Article

Fast Charging Impact on the Lithium-Ion Batteries’ Lifetime and Cost-Effective Battery Sizing in Heavy-Duty Electric Vehicles Applications

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Abstract: Fast charging is an essential stakeholder concern for achieving a deeper penetration of Electric Vehicles (EVs), as optimizing the charging times of conventional vehicles is as yet a bottleneck to be solved. An important drawback of EV’s fast charging lies in the degradation suffered by the Li-ion Batteries (LIBs) at high charging currents. A deep understanding of the how these fast-charging activities affect the LIBs’ degradation is necessary in order to design appropriate fast charging stations and EV powertrains for different scenarios and contexts. In this regard, the present paper analyzes the effect of fast charging on Libs’ degradation under operation profiles from real driving cycles. Specifically, Battery Electric Buses (BEBs) driving profiles from three demos in European Cities (Gothenburg, Osnabrück and Barcelona) have been used in this analysis. In order to deduce the best practices for the design of the charging stations, different sizes for the chargers have been simulated, focusing on the analysis of the LIB degradation under each situation. Besides, for the design of the EV powertrain, different LIB sizes and LIB chemistries (Lithium Nickel Manganese Cobalt-NMC, Lithium Iron Phosphate-LFP, and Lithium Titanate Oxide-LTO) have also been proposed and compared in terms of LIB degradation. The results demonstrated that LTO batteries exhibited the lowest degradation, with capacity fade values under 1.5%/year in the nominal scenario (nominal charger and LIB sizes). As long as a full charging is ensured, reducing the fast charger size has been found to be a cost-effective measure, as the LTO degradation can be reduced at least to 1.21%/year. In addition, increasing the battery (BT) size has also been found to be a cost-effective approach for LTO batteries. In this case, it was found that for a 66% increase in capacity, the degradation can be reduced at least to 0.74%/year (more than 50% reduction). The obtained conclusions are seen as useful for the design of charging stations and EV’s BT systems that undergo fast charging.

Keywords: electric vehicles; electric buses; battery aging; capacity degradation; lithium-ion batteries

1. Introduction

Climate change has generated huge concern over the past few decades. The pertinent organizations and governments have been working together to reduce CO₂ emissions. The transportation sector creates around 21% of the total world CO₂ emission [1]. Due to climate change, several regulations over the past few decades have been imposed on Internal Combustion Engine Vehicles (ICEVs) to minimize their CO₂ emissions. The CO₂ regulation standards named “Euro” have been adopted in the EU, starting with “Euro 1” in 1992, and updated every few years to impose lower emissions. Vehicles sold in the EU area must be subjected to the Real Driving Emissions (RDE) test, which ensures the vehicles
comply with the defined emissions limits according to Euro standards. The currently adopted standard is Euro 6d, which is much stricter than the previous ones, and sets acceptable limits of the ICEVs’ exhaust emissions. Vehicles sold in the EU area must be subjected to the RDE2 test, which is much stricter than RDE.

The EC launched a target to reduce CO$_2$ emissions by 55% by 2030 and to achieve neutral CO$_2$ emission by 2050. While 80% of the CO$_2$ emissions come from conventional energy sources, as much as 20% comes from ICEVs [2]. Conventional energy sources have been replaced by renewable ones, such as PV, wind turbines, etc. Electric Vehicles (EVs) are taking the place of ICEVs on a large scale due to their low/zero CO$_2$ emission nature. Figure 1 shows the EV penetration in some overseas countries [3].

1.1. Electric Vehicles Overview

Low-and zero-emission vehicles (LZEVs) are broken down into two categories: hybrid EVs (HEVs) and full/all EVs (AEVs). The HEV combines the internal combustion engine (ICE) system with an electric propulsion system (hybrid vehicle drivetrain). One type of HEV is a plug-in EV (PHEV), with an option to recharge its battery from an external power source. On the other hand, the AEVs are equipped with an electric propulsion system only which is powered by an electrical source. Based on the power source, the AEVs break down into Battery EVs (BEVs) and Fuel Cell EVs (FCEVs). The former needs an external power source (e.g., grid) for battery charging, while the latter does not need an external charging system.

The main advantage of EVs lies in the reduction of operational costs due to the reduction of fuel use. This reduction balances the increase of the acquisition costs related to the integration of the battery technology. In the medium- and heavy-duty applications, such as Battery Electric Buses (BEBs), the operational costs can be even further reduced, due to their longer operational time per day. However, a longer operational workday means that the battery has to be oversized or that fast charging activities have to be deployed during the day.

The operation time of the Medium-Duty (MD) and Heavy-Duty (HD) EVs is around 18 h per day, which is much more than the operational time of the Light-Duty (LD) EVs. Due to this reason, there are several projects around Europe, such as ASSURED [4], ZEUS [5], ORCA [6], etc., which were launched to partially or fully electrify public transportation. Nowadays, the vast majority of the MD and HD vehicles are powered by diesel (94.5% of buses, 97.8% of trucks). It is expected that over 40 k of MD and 270 k of HD battery EVs will be in operation around Europe by 2025 and 2030, respectively [7]. Although the Total Cost of Ownership (TCO) of the EVs is higher than the ICEVs, their operational cost is much less. Furthermore, the EVs’ owners could participate in the energy market by providing Ancillary Services (AS), such as primary AS, voltage control, congestion management, etc. This could bring more revenues although it could have an impact on user comfort and on battery lifetime, due to the frequent charging and discharging of the batteries, etc. However, these limitations could be considered as constraints before the EVs provide AS to the grid to make it more cost-effective. To provide such AS, the EVs should be aggregated by an aggregator or be part of an Energy Community (EC). From the grid point of view, when the EVs provide an AS to the grid this could help the integration of more EVs with less impact. The legislation regarding the provision of AS is set out by the System Operator (SO), which must be followed by all the electricity market participants to enter the energy market pool. The AS provision will be discussed in detail in this work.

1.2. Battery System

1.2.1. Technologies

The full EVs have an electric motor, which is solely powered by an energy storage system (ESS) that is charged from the grid. HEVs have both an ESS propelled system and another propelling system. The ESS can be charged from the grid and/or from the conventional motor. The ESS should have some operational requirements, such as high-
power density, quick charging time (to increase the vehicle availability), sufficient lifetime, and affordability. The available ESSs have a trade-off of these features. Figure 1 shows the Ragone chart for some available battery ESS technologies [8].

![Ragone chart for some available battery ESS technologies](image)

**Figure 1.** Available ESS characteristics [9]. Reproduced from [9], MDPI/energies 2019.

Most of the current EV manufacturers are using Li-ion batteries (LIB) on their vehicles (see Table 1), due to high power density, high specific energy, stability, very slow self-discharge, etc. The current available Li-ion batteries (LIB) in the market include Lithium Nickel Manganese Cobalt (NMC), Lithium Nickel Cobalt Aluminum (NCA), Lithium Iron Phosphate (LFP), Lithium Titanate Oxide (LTO), etc. In this work, the capacity fade of the LFP, NMC, and LTO were investigated.

| EVs Manufactured | Battery Technology | Battery Capacity |
|------------------|--------------------|-----------------|
| Renault Twizzy   | LIB                | 6.1             |
| Hyundai Ioniq    | LIB                | 28              |
| Nissan Leaf      | LIB                | 30              |
| VW E-Golf        | LIB                | 24.2            |
| Tesla Model S    | LIB                | 100             |

**Table 1.** Some EVs manufactured and the adopted ESS [10].

Most EV manufacturers have adopted the LIB in their vehicles due to its intrinsic characteristics. The development in the research field has minimized the LIB cost from 1100 USD/kWh in 2010 to 156 USD/kWh in 2019. Furthermore, improvements in the energy density of integrated battery cells and in the optimization of the battery pack design are allowing EV manufacturers to increase the battery pack sizes integrated into their vehicles. Table 2 shows some of the most recent EV models and their main characteristics, including range and battery capacity.

The battery pack is the most critical part of EVs. The battery technology, capacity, chemistry, and weight play a vital role in specifying the EVs’ TCO, technical operation including operational cost. The battery cells work efficiently within a limited temperature range, state-of-charge (SoC), or voltage range. Therefore, the battery pack under operation should be always monitored and controlled to keep it within safe operational conditions, which could prolong the battery lifetime. In order to monitor the battery, battery models should be built.

Based on the battery pack capacity, the charging time of the batteries is specified. It is more convenient to charge the battery pack in a very short time. However, this could impact the battery age, the grid, equipment, safety, etc. Accordingly, the power levels to charge the batteries have been also standardized based on some international standards organizations, such as the International Electrotechnical Commission (IEC), and the Society of Automotive
Engineers (SAE). Due to the existence of some Original Equipment Manufacturers (OEMs), some standards have been realized regarding the connectors, CO₂ emission limits, mileage estimation, etc. Furthermore, some protocols have been defined to communicate between the EV and the Electric Vehicle Supply Equipment (EVSE).

Table 2. Some of the EVs’ characteristics including battery capacity [11].

| EV Model (Release)         | Range EPA (km) | Battery Capacity (kWh) | Motor Power (kW) | Charging Power, kW, AC (DC Fast) |
|---------------------------|----------------|------------------------|------------------|----------------------------------|
| SAIC Roewe Ei5 (2020)     | 261            | 52.5                   | 86               | 7 (50)                           |
| Peugeot e-208 (2020)      | 200            | 50                     | 100              | 7 (100)                          |
| Porsche Taycan TurboS (2020) | 192         | 93.4                   | 560              | 22 (270)                         |
| Lexus UX 300 e (2020)     | 250            | 54.3                   | 150              | 6.6 (50)                         |
| Jaguar I-PACE (2020)      | 234            | 90                     | 300              | 7 (50/100)                       |
| Hyundai Ioniq             | 274            | 38.3                   | 100              | 7.2 (44/100)                     |
| Mazda MX-30 (2021)        | 124            | 35.5                   | 105              | 7 (50)                           |
| Volkswagen ID.4 (2021)    | 300            | 83                     | 225              | (125/150)                        |
| Mercedes EQ EQA (2021)    | 217            | 60                     | 200              | 11 (100)                         |
| BMW i4 (2021)             | 375            | 80                     | 395              | (150)                            |
| Audi Q4 e-tron (2022)     | 281            | 82                     | 225              | 7 (125)                          |
| BMW i7 (2023)             | 430            | 120                    | 500              | (up to 150)                      |

1.2.2. Impact of Battery System on the EVs Operation

The battery packs are the core of the EV industry. The battery pack capacity, weight, and efficiency are factors determining the EV price, performance, mileage, and consumption. The battery’s weight is raised by some extra elements, e.g., the cooling and safety system, the Battery Management System (BMS), as well as the assembly box for the battery pack. In view of the elements of the battery system, its cost can reach 1EUR/Wh. The batteries occupy a large volume, around 0.1–0.6 m³. The most popular battery technology adopted by EV manufacturers is the Li-ion batteries [12].

The EVs intended for urban driving (Compact-class EVs) do not have high-capacity battery packs. These vehicles are heavier by 10–15% compared with their counterparts of the ICEVs. The medium-class EVs have a battery capacity of 1.1 kWh and a mileage around 8 km. For some special vehicles that can reach a mileage of 300 km, their battery pack weighs around 500 kg [12]. Figure 2 shows the gross weight of some EVs and their batteries.

Figure 2. Weights of some EVs and their battery packs.
The small size EVs have a low battery capacity range (6.1–12.3 kWh), with a battery pack weight of 100–150 kg. Some larger EVs have a battery pack of 23 kWh capacity with a weight of around 286 kg. The EVs that have a high battery capacity (60–100 kWh) with weight range of 385–544 kg have a gross weight in the range of 2050–3070 kg. Table 3 shows real average data observed in 2017. There is much research ongoing to improve the energy density of the existing LIB battery, which is expected to reach 350 Wh/kg and EV mileage of 560 km [13].

Table 3. Features of battery technologies [13].

| Li-ion Battery Technology | Energy Density (Wh) | Vehicles Range (km) |
|---------------------------|---------------------|---------------------|
| NCA                       | 250                 | 130–160             |
| NMC                       | 200                 | 160                 |
| LFP                       | 190                 | 250                 |
| ZEBRA                     | 140                 | 130–160             |
| LMP                       | 100                 | 120–250             |

The gross EV weight including the battery weight has an impact on the total vehicle energy consumption and efficiency [12]. For example, the average consumption for Renault Twizy is 67.8 Wh/km, while for Tazzari Zero it is 87.9 Wh/km, for Tesla Model S (85) it is 199.5 Wh/km, and for Kia Soul it is 216.7 Wh/km. This high consumption for the Tesla Model S and Kia Soul due to their high weight impacts the operational cost of the EV which is different from one country to another based on the energy price. Accordingly, the new medium-class EVs tend to have lightweight new generation batteries, such as the Renault Zoe model 2017 which has a new generation battery of 41 kWh, compared with the previous generation that has a battery capacity of 22 kWh and weight around 26 kg [12].

For the BEB, a large battery pack is needed to meet the BEB load demand, as shown in Table 4. The battery modules are distributed around the bus to keep the BEB balance. Oslo articulated EBs using 348 kWh, 170 kWh of battery capacity with a battery weight of 2.6 tons, and 3 tones, respectively [14]. Figure 3 summarizes the impact of the batteries on EV performance.

Table 4. Battery packs adopted in some BEBs in the ASSURED project [4].

| EB Model/Brand | Bus Length (m) | Battery Capacity (kWh) |
|----------------|----------------|------------------------|
| Irizar ieTram  | 18.73          | 120                    |
| Heuliez bus    | 18             | 340 kWh                |
| VOLVO bus      | 12             | 4 × 19 kWh             |
| Solaris Urbino | 8.9/12/18      | 160/160/240            |

1.3. Research Gap

As mentioned earlier, fast charging may impact battery aging. There is a wide literature of research works dealing with the effect of fast charging on the degradation suffered by battery cells [15,16]. Mathieu et al. [17] developed an experimental aging study under fast charging conditions. Three cells of different materials and energy densities were investigated and they evaluated the impact of three parameters on the degradation: charge current, end-of-charge voltage, and ambient temperature. Keil et al. [18,19] also analyzed experimentally the effect of fast charging on cells composed of different materials. Some other authors have focused their research on the effect of the charging protocol, such as Abdel Monem et al. [20], Ansean et al. [21], and Mussa et al. [22]. In these works, different charging currents and charging times were evaluated in experimental tests. Xie et al. [23] also compared the degradation suffered by an NMC cell under different fast charging profiles (from 1C to 3C).
Tanim et al. [24] compared the aging suffered at both cell level and pack level under two charging profiles: 50 kW (DC fast charging) and 3.3 kW (AC Level 2 charging).

Figure 3. Impact of the batteries on the EV performance [12]. Reproduced from [12]. ENGINEERING FOR RURAL DEVELOPMENT: 2017.

However, these works are focused on tests carried out in static conditions, which differ from the real power or current profiles that batteries undergo in real operation. Therefore, the next step consists of evaluating battery degradation under real operation profiles. This issue has been partially addressed in the literature. Some authors have evaluated the battery degradation under real operation profiles of EVs, but they did not focus on the effect of fast charging [25] (charging below 1C). Liu et al. [26] estimated the battery degradation under different driving cycles, ambient temperatures, and charging modes (slow and fast charging). They evaluated the influence of the main parameters related to fast charging on battery degradation. However, their work does not analyze how this degradation can be reduced by means of an appropriate design of the charging stations and EV powertrain. Indeed, the effect of the fast charging can be mitigated if the charging speed (and thus, charging C-rate) is reduced. In addition, an increase of the battery capacity is also supposed to reduce the degradation, since with the same charger size a lower C-rate is deployed. Last but not least, fast charging affects battery degradation differently depending on the battery chemistry. The influence of the previously mentioned fast charging related parameters may also vary depending on the mentioned chemistry.

Therefore, this paper analyses the effect of fast charging on battery degradation under real operation profiles. The analysis will be also focused on how an appropriate design of the charging stations and EV powertrain (battery size and chemistry) can mitigate the undesired effect of fast charging on battery degradation, this being one of the main contributions of the paper.

1.4. Contributions

In this work, we aim to evaluate the effect of fast charging on battery degradation under real operation profiles of BEBs. Specifically, driving cycles from three demos in European cities (Gothenburg, Osnabrück and Barcelona) are used in this analysis. Each driving cycle shows different characteristics related to fast charging and battery degradation, e.g., frequency of charging activities, route overall demand, or climate of the region. Therefore, the influence of these parameters on battery degradation will also be evaluated. As has been specified previously, the negative effect that fast charging has on battery degradation
can be mitigated by means of an appropriate design of the charging stations and the BEB powertrain. Therefore, this work also aims to evaluate how the degradation changes when varying the charger size, battery chemistry, and battery size under the mentioned driving cycles, which include fast charging activities. For this approach, a comprehensive sensitivity analysis will be set up. The conclusions obtained in this analysis will allow gaining more insight regarding the design of battery systems for electric vehicles and the design of the fast charging activities required by these applications.

The paper is structured as follows: Section 2 illustrates the materials and methods adopted in this work. Section 3 illustrates the obtained results and discussion. Section 4 shows the obtained conclusions based on the results.

2. Materials and Methods

In this section, the methodology used to evaluate the impact of fast charging profiles on battery lifetime is evaluated. A Matlab/Simulink model was been developed in order to evaluate the performance of an BEB during a 1-year operation. The model includes subsystems for the BEB charger and for the battery, see Figure 4. This last element also includes models for the electric, thermal, degradation, and cooling subsystems. The Matlab/Simulink model evaluates together the performance of three battery packs of diverse chemistries (NMC, LTO, and LFP). The effect of fast charging will be evaluated by the different charger and battery capacities and in different bus lines located in three different European cities. These case studies and scenarios are also introduced in this Section.

![Figure 4. Analysis procedures of the battery’s capacity fade, $P_{\text{ch}}$: charger power; $C_{\text{ch}}$.](image)

2.1. Battery Model

The developed MATLAB/Simulink model aims to simulating the performance of the BEB battery system and the BEB charger system.

In order to evaluate the BEB performance, the model uses as inputs the environment temperature profile, the current profile to be covered by the battery, and the battery charging command (which is activated when the bus reaches a charging station). The BEB performance is then evaluated by means of the battery and charger models. Three batteries and charger subsystems are included, one for each battery chemistry (LTO, LFP, and NMC).

This charger model allows obtaining the required energy to charge the battery, the charger efficiency, and the charger power factor.

Finally, the subsystem related to the battery model includes sub-models related to the battery thermal and electric performance, cooling system, and battery degradation. These models allow eventually obtaining the evolution of the SOC and the Fade Capacity EBs (CF) values.

As previously mentioned, three different battery models were included in the current approach. These models represent three different battery chemistries, namely LTO, LFP, and NMC. The electric characteristics of these chemistries are presented in Table 5. These values correspond to the cell level characteristics. Depending on the case study being
analyzed, the battery cells will be arranged in parallel-connected branches to reach the required energetic characteristics.

Table 5. Battery characteristics at cell level.

|               | LTO | LFP | NMC |
|---------------|-----|-----|-----|
| Capacity [Ah] | 20  | 14  | 20  |
| Nominal Voltage [V] | 2.4 | 3.2 | 3.6 |
| Max. C-rate (ch) [C] | 5  | 3.75 | 2.7 |
| Max. C-rate (dch) [C] | 10 | 7.5 | 5  |

2.2. Methodology for Fast Charging Evaluation

In order to evaluate the effect of fast charging on LTO, LFP, and NMC batteries, different case studies are proposed. These cases aim to evaluate the impact of different parameters on the degradation that the batteries suffer. In the context of fast charging, two parameters were identified as influential in the mentioned degradation:

- **Charger power** ($P_{ch}$). Considering a scenario with fixed charging points and fixed battery capacity, the power provided by the charger defines the C-rate at which the battery is charged ($C_{ch}$). Therefore, at higher charger power, the battery is expected to be degraded faster. The minimum charger power is constrained by the route demand (which specifies the amount of energy required to recover the initial battery SoC) and the feasible charging time (time in which the bus is stopped).

- **Battery capacity** ($E_{BT}$). Considering a scenario with fixed charging points and fixed charger capacity, varying the battery capacity may affect the depth-of-discharge (DOD) it may accomplish and the C-rate ($C_{ch}$) in which it is operated. At higher battery capacity, lower DOD and C-rate values are obtained, which are expected to reduce battery degradation. Depending on the saved capacity fade, increasing the battery capacity may or may not be cost-efficient.

The evaluation of $P_{ch}$ and $E_{BT}$ parameters is conducted by means of independent sensitivity analyses. For this approach, the first step consists of defining a Base Case (BC). The charger capacity has been defined at 600 kW, this being the fast charger proposed in the E.U. funded ASSURED project [4]. When deploying fast chargers for BEBs around this size, battery capacities of around 100–200 kWh are usually integrated on-board [15]. Based on this sizing procedure, the following battery capacities are defined in the BC: 120 kWh for LTO, 200 kWh for LFP, and 150 kWh for NMC. Considering the $C_{ch}$ constraint defined in Table 5 for NMC (2.7 C), the BC charger size has been downsized to 400 kW. Therefore, in the sensitivity analyses proposed in this paper, $P_{ch}$ and $E_{BT}$ will be varied from the values proposed in the BC. Specifically, at each sensitivity analysis three cases are proposed, which are detailed in the following paragraphs: High Case (HC), Medium Case (MC) and Low Case (LC).

On the one hand, the sensitivity analysis to the charger power is focused on evaluating the effect of reducing the charger size, as chargers higher than 600 kW are not common yet. Therefore, the BC is defined as the HC in this sensitivity analysis. To define the other two cases (MC and LC), the following criterion has been followed: the lowest $P_{ch}$ value cannot provide a charging rate lower than 1 C (limit of fast charging). Therefore, in the LC a $P_{ch}$ value of 200 kW is defined for the three chemistries. In the MC, the medium value between HC and LC is defined for each of the chemistries. Table 6 resumes the information related to this sensitivity analysis. The table also includes the charging C-rate ($C_{ch}$) related to each combination of $E_{BT}$ and charger power $P_{ch}$. The values $\Delta E_{BT}$, $\Delta P_{ch}$ and $\Delta C_{ch}$ refer to the variation of these values in the MC and LC in relation to the BC/HC.
### Table 6. Sensitivity analysis in relation to charger power.

|                      | Base Case-High Case | Medium Case | Low Case |
|----------------------|--------------------|-------------|----------|
|                      | LTO  | LFP  | NMC | LTO  | LFP  | NMC | LTO  | LFP  | NMC |
| $E_{BT}$ [kWh]       | 120  | 200  | 150 | 120  | 200  | 150 | 120  | 200  | 150 |
| $\Delta E_{BT}$      | -    | -    | -   | +0%  | +0%  | +0%  | +0%  | +0%  | +0% |
| $P_{ch}$ [kW]        | 600  | 600  | 400 | 400  | 400  | 300 | 200  | 200  | 200 |
| $\Delta P_{ch}$      | -    | -    | -   | -33% | -33% | -25% | -67% | -67% | -50% |
| $C_{ch}$ [C]         | 5    | 3    | 2.67 | 3.33 | 2  | 1.67 | 1    | 1.33 |
| $\Delta C_{ch}$      | -    | -    | -   | -33% | -33% | -25% | -67% | -67% | -50% |

On the other hand, the sensitivity analysis to the battery capacity is focused on evaluating the effect of increasing the battery size. Indeed, the objective of this analysis is to analyse the benefit that increasing the battery size has on its degradation. It is understood that at higher sizes, the degradation is reduced, but the cost-efficiency of that increase is uncertain. Therefore, the BC is defined as the LC in this analysis. The capacities of each chemistry have been differently increased in the MC and HC. Indeed, in the HC the $E_{BT}$ values of NMC and LFP have been doubled, as it is understood that even higher batteries are unlikely to be integrated in BEBs with fast charging. The increase of LTO in the HC is lower (66%), as its lower energy density impedes the integration of high battery capacities. In the MC medium values between the HC and LC are defined. In some cases, instead of the exact medium value, rounded values have been defined (as it is understood that they are more likely to be selected by BEB manufacturers). For instance, in the MC of NMC a capacity of 200 kWh (33% increase) is defined, rather than 225 kWh (50% increase). Table 7 resumes the information related to this sensitivity analysis, including also the related $C_{ch}$ values and the variation of the different parameters in relation to the BC/LC.

### Table 7. Sensitivity analysis in relation to battery capacity.

|                      | Base Case-Low Case | Medium Case | High Case |
|----------------------|-------------------|-------------|-----------|
|                      | LTO  | LFP  | NMC | LTO  | LFP  | NMC | LTO  | LFP  | NMC |
| $E_{BT}$ [kWh]       | 120  | 200  | 150 | 150  | 300  | 200 | 200  | 400  | 300 |
| $\Delta E_{BT}$      | -    | -    | -   | +25% | +50% | +33% | +67% | +100% | +100% |
| $P_{ch}$ [kW]        | 600  | 600  | 400 | 600  | 600  | 400 | 600  | 600  | 400 |
| $\Delta P_{ch}$      | -    | -    | -   | +0%  | +0%  | +0%  | +0%  | +0%  | +0% |
| $C_{ch}$ [C]         | 5    | 3    | 2.67 | 4    | 2    | 2   | 3    | 1.5  | 1.5 |
| $\Delta C_{ch}$      | -    | -    | -   | -20% | -33% | -25% | -40% | -50% | -44% |

These two sensitivity analyses are replicated in three different scenarios, i.e., in three bus lines located in three different cities. These bus lines (introduced in the next subsection) are characterized by different lengths, average demands, and even climates, which will inevitably vary the effect that the fast charge has on the batteries. Therefore, this paper analyses holistically the effects of the battery chemistry, battery capacity, charger power, and scenario on the degradation suffered by batteries subjected to fast charging.

### 2.3. Study Cases

As mentioned, in this paper three bus lines located in different European cities are considered as study cases. The selected cities are Barcelona (BCN, Spain), Osnabrück (OSN, Germany), and Gothenburg (GOT, Sweden), and the simulated lines are L33, N5, and R55, respectively. Table 8 shows the main characteristics of these bus lines. Besides, Figures 5–7 depict for each scenario some representative one-day profiles of the inputs required by
the simulation model: battery current profile and environment temperature profile. As the simulations have been performed considering one-year profiles, each variable graph is duplicated so as to represent winter (January) and summer (July) profiles. The current profiles also represent the charger locations to visualize the charging frequency defined at each scenario.

![Figure 5. Current and temperature profiles in BCN scenario. (a) Current profile, 1 January. Cyan: Charging Points. (b) Current profile, 1 July. Cyan: Charging points. (c) Temperature Profile. Blue: January; Red: July.](image-url)
Figure 6. Current and temperature profiles in OSN scenario. (a) Current profile, 1 January. Cyan: Charging Points. (b) Current profile, 1 July. Cyan: Charging points. (c) Temperature Profile. Blue: January; Red: July.
Figure 7. Current and temperature profiles in GOT scenario. (a) Current profile, 1 January. Cyan: Charging Points. (b) Current profile, 1 July. Cyan: Charging points. (c) Temperature Profile. Blue: January; Red: July.

Even if all scenarios share similar service durations (around 13–15 h), the route length, route average speed, and charging strategy (number of chargers per route) vary among the different routes. This variety allows evaluating the impact of fast charging under different circumstances: BCN is characterized by a less demanding route, but few charging activities are deployed; OSN is characterized by a more demanding route, but more charging activities are deployed; and GOT is characterized by a highly demanding route, with even more charging activities compared to OSN. The climate may also affect the performance of the battery systems: BCN has a warmer temperature over the year, while OSN and GOT are characterized by cooler temperatures.
Table 8. Demo route lines and their characteristics.

| Characteristics          | Barcelona (BCN) | Osnabrück (OSN) | Gothenburg (GOT) |
|--------------------------|-----------------|-----------------|------------------|
| Bus Line                 | L33             | N5              | R55              |
| Return trip distance [km]| 19.4            | 12.2            | 15.2             |
| Average speed at peak hour [km/h]| 11.64       | 19.75           | 18.24            |
| Number of return trips per day [-]| 8            | 16              | 11               |
| Number of chargers per return trip [-]| 1         | 1               | 2                |
| Operational time per day [h/day]| 15.33      | 14.15           | 13               |
| Operational distance per day [km/day]| 155         | 195             | 167              |
| Maximum/Minimum temperature [°C]| 29/9        | 23/0            | 22/−2            |

Main characteristics

- Low demand
- High demand
- Low ch. freq.
- Mid. ch. freq.
- Warm climate
- Cool climate
- Cool climate

3. Results and Discussion

In this section, the results related to the one-year simulations developed at different scenarios and case studies are presented and discussed in detail. In order to quantify the effect of fast charging in the different scenarios and case studies, the results will be focused on the analysis of the degradation suffered by the battery. The degradation can be measured by the CF<sub>y</sub> value returned by the simulation model (capacity fade after 1 year), or the expected battery lifetime (y<sub>BT</sub>), which is calculated as follows:

\[ y_{BT} = \frac{CF_{EOL}}{CF_y} [\text{years}] \]

where CF<sub>EOL</sub> is the capacity fade at battery End of Life (EOL), typically defined at 20%.

For each case study being analysed, two graphs are presented. On the one hand, the absolute degradation (represented by CF<sub>y</sub>) is given in relation to the absolute value of the parameter whose sensitivity is being analysed (P<sub>ch</sub> or E<sub>BT</sub>). The aim of this representation is to compare the degradation suffered in the different case studies (different battery chemistries, BEB lines, charger powers, and battery capacities) in absolute figures. On the other hand, in a second graph, the increase/decrease of the battery lifetime (represented by Δy<sub>BT</sub>) is given in relation to the increase/decrease of the analysed parameter (ΔP<sub>ch</sub> or ΔE<sub>BT</sub>). The aim of this second representation is to analyse the relative increase/decrease of the degradation or battery lifetime in relation to the relative increase/decrease of the analyzed parameter. The relative parameters Δy<sub>BT</sub>, ΔP<sub>ch</sub>, and ΔE<sub>BT</sub> are obtained in relation to the BC, therefore:

\[ \Delta y_{BT_x} = \frac{CF_{y_BC}}{CF_{y_x}} [-] \]

\[ \Delta P_{ch_x} = \frac{P_{ch_x}}{P_{ch_BC}} [-] \]

\[ \Delta E_{BT_x} = \frac{E_{BT_x}}{E_{BT_BC}} [-] \]

where the variables with the suffix _BC refer to the values in the BC, and the variables with the suffix _x to the values in the case being analyzed (which can be the LC, MC, or HC).

3.1. Sensitivity to Charger Power

In this first sensitivity analysis, the impact of the charger power in the battery lifetime is evaluated. Figures 8 and 9 show the two graphs previously explained. Figure 8 represents
the CFy values in relation to the absolute charger power values for the different battery chemistries and BEB lines, while Figure 9 represents the battery lifetime change ($\Delta y_{BT,x}$) in relation to the relative charger power ($\Delta P_{ch,x}$) for the different battery chemistries and BEB lines. In addition, Figure 10 depicts the SoC evolution graphs obtained from the simulation. These graphs represent simulation results from the BC on 1 January and help obtain the conclusions regarding battery degradation.

Figure 8. CFy in the different case studies and scenarios (bus lines). (a) Barcelona bus line. (b) Osnabrück bus line. (c) Gothenburg bus line.
Figure 9. BT life increase/decrease in relation to charger power increase/decrease. (a) Barcelona bus line. (b) Osnabrück bus line. (c) Gothenburg bus line.
On the one hand, the results of Figure 8 allow the comparison of the degradation suffered by LTO, LFP, and NMC batteries in the various proposed scenarios and case studies. In the three scenarios, LTO batteries exhibit the lowest degradation, with capacity fades always under 1.5%/year (lifetimes higher than 13 years). LFP batteries showcase CF values around 2.5–3%/year (lifetimes of around 6–8 years), and in all cases the degradation is doubled compared to LTO. Finally, NMC batteries exhibit the highest degradation, with CF values between 5.1–8.7%/year (lifetimes of around 2.3–4 years). In almost all the cases, it is observed that the degradation is doubled compared to LFP chemistry. Compared to LTO, the degradation is even 4 times higher.

The results can be also analysed scenario by scenario. In BCN, it is important to highlight that deploying a charger of 200 kW turns out to be unfeasible. The reason is that BCN is the scenario where the BT is most discharged between consecutive charging activities (see Figure 8a). Therefore, a charger of more than 200 kW is required in order to recover that energy in the considered stop time. NMC suffers the highest degradation in this scenario, which demonstrates that its degradation is sensitive to high DODs (see graphs in Figure 8).

Regarding the scenario in OSN, the power of the charger can be reduced up to 200 kW. For LFP and LTO chemistries, OSN is the scenario where the batteries are most degraded. This evidences that the feature that most degrades these chemistries is not the realized degradation.
DOD, as the highest DOD is obtained in BCN (see Figure 8a,b). OSN is characterized as being a demanding scenario, which can cause the higher degradation of these chemistries. Finally, in GOT the charging power can be also reduced up to 200 kW. The degradation is lowest in this scenario. This demonstrates that increasing the charging frequency does not directly accelerate the degradation suffered by the batteries and that therefore, reducing the DOD realized by the battery can efficiently increase its lifetime (see Figure 8c). The obtained results are summarized in Table 9.

Table 9. Summary of CF<sub>y</sub> results for sensitivity to the charger power.

| Chemistry | Charger Power (kW) | CF<sub>y</sub> (%) | Minimum | Maximum |
|-----------|--------------------|-------------------|---------|---------|
| LTO       | 200                | 1.0–1.2           | GOT     | OSN     |
|           | 400                | 1.1–1.3           | GOT     | OSN     |
|           | 600                | 1.2–1.4           | GOT     | OSN     |
| LFP       | 200                | 2.5–3.0           | GOT     | OSN     |
|           | 400                | 2.5–3.0           | GOT     | OSN     |
|           | 600                | 2.5–3.0           | GOT     | OSN     |
| NMC       | 200                | 5.1–5.7           | GOT     | BCN     |
|           | 300                | 5.5–6.6           | GOT     | BCN     |
|           | 400                | 6.3–8.3           | GOT     | BCN     |

On the other hand, the graphs in Figure 9 permit evaluation of the impact of reducing the charger power (P<sub>ch</sub>) in relation to the defined BC. The first conclusion obtained when analyzing the depicted results is that the chemistry that most benefits from the P<sub>ch</sub> reduction is NMC. As this chemistry is close to its maximum charging C-rate in the BC, this high degradation reduction becomes reasonable. The lifetime gain reaches 25% in BCN (when reducing the charging power by 25%), 30% in OSN, and 22% in GOT (in these two scenarios when reducing the charging power by 50%). Therefore, in NMC the lifetime gain is sensitive to the scenario.

Regarding LTO chemistry, the lifetime gain is 12% when reducing the charging power by 33%, and 24% when reducing the charging power by 67%. In contrast to NMC, in this case, the degradation variation is not sensitive to the scenario. Finally, the degradation of LFP chemistry remains unaltered when reducing the charger power. Therefore, it can be concluded that from the degradation point of view, in the case of NMC and LTO, reducing the charger size below 600 kW can be a good practice. Depending on the scenario, this reduction can be higher or lower, as enough room must be left to ensure the full SOC recovering at the charging point. As LFP is not affected by high charging C-rates, the 600 kW charger becomes an appropriate option.

The obtained results are summarized in Table 10. The variable lifetime improvement ratio defines how much the BT lifetime is improved when downsizing the charger (value 1 defines that the lifetime is improved by 25% when downsizing the charger by 25%).

Table 10. Summary of results for the sensitivity to the charger power.

| Chemistry | Lifetime Improvement Ratio (%) | Minimum | Maximum |
|-----------|--------------------------------|---------|---------|
| LTO       | 0.36                           | Equal in all scenarios | Equal in all scenarios |
| LFP       | 0                              | Equal in all scenarios | Equal in all scenarios |
| NMC       | 0.4–1                          | GOT     | BCN     |

3.2. Sensitivity to Battery Capacity

In this second sensitivity analysis, the effect of increasing the battery capacity is analyzed. The battery capacity effect is more complex than the effect analysed in the
previous sensitivity analysis. In this case, the analyzed variable affects both the C-rate in which the battery is charged and the DOD that it performs (in the previous analysis only the $C_{ch}$ value was altered). Figure 11 represents the $CF_y$ values in relation to the absolute battery capacity values for the different battery chemistries and BEB lines, while Figure 12 represents the battery lifetime change ($\Delta Y_{BT,x}$) in relation to the relative battery capacity ($\Delta P_{ch,x}$) for the different battery chemistries and BEB lines. Figure 13 depicts some representative SoC profiles obtained from simulation. These graphs help understand the results depicted in the previous figures.

![Graphs showing capacity fade after 1 year for different battery chemistries and BEB lines.](image)

**Figure 11.** CF in the different case studies and scenarios (bus lines). (a) Barcelona bus line. (b) Osnabrück bus line. (c) Gothemburg bus line.
Figure 12. BT life increase/decrease in relation to battery capacity increase/decrease. Dotted lines represent cost-efficiency borderline. (a) Barcelona bus line. (b) Osnabrück bus line. (c) Gothenburg bus line.
Regarding the results depicted in Figure 11, the same patterns identified in the previous sensitivity analysis are noticed. In all scenarios, LTO is the chemistry showing the lowest degradation, while NMC is the most degraded chemistry. Comparing the different scenarios, NMC degrades the most in BCN and the least in GOT, while LFP and LTO degrade the most in OSN and the least in GOT. The degradation reduction induced by the battery capacity increase allows LTO to reach CF$_y$ values up to 0.6–0.75%/year (lifetimes up to 30 years), NMC to reach CF$_y$ values around 1.3–1.5%/year (lifetimes up to 15 years), and LFP to reach CF$_y$ values around 3.25–3.62%/year (lifetimes up to 6.15 years). Therefore, and as will be further analysed with the help of Figure 11, it can be deduced that the degradation is reduced more with the capacity increase than with the charger power downsizing. The obtained results are summarized in Table 11.

Focusing on the relative lifetime increases depicted here, further observations can be obtained. First of all, it is confirmed that, compared to Figure 9, the lifetime improvements are higher. However, it has to be considered that reducing the charger size does not involve an additional cost while increasing the battery capacity requires an additional investment. The obtained lifetime increase has to be higher than the capacity increase in order to be a cost-efficient option. This is represented by the dotted lines depicted in the graphs: below the dotted lines, increasing the battery capacity is not cost-efficient; and above the dotted lines, increasing the battery capacity becomes cost-efficient.
Table 11. Summary of CF<sub>y</sub> results due to the sensitivity to the battery capacity.

| Chemistry | BT Capacity (kWh) | CF<sub>y</sub> (%) | Minimum | Maximum |
|-----------|-----------------|-----------------|---------|---------|
| LTO       | 120             | 1.2–1.4         | GOT     | OSN     |
|           | 150             | 0.9–1.1         | GOT     | OSN     |
|           | 200             | 0.6–0.7         | GOT     | OSN     |
| LFP       | 200             | 2.5–3.0         | GOT     | OSN     |
|           | 300             | 1.7–2.0         | GOT     | OSN     |
|           | 400             | 1.3–1.5         | GOT     | OSN     |
| NMC       | 150             | 6.3–8.3         | GOT     | BCN     |
|           | 200             | 4.5–5.5         | GOT     | BCN     |
|           | 300             | 3.3–3.6         | GOT     | OSN     |

The chemistry most benefiting from the capacity increase turns out to be LTO, mainly when the capacity is increased more than 25%. In the three scenarios (BCN, GOT, and OSN) similar tendencies are observed: 30% lifetime increase with a 25% capacity increase, and 92% lifetime increase with a 67% capacity increase.

Regarding LFP, it is at the borderline of the cost-efficiency in all the cases: 50% lifetime increase with a 50% capacity increase and a 96% lifetime increase with a 100% capacity increase. Therefore, it can be concluded that LFP is not much benefited by the capacity increase.

Finally, the graphs from Figure 12 show that the cost-efficiency of increasing NMC capacity depends on the scenario. In BCN and OSN, increasing the capacity becomes cost-efficient: with a 33% capacity increase, the lifetimes are increased by 50% (BCN) and by 43% (OSN), and with a 100% capacity increase the lifetimes are increased by 135% (BCN) and by 106% (OSN). However, in the GOT scenario, cost efficiency is only obtained when increasing the capacity by 33% (38% lifetime increase), as with a 100% capacity increase the lifetime is only increased by 93%. This reinforces the idea that NMC is more sensitive to the scenario characteristics than LTO and NMC, as was already concluded in the previous sensitivity analysis.

The obtained results are summarized in Table 12. The variable lifetime improvement ratio defines how much the BT lifetime is improved when oversizing it (value 1 defines that the lifetime is improved by 25% when increasing the BT size by 25%).

Table 12. Summary of results for the sensitivity to the battery capacity.

| Chemistry | Lifetime Improvement Ratio (%/%) | Minimum | Maximum |
|-----------|--------------------------------|---------|---------|
| LTO       | 1.15–1.16                      | OSN     | GOT     |
| LFP       | 0.98–0.99                      | OSN     | GOT     |
| NMC       | 0.97–1.18                      | GOT     | BCN     |

In short, increasing the battery capacity is appropriate for LTO, especially the more the capacity is increased. In NMC the capacity increase is also appropriate, but in this case, the oversizing should not be very high. And for LFP, the recommendation is not to increase the battery capacity very much, as the benefit is barely visible.

4. Conclusions

This paper has evaluated the effect of fast charging on LIB degradation under operation profiles from real BEB driving cycles. Specifically, 1-year driving cycles from three European cities (BCN, OSN and GOT) have been simulated in a Matlab/Simulink-based platform. Each driving cycle is characterized by different characteristics related to the fast charging and battery degradation (e.g., frequency of charging activities or route overall demand), what has enabled analyzing their effect on battery degradation. The paper has also analyzed
how an appropriate design of the fast chargers and the battery systems (definition of chemistry and size) can mitigate the negative effects of fast charging on the batteries degradation. For this approach, a methodology based on two sensitivity analyses has been proposed: on the one hand, the effect of varying the fast charger size has been analyzed; and on the other hand, the effect of varying the battery size. The sensitivity analyses have been replicated for the different battery technologies (LTO, NMC and LFP) and with the operation profiles of the mentioned European cities (BCN, OSN and GOT). Both sensitivity analyses have unveiled that LTO is the chemistry with the lowest degradation under fast charging profiles. On the contrary, NMC is the chemistry most degraded in the analyzed scenarios. Comparing the results of the different operation profiles, NMC suffers the highest degradation in BCN, which is the scenario where the highest DOD is realized. LTO and LFP suffer the highest degradation in OSN, a scenario with higher demand and charging frequency compared to BCN. Therefore, it has been concluded that NMC is more sensible to the DOD than LTO and LFP.

Regarding the sensitivity analysis to the charger power, additional conclusions have been obtained. NMC is the chemistry most benefited from the charger downsizing: the degradation can be reduced up to 30% when reducing the charger capacity by 50%. In contrast, the degradation of LFP is not sensitive to the charging power, as it stays unchanged when reducing the charger size.

Finally, some other conclusions have been obtained from the sensitivity analysis for battery size. LTO is the chemistry most benefited from a capacity increase, especially when the increase is higher than 25%. In the best case, the lifetime is increased by 94% when increasing the capacity by 66%. In order to obtain a cost-efficient solution, the lifetime increase has to be higher than the capacity increase. Therefore, increasing the LTO capacity is a cost-efficient solution. LFP is maintained around the borderline of the cost-efficiency in all the cases (50% lifetime increase with a 50% capacity increase, and a 96% lifetime increase with a 100% capacity increase). Therefore, it can be concluded that there is not much benefit when increasing its capacity. Eventually, it has been concluded that oversizing NMC is cost-efficient when the capacity increase is not very high: around 38–50% lifetime increase when increasing the size a 33%. At higher sizing increases, the cost-efficiency is reduced.

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