable does not mean that it takes the share of the whole market. As seen in the graph for the share of types of vehicles in the float (figure 21), BEV is available in the float and continues to increase slightly even if it is a slower increase than ERSV until 2040.

In the previous study, battery capacity is assumed to have a bigger development between 2025 and 2040 with a lower starting capacity in 2025. Charging speed is however higher in this study. One of the main assumptions that have been adjusted was the ability to charge during the 45-minute rest paus allocated to drivers every 4,5 hours. Comparing the results, this study confirms the conclusions formed in the previous study. ERSV and BEV have close TCO, and the differences between the two types of trucks and between results of the studies are insignificant. The development of shares of the types of trucks in the fleet are, by consequence, quite similar between both studies.

To identify critical components, the updated assumptions have been changed in multiple sensitivity analysis. The changes in TCOs between the base scenarios and most sensitivity analysis are however insignificant, proving the robustness of the relationships and components. The only sensitivity analysis that leads to a significant difference between ERSV's and BEV's TCOs is the one assuming autonomous vehicles in 2040. It is thus cheaper to drive ERSVs that do not require to stop for static charging.

It is important noting that many of our assumptions have been simplified. One of these assumptions is the availability of ERS whenever necessary along the road. This will probably not be the case. This simplification leads to underestimates the cost of need for static charging and thus of the TCO for ERSV and thus an overestimation and a faster increase of the share of ERSV in the system.

6. CONCLUSION

Since battery costs are a significant part of the total costs for BEV, their development directly impacts when cost parity can be achieved between BEV and ICEV, and between BEV and ERSV. In this report, we have discussed various factors that could affect these costs and thus influence the development and demand for electric road systems relative to BEV. In this chapter, we summarize our conclusions from the report.

Historically, battery costs have fallen dramatically, making electric vehicles more economically attractive. However, the reduction in battery costs has now started to slow down and we have not yet reached a break-even point where electric vehicles are cheaper than fossil-fueled vehicles, particularly for heavy-duty vehicles. The demand for electric road systems (ERS) from vehicle owners will largely depend on when the break-even point between fossil-fueled trucks and electric trucks is reached. The earlier this cost parity is achieved, the less advantageous it becomes to invest in ERS, as battery-powered trucks will be more economically competitive for a longer period, thereby having a longer window to establish themselves in the electric vehicle market.

However, the study by Link et al. (2024), which we examine in this report, shows that battery costs are decreasing faster than previously anticipated, suggesting that cost parity with diesel trucks could be reached in the near future. It is not surprising that the reduction in costs is slowing down since the major innovations have already been implemented. However, even small future cost reductions are of great significance, as they can be crucial for achieving cost parity with diesel.

Our own results from the SD model, show that cost parity between BEV and ICEV will occur in year 2028 and in 2031 for ERSV and ICEV. ERSV is more expensive than BEV at the start of the studied period, but its TCO decreases steadily over time, in line with the development of ERS in the network. Cost parity between BEV and ERSV is expected to be achieved around the year 2032 in the model, after which the cost difference between the two technologies will be relatively small and consistent.

EU legislation requires drivers to rest for 45 minutes after 4.5 hours of driving. Volume and weight no longer seem to be the main technological challenges for HDEV applications; instead, the focus has shifted to reducing charging time and increasing range. Recent advancements in the efficiency and energy density of heavy-duty electric vehicles suggest that the range will likely increase to 500-600 km by 2025. This corresponds to a battery capacity of around 600 kWh, indicating that batteries are reaching a level where they can support 4.5 hours of driving on a single charge for a truck, thereby reducing the need for ERS. There is much to suggest that this will be possible in the very near future. According to our results, it will be possible already by 2025.

At current fast-charging power levels, it can take up to 100 minutes to fully charge a 600-kWh truck. Therefore, MW charging systems are necessary to charge large batteries within 45 minutes. Although MCS is not yet established and is not currently included in the EU's AFIR legislation, charging operators and vehicle manufacturers have ambitious plans to develop MCS, which could result in numerous charging points in the future. It is worth noting that during these 45-minutes rest periods, the charging is needed only for the battery power used for 4.5 hours. With increased efficiency battery capacity paired, and charging speed, 45 minutes charging time will be possible by 2029 in our model, based on the results from our investigation in this report.

Both ERS and MCS have the potential to further stress the distribution grid in an increasingly electrified society. ERS allows multiple vehicles to charge simultaneously, while MCS involves high power at a single point. This can lead to longer waiting times for grid connection and higher electricity tariffs, especially with MCS. WSP's analysis of current studies on ERS does not provide a clear assessment of whether ERS is significantly better than MCS in terms of power demand and its impact on the distribution grid. Therefore, in-depth studies are needed to determine this trade-off.

In the previous study by WSP (WSP, 2024), battery capacity is assumed to have a bigger development between 2025 and 2040 with a lower starting capacity in 2025. Charging speed is however higher in this study. One of the main assumptions that has been adjusted is the ability to charge during the 45-minute rest paus allocated to drivers every 4,5 hours. Comparing the results, this study confirms the conclusions formed in the previous study. ERSV and BEV have close TCO, and the differences between the two types of trucks and between results of the studies are insignificant. The development of shares of the types of trucks in the fleet are, by consequence, quite similar between both studies.

To identify critical components, the updated assumptions have been changed in multiple sensitivity analysis. The changes in TCOs between the base scenarios and most sensitivity analysis are however insignificant, proving the robustness of the relationships and components. The only sensitivity analysis that leads to a significant difference between ERSV's and BEV's TCOs is the one assuming autonomous vehicles in 2040. It is thus cheaper to drive ERSVs that do not require to stop for static charging.

The fact that ERSV is more profitable at a certain point does not mean it will capture the entire market share of electric vehicles. Our model results show that BEV will remain in the vehicle fleet and continue to increase, albeit at a slower rate than ERSV. However, there are other factors that influence battery development and its impact on ERS that we covered in the report.

Battery costs also depend on the availability of raw materials and where battery production occurs. Currently, a large portion of battery production takes place in China, and much of the raw materials also come from China. Due to the current global trade and geopolitical situation, there may be several reasons to reduce dependence on Chinese supply chains in order to mitigate vulnerabilities and the potential risk of battery shortages. Such reduced dependence would imply that a larger share of battery production should take place outside of China. If battery production (as well as mining and processing raw materials) is to increase outside China in the future, there is a risk that battery costs could rise again. This would negatively impact the economic attractiveness of batteries and increase costs, but at the same time increase the need for ERS relative to BEV, as smaller batteries would be required, reducing costs and increasing the profitability gap between the two technologies.

The future ability to recycle raw materials will have a significant impact on the availability and cost of batteries, and thus also affect the need for alternatives like ERS. If recycling can largely supply the required materials for electric vehicles, the demand for ERS may decrease. Currently, only NMC batteries are profitable to recycle.

The results of this study have shown that from a vehicle buyer's point of view, there are both economic and practical arguments for using electric roads and that there is a rationale for ERSV and BEV to coexist in a market. However, the study does not take into account either the investment costs for the expansion of the electric road network (or the stationary charging) or the total social economic costs. But the results of this study show that the capacity, performance and costs of batteries will most likely meet the needs of the market for heavy electric vehicles by 2032 at the latest. This suggests that the window of opportunity is small to also build up and establish a market for electric road vehicles during this time. The calculations are also based on the fact that electric roads will be introduced to the market in 2030 and that an electric road system will be lauched in 2035. This is not likely for the Swedish market. It will therefore most likely mean that it will be even more difficult for electric roads to take market shares in the future.

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