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# The environmental impact of electric vehicle range

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Executive Summary

The purpose of this study is to investigate how resource demand and climate impact from electric cars can be reduced by aiming for more resource efficient battery sizes and charging strategies that takes into consideration the use patterns of car owners and the availability of charging infrastructure. A comparative environmental assessment is performed for a set of use cases representing different owners of battery electric cars. The use cases include batteries of different sizes, chemistries and charging possibilities, including battery swapping where the user can change the size of the battery depending on the trip length. The results show that the configuration with the largest battery and NMC chemistry has the highest climate impact as well as resource demand in a life cycle or system perspective.

*Keywords: Electric Vehicles, Environmental Impact, Life Cycle Assessment, Batteries, AC and DC charging technology*

*Acronyms used: AC, Alternating current; ADP, Abiotic depletion potential; BEV, Battery Electric Vehicle; CO2-eq, Carbon dioxide equivalents; DC, Direct current; EV, Electric vehicle; EPD, Environmental Product Declaration; FI, Finland; GLO, Global; ICCT, International Council on Clean Transportation; ICE, Internal combustion engine; IEA, International Energy Agency; LCA, Life cycle assessment; LFP, Lithium ion phosphate; NA, Not applicable; NMC, Nickel Manganese Cobalt; p, piece; S, System process; SE, Sweden; Sb-eq, Antimony equivalents; SIB, Sodium Ion Batteries; SSC, Swapping Station per Car*

## 1 Introduction

The production of batteries for electric cars cause negative environmental and climate impacts and there is a shortage of several of the raw materials needed. At the same time, there is a trend of increasing battery capacity (range) in BEVs. Especially for medium sized cars, the range and battery capacity has increased significantly during recent years [1]. The focus of this study is to investigate how different battery sizes, chemistries, charging strategies, including battery swapping and carbon intensities of electricity mixes, influence the climate impact and resource use of electric cars from a life cycle perspective, and possibly identify opportunities for improved sustainability of BEVs. [2]

## 2 Method and data

The study aims to show the current, 2025, situation of electric vehicles and charging options with an outlook to 2030. To be relevant, the use cases were developed in close collaboration between manufacturers (Volvo Cars and Zeekr) and researchers (RISE and VTI). The life cycle assessment, LCA, is performed in accordance with ISO 14044 [3]. Data for upstream production of raw materials and batteries are generic, i.e. taken from generally available data (mostly Ecoinvent 3.10 [4]) and from scientific articles. These data generally represent global or European averages and includes emissions and resources for necessary infrastructure, such as production equipment, roads, facilities, etc.

## 2.1 Functional unit or declared unit

The functional unit used is one vehicle kilometre, which means that the life cycle impacts are summed up and distributed on one kilometre driving, assuming 200 000 kilometre vehicle life.

## 2.2 System boundary

The main purpose of the study is to compare the environmental impact of different battery sizes (capacities) and charging strategies to each other. Therefore, the assessments only include the parts of the vehicles and charging infrastructure that differs between the compared cases, and do not include the entire vehicle. Included in the investigated system is:

- Battery manufacturing
- Charging infrastructure manufacturing.
- Battery swapping station manufacturing
- Slow and fast charging and charging in swapping station
- Use of the batteries in a vehicle, i.e., propulsion of vehicle
- Recycling of the batteries and the charging infrastructure and swapping stations

The main processes, equipment and flows involved in the investigated system, are shown in Figure 1.

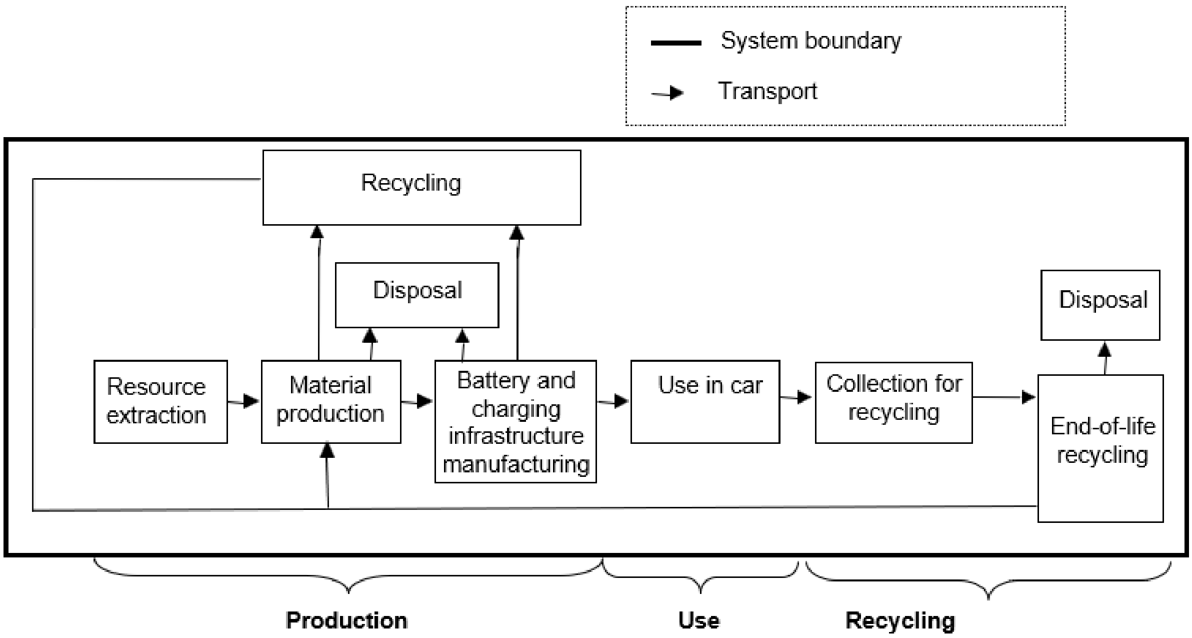


Figure 1 System boundary of study. Note that in the Production and Recycling stages, the vehicle itself, is not included, only the battery

Note that production and recycling of the rest of the vehicle is excluded from the investigated system. Some results are however extended to a complete vehicle scenario, by use of an assumption about the relation between battery production and rest-of-vehicle production. The use phase is modelled by the energy requirement for driving the vehicle.

## 2.3 Environmental impact assessment

The two most relevant environmental impact categories for LCA involving vehicle electrification [5], climate impact and resource depletion, were selected for the study. The unit for climate impact is kilogram $CO_2$-eq. The method Environmental Footprint 3.1 (adapted) as implemented in SimaPro 9 was used. This method is also used for abiotic resource depletion of mineral reserves, with the unit kg Sb-eq, antimony equivalents.

## 2.4 Driving distance, charging availability and battery size

The aim was to model average use of a private car in Europe with an outlook to 2030. The assumed annual driving distance is 12 800 km, split into a work-day driving distance (40 km), weekend driving distance (200 km) and occasional longer trips (400 km) based on statistics from literature [6,7] and proprietary Volvo Car fleet data [8]. The use cases include a base case with a 70 kWh battery configuration, a smaller 35 kWh battery configuration and a swappable battery configuration with two different battery sizes. The charging availability was varied as explained in Table 1.

Table 1: Overview of the six use cases. The charging infrastructure assumed for each configuration is given as x AC=alternating current charger, y DC=direct current charger and z SSC=swapping station per car.

| User/Battery size | **Normal**<br>70 kWh | **Minimal**<br>35 kWh | **Swapping**<br>35 or 70 kWh |
|---|---|---|---|
| **BEV owners with access to home charging** | Charging at home for all trips. No need for public charging.<br>1 AC, 0 DC | Charges at home for daily needs, but public charging needed for longer trips<br>1 AC, 0.03 DC | Charging at home for daily trips. Swapping to larger battery for longer trips.<br>1 AC, 0.0004 SSC |
| **BEV owners without access to home charging** | Uses only fast public charging<br>0 AC, 0.03 DC | Uses only fast public charging<br>0 AC, 0.03 DC | Swapping small battery for daily trips and to larger battery for longer trips<br>0.0004 SSC |

Note that alternating current, AC, is assumed for home charging, while direct current, DC, is assumed for fast charging and in swapping stations.

## 2.5 Electricity mixes, battery chemistries and charging infrastructure

The influence (on the environmental impact) of different electricity mixes, battery chemistries and amount of charging infrastructure (swapping batteries and stations and charging stations), were investigated by calculating climate impact and resource depletion while varying the above parameters one at a time, noting the difference compared to the base case. The base case was defined as NMC chemistry, “2030” European electricity mix, 1.15 swapping battery per vehicle and 0.0004 swapping stations per vehicle, see 2.5.3.

### 2.5.1 Electricity mixes

By 2030, the global electricity mix is forecasted to consist of 50% renewables [1]. Finland has 47.9% renewables according to Eurostat 2022. Thus, the Finnish mix is here used to represent an average global mix by 2030, which is defined as the base case electricity mix. The influence of Swedish and Chinese electricity mix respectively, were investigated by one at a time variations. The carbon footprint of the used electricity mixes is, for medium voltage assumed for DC-charging, 30 g $CO_2$-eq/kWh in Sweden, 146 g $CO_2$-eq/kWh in Finland (assumed as European by 2030) and 950 g $CO_2$-eq/kWh in China. The low voltage assumed for AC-charging has somewhat higher carbon footprint due to higher distribution losses.

### 2.5.2 Battery chemistries

The base case battery chemistry is NMC811, 80% Nickel, 10% Manganese and 10% Cobalt. Lithium ion phosphate (LFP) and sodium ion batteries (SIB) are also investigated. The production of the batteries was modelled using the Ecoinvent database. The different battery types have different energy densities, and the battery size influences the weight of the car and thus the energy consumption while driving, according to Table 2.

Table 2: Electricity used for driving the vehicle configurations

| Chemistry/Configuration | Normal, 70 kWh | Minimal, 35 kWh | Swapping, 35 or 70 kWh |
|---|---|---|---|
| *NMC811* | 0.2 kWh/km | 0.185 kWh/km | 0.2 kWh/km |
| *LFP* | 0.209 kWh/km | 0.189 kWh/km | 0.209 kWh/km |
| *SIB* | 0.209 kWh/km | 0.189 kWh/km | 0.209 kWh/km |

It was assumed that the 70 kWh battery configuration uses 0.2 kWh/km of battery energy, a value which is taken to include the impact from non-ideal conditions such as weather variations and the use of comfort functions. This can be compared to official WLTP certified values (see e.g. NIO ET5 [9] or Volvo EX90 [10]) which correspond to ideal conditions, but include losses associated with slow grid charging. It is assumed that the size of the charging losses in WLTP are equal to the average energy consumption impact from non-ideal conditions. Distribution and charging losses are added on top of this value. To calculate the consumption for the 35 kWh configuration, an energy reduction value, ERV, due to weight, of 0.65 kWh/(100 kg * 100 km) was assumed [11, 12], and half the battery weight (because half the capacity). The swapping configuration was assumed to use a box of the same size for both 35 kWh and 70 kWh batteries and therefore have limited possibilities for weight savings; an assumption which was backed by data from NIO [9]. LFP and SIB batteries are assumed slightly less energy dense, 116 Wh/kg, compared to NMC811, 149 Wh/kg. The production phase of the battery includes raw materials, production (of the battery) and distribution of the battery, in one system process, meaning that no details about these phases were available.

### 2.5.3 Swapping infrastructure

For the swapping case, 1.15 batteries per vehicle was assumed as base case [13]. NIO claims [14] that swapping prolongs the battery life (from 70% capacity left after 8 years, to 80% capacity left after 12 years). This extension of life is assumed to be incorporated in the 1.15 batteries per vehicle used. The smallest swapping battery, 35 kWh, gives a maximum range between 167-175 km (depending on chemistry), which is less than the 200 km weekend trip. Thus, the 70 kWh swapping battery is required for 37.5% of the annual distance because all the longer or non-work trips sum up to 37,5%. The total battery capacity per vehicle needed for the base case is therefore assumed to: 1.15 batteries*( 62.5% 35 kWh plus 37.5% 70 kWh)= 55 kWh swapping battery capacity per configuration (to be compared with the 35 kWh or 70 kWh configurations). In a sensitivity analysis, the number of batteries needed was decreased to 0.77 and increased to 1.3 batteries (or 0.77*55 kWh= 42 kWh minimal and 1.3*55=71.5 kWh maximum swapping station battery capacity per vehicle).

The number of swapping stations needed per vehicle was estimated to 0.0004 per vehicle based on information from NIO [15] on maximum number of swaps in their newest swapping stations (480 per day) in relation to how many swaps each user category needed. Since this number models maximum utilization, also 0.004 swapping station per vehicle was calculated in the uncertainty analysis.

### 2.5.4 Charging stations

Depending on the use case, there is a varying need of charging infrastructure. BEV owners with access to home charging use one home charger per car. The users with need for fast charging need 0.03 fast chargers per car based on IEA global outlook for 2030 [1]. Slow home charging is done by alternating current (AC) and fast charging (public) by direct current (DC), each with associated charging losses and standby power use. The charging infrastructure is modelled with the Ecoinvent database with additions from literature [16, 17].

# 3 Results

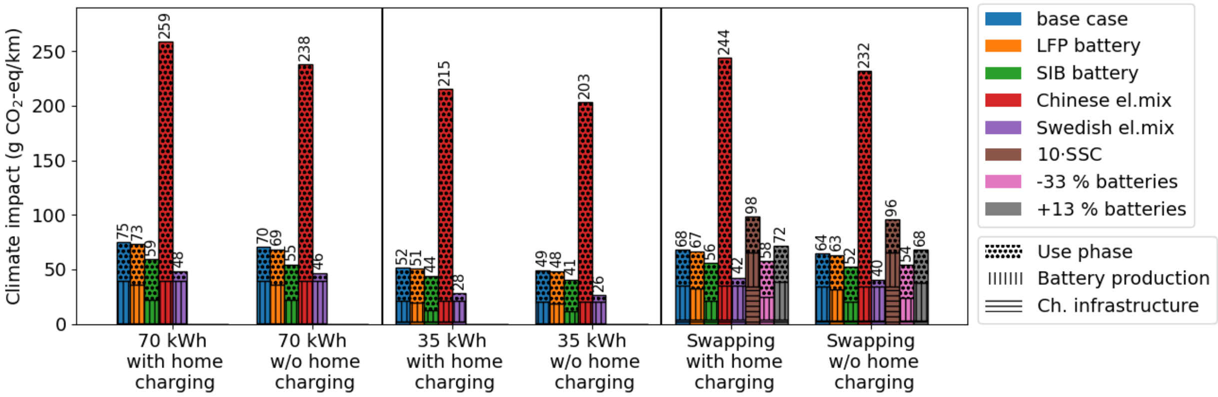


Figure 2: Climate impact from the six use cases (x-axis) with one-at-a-time variations from the base case (blue bar) of battery chemistry, electricity mix, number of swapping stations per vehicle (SSC) and number of batteries for each swapping vehicle. Each bar is divided into impacts from Use phase, Battery production and Charging infrastructure. The base case is defined as NMC chemistry, Finnish electricity mix, 0.0004 swapping station per swapping car and 1.15 swapping battery per swapping vehicle.

Figure 2 shows the resulting climate impact for the base case and all the one-at a time variations of battery chemistry, electricity mix, number of swapping stations per vehicle (SSC) and number of batteries for each swapping vehicle. It shows that:

- under base case conditions (the first blue bar for each of the six use cases):
    - The 70 kwh configuration give most climate impact and the 35 kwh configuration gives the smallest climate impact, regardless of charging regime.
    - The climate impact of swapping is in between the 35 and 75 kWh configuration.
    - Home charging gives more use phase climate impact than public fast charging
- With LFP chemistry, but otherwise base case conditions (orange bars): the climate impact is a little bit smaller compared to base case, but the hierarchy is the same, i.e., most climate impact from 70 kWh, least from 35 kWh and swapping in between.
- With SIB chemistry, but otherwise base case conditions (green bars): the climate impact is significantly smaller compared to the base case, but the hierarchy is the same, i.e., most climate impact from 70 kWh, least from 35 kWh and swapping in between. The differences stem mainly from the battery production.
- With Chinese electricity mix, but otherwise base case conditions (red bars), the climate impact is considerably higher for all cases, but the hierarchy remains the same.
- With Swedish electricity mix, but otherwise base case conditions (purple bars), the climate impact is considerably lower for all cases, but the hierarchy remains the same.
- For the base case electricity mix, half the climate impact stems from use of the vehicle and half from the battery production (and very little from production of the charging infrastructure). With Chinese electricity mix, the use phase dominates and with Swedish electricity, the battery production dominates.

The three last bars in the swapping cases, should be compared to the first blue base case bars. They show that:

- If the number of swapping stations per car is assumed ten times higher (0.004 instead of 0.0004), but otherwise base case conditions, the swapping alternative would give most climate impact.
- If the number of batteries per vehicle, assumed to 1.15, is decreased 30% or increased 13%, the climate impact from the swapping configuration would still remain in between the 35 kWh and 70 kWh base case configurations.

The climate impact results can be summed up as a

- A maintained *hierarchy* where the large 70 kWh configuration has most climate impact, the 35 kWh battery least climate impact and swapping in between the two, under almost all

investigated cases. Only when the number of swapping stations are ten-folded, will the swapping configuration give most climate impact.
- Home charging gives more use phase climate impact than public fast charging.
- For the base case electricity mix, half the climate impact stems from use of the vehicle and half from the battery production (and very little from production of the charging infrastructure). With Chinese electricity mix, the use phase dominates and with Swedish electricity, the battery production dominates

**Fel! Hittar inte referenskälla.** shows the resulting abiotic depletion for the base case and all the one-at a time variations of battery chemistry, electricity mix, number of swapping stations per vehicle (SSC) and number of batteries for each swapping vehicle. It shows that:

- For the base case (blue bars) the large 70 kWh configuration gives most resource depletion, the 35 kWh least, with swapping in between the two cases with fixed batteries, i.e., the same as for climate impact. The same hierarchy is found also for LFP chemistry and for all electricity mixes. As for the climate impact, when the number of swapping stations soar to 0.004 per vehicle, swapping gives more resource depletion than the 70 kWh configuration. Thus, *the hierarchy observed for the climate impact is the same for resource depletion for all cases except for SIB chemistry and for +13% batteries in swapping stations.*
- There is very little difference in resource depletion from using different electricity mixes. This is a major difference compared to the climate impact, for which the electricity mix matters a lot.
- The influence of the chemistry is more significant for resource depletion than for climate impact. Also LFP chemistry, not only SIB chemistry, contributes significantly to less resource depletion compared to the base case NMC chemistry. However, the hierarchy (70 kWh most impact, then swapping, then 35 kWh) is not maintained for SIB chemistry. The reason for this is that the swapping station production contribution becomes significant when the battery production contribution decreases, as with SIB chemistry.
- The battery production dominates the resource depletion for all cases except when the number of swapping stations per vehicle are ten-folded. As mentioned above, all modelling and figures related to the swapping alternative is very uncertain due to lack of data.

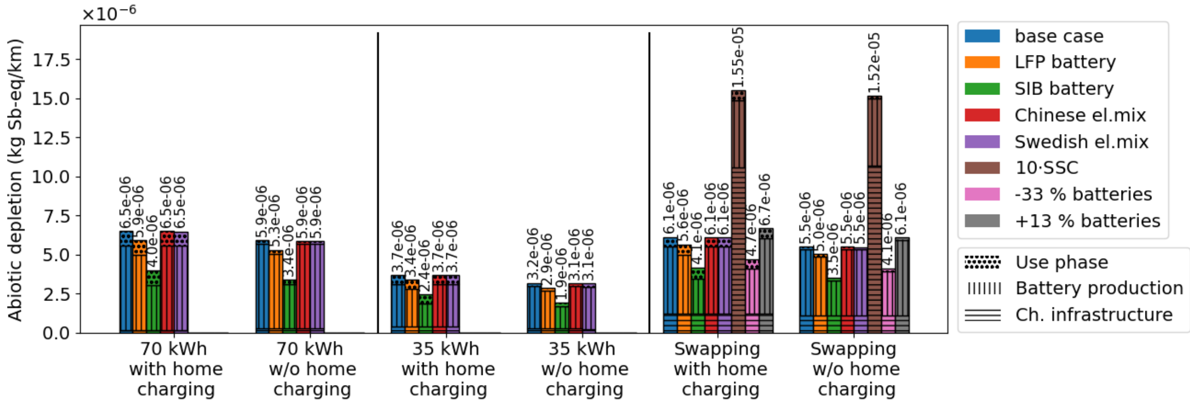


Figure 3: Resource depletion from the six use cases (x-axis) with one-at-a-time variations from the base case (blue bar) of battery chemistry, electricity mix, number of swapping stations per vehicle (SSC) and number of batteries for each swapping vehicle. Each bar is divided into impacts from Use phase, Battery production and Charging infrastructure

# 4 Discussion and conclusions

## 4.1 Discussion

### 4.1.1 Swapping batteries and swapping stations

The correct number of batteries per swapping vehicle and number of swapping stations per swapping vehicle is unknown due to lack of data. The conclusions regarding the swapping configuration are therefore very uncertain. The potential of battery swapping to deliver electric drive with less climate and resource impact and less charging time than normal electric vehicles is there, but has yet to be proven.

#### 4.1.2 Climate impact from the complete vehicle

As mentioned in section 2.2, the production and the end-of-life of the rest of the vehicle is excluded from the investigated system. Only the battery and the charging infrastructure are modelled in the complete life cycle. The use phase, however, is modelled by the energy requirement for driving the whole vehicle. This means that the real environmental footprint for the complete vehicle is higher than calculated here. According to the only available EV model in the Ecoinvent database, the climate impact from production of the rest of the vehicle could amount to double those from the production of the battery. This relationship between the climate impact for production of the vehicle and production of the battery is confirmed by [18, 19, 20, 21 and 22], although there is a considerable spread between 1.6 and 2.7, with no clear indication of what causes the variation. This relationship (i.e. double the battery production impact plus use phase impact equals the impact for complete vehicle) is used to extrapolate some of the results to a complete vehicle level.

#### 4.1.3 The life cycle climate impact of range

The results show that the 70 kWh configuration has a higher climate footprint and resource depletion (than the 35 kWh configuration) for all battery chemistries and electricity mixes investigated. An attempt to calculate the climate impact of additional range, indicate that, in a Chinese context, the climate impact for the extra 161 km range obtained by the 70 kWh configuration compared to the 35 kWh configuration, is 34 g $CO_2$-eq/vehicle km. Upscaling to the whole vehicle level, according to above, the difference is 315-240=75 g $CO_2$-eq/vehicle km, for the 161 km extra range. The additional climate impact should be considered for the entire vehicle lifetime, i.e. 200000 km, in total 200000*75E-6=15 ton $CO_2$-eq, for the extra 161 km range. In a global 2030 context, simulated with today's Finnish electricity, the additional climate impact is 62 g $CO_2$-eq/km range or 12.4 ton throughout the vehicle lifetime, at the vehicle level, for the extra 161 km range. The life cycle climate impact for every extra kilometre range is thus 12400 kg $CO_2$-eq/161 km = 77 kg $CO_2$-eq /km range in a global life cycle perspective and 15000/161=93 kg/km range in a Chinese perspective. Say that you would like to have a range of 550 km to reach your summer house without requiring charging stops, this would demand 550*77=42 ton $CO_2$-eq in a global life cycle perspective. If you can stop once, half the size battery would suffice and thus half the climate impact, i.e. 21 ton less $CO_2$-eq emitted. A recent ICCT study [23] sees reduced battery sizes as a viable policy option to decrease overall battery material demand.

### 4.2 Conclusions

This report aims to provide knowledge on how to decrease the environmental impact of electric vehicles by optimizing the size of the battery carried by the vehicle. Two different sizes of batteries, permanently installed in a fictional vehicle, have been compared with life cycle assessment, assuming possibilities to charge at home and no such possibilities. In addition, a fictional vehicle of corresponding size with possibility to swap between these two sizes of batteries in a swapping station was also evaluated. The results indicate the following conclusions:

- The large (70 kWh) permanently installed battery gives the largest climate impact and the largest abiotic depletion in (almost) all conceivable scenarios.
- The climate impact for the swapping alternative ends up in between the small (35 kWh) and the large (70 kWh) battery, under most conditions. Only when the number of cars per swapping station are reduced by a factor of 10 will the swapping alternative give the largest climate impact and largest abiotic depletion. For abiotic depletion, also the scenario with 1.3 battery in swapping station per car (instead of 1.15 as in base case) gives a larger abiotic depletion compared to the

base case. However, the data currently obtained and used for swapping stations is incomplete and therefore any related conclusion is uncertain.

- The charging infrastructure contributes with 1.2-3.5% to the total climate impact per vehicle kilometre. The charging losses could amount to 3.2-5.7% of the total climate impact per vehicle kilometre. These percentages would be smaller in a complete vehicle scenario.
- Sodium ion chemistry (compared to NMC chemistry) could provide 15-25% less total climate impacts and 32-42% less resource depletion. Also LPF chemistry perform better than NMC chemistry, both in terms of climate impact and resource depletion, but less so than sodium ion chemistry. These percentages would be smaller in a complete vehicle scenario.
- When Chinese electricity mix is used, the total carbon impact is 3-4 times higher than with the assumed base case global 2030 mix. With Chinese electricity, but otherwise base case conditions, the 70 kWh configuration scores 255 grams $CO_2$-eq/km, which is the highest total climate impact calculated. This figure would be 333 grams $CO_2$-eq/km in a complete vehicle scenario.
- When Swedish electricity is used for charging, the use phase carbon impact is 4-5 times lower than with the assumed base case 2030 global electricity mix, and the battery production phase dominates the total carbon footprint. With Swedish electricity for the use phase, but otherwise base case conditions, the 35 kWh configuration scores 27 grams $CO_2$-eq/km, which is the lowest total climate impact calculated. This figure would be 65 grams $CO_2$-eq/km in a complete vehicle scenario.

## 5 Acknowledgments

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# 7 Presenter Biography

Mats Zackrisson holds a Degree of Doctor of Philosophy in Production Engineering from the Royal Institute of Technology, Stockholm, and a Master of Science in Mechanical Engineering from Chalmers University of Technology, Gothenburg, Sweden. The title of his doctoral thesis from 2021: "Life Cycle Assessment of Electric Vehicle Batteries and New Technologies", is also a good description of his present field of work at RISE, Research Institutes of Sweden.