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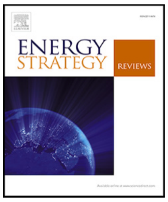

Review

Charging strategies and battery ageing for electric vehicles: A review

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ABSTRACT

Introducing electric vehicles in society requires access to charging infrastructure and a robust electric grid. This development concernsstrategic planning of policymakers. However, much uncertainty still exists about how new charging strategies affect the vehicle batteries, due to the fast development. This review article provides an overview of recent literature on how electric vehicle batteries are aged during different charging strategies, such as conductive charging, inductive charging, and battery swapping. This study finds that some charging conditions, such as fast charging at low temperatures, degrade batteries faster. Battery ageing is a non-linear process and depends on, for example, temperature, charging current, and state-of-charge. The high charging rates strongly influence battery degradation. It is concluded that there is a trade-off between faster charging and a longer battery lifetime. There is an interest in vehicle-to-grid to add revenues and grid flexibility. However, the related battery degradation needs to be further investigated. A key challenge in the decision-making process is to plan for charging infrastructure suitable for electric vehicle owners while contributing to the long life of electric vehicle batteries and ensuring socially acceptable and economically viable solutions. More interdisciplinary research in this field is recommended to support the clean energy transition.

Contents

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List of abbreviations

AC	Alternating current
B2G	Battery-to-grid
BEV	Battery electric vehicle
BMS	Battery management system
BTMS	Battery thermal management system
C-rate	Charging rate
CET	Clean energy transition
CC	Constant current
CC-CV	Constant-current constant-voltage
CCS	Combined Charging System
CP	Constant power
CT	Constant temperature
CV	Constant voltage
DC	Direct current
DoD	Depth-of-discharge
EOL	End-of-life
EV	Electric vehicle
FCS	Fixed charging station
GPR	Gaussian process regression
IPT	Inductive power transfer
IEC	International Electrotechnical Commission
ISC	Internal short-circuit
LAM	Loss of active material
LIB	Lithium-ion battery
LLI	Loss of lithium inventory
NMC	Nickel-Manganese-Cobalt
MCS	Mobile charging station
ORI	Ohmic resistance increment
OBC	Onboard charger
PHEV	Plug-in hybrid electric vehicle
PC	Pulse current
RUL	Remaining useful life
SEI	Solid electrolyte interphase
SOC	State-of-charge
SOE	State-of-energy
SOH	State-of-health
SOX	State-of-everything
TR	Thermal runway
V2B	Vehicle-to-building
V1G	Controlled charging
V2G	Vehicle-to-grid
V2H	Vehicle-to-home
V2X	Vehicle-to-everything
WPT	Wireless power transfer
XFC	Extreme fast-charging

1. Introduction

To meet the sustainability goals, the development of an electrified transportation sector relies on electric vehicle (EV) battery systems, reliable and affordable access to charging infrastructure, and a robust electric grid. The clean energy transition (CET) of the mobility sector includes decarbonized transportation. The EVs can enable the CET by electrifying the transport sector and contributing to enhanced flexibility in the energy system, and there is ongoing and rapid development in this area. Therefore, the EVs and charging strategies are important to study continuously to support the CET. The overall energy policy debate includes perspectives on how the transportation sector can be electrified and what needs to be done with the transportation systems and energy systems to contribute to the CET. Available charging infrastructure is important to ensure that the EV is charged before and during a trip. Access to charging infrastructure and wide-reaching battery capacity mitigate range anxiety. There are demands for shorter charging times for future EVs, to come closer to the limited time and trouble when refueling a vehicle with an internal combustion engine, but the questions on how to get there remain. To meet the needs of EV users, new charging strategies are being introduced. However, the charging strategies affect the EV batteries differently and affect the batteries both in the short and long term. It is still unclear how the EV batteries are degraded from different charging strategies.

The questions regarding EV charging relate to decisions and planning of policymakers and industries on how, where, and to what extent the charging infrastructure needs to be deployed at the national-, regional-, and city scales. Also, it relates to resource management for battery systems and investments in the transportation system. To enhance the amount of EVs in society, there is a need for infrastructure investments. The charging infrastructure should be widespread enough and available in different parts of a region to meet the EV charging needs for various types of trips. The existing EV battery market mainly focuses on one type of battery chemistry, and a large size of batteries for EV applications. However, the future battery market could have different types of battery chemistry and smaller batteries, to reduce costs and the resources needed. The ongoing electrification of the transportation sector comes with new business models and new actors e.g., owning and operating the charging stations or battery swapping stations, working with EV manufacturing, and new actors are taking place in the transportation sector, such as the electric grid owners and electricity suppliers. Therefore, the ongoing CET of the mobility sector requires an analysis of technical, financial, and societal aspects.

Cable charging, i.e., conductive charging, is the most established way to charge an EV today. Cable charging is used at home, work, or a public charging station [1]. Home charging with alternating current (AC) may take several hours, and EV charging can occur when the EV is plugged in at home at nighttime. Opportunistic home charging is charging at home that is initiated as soon as the EV arrives there provided that the battery is not fully charged [2]. Opportunistic home charging plays an important role, as it is commonly used today. In contrast, charging with direct current (DC) can be used at higher power levels at a public charging station to provide faster charging. The public DC fast charging infrastructure is installed along the roads in society to meet the driver needs for private vehicles and heavier EVs. While fast charging may interest the EV owner, fast charging can result in enhanced battery degradation, limiting the overall lifetime of the EV. There are many expectations from an EV owner, as summarized in Fig. 1, that could affect the way that the EV battery is being designed and the implementation of new charging infrastructure in society.

This review article provides an overview of recent scientific literature analyzing how different charging strategies affect the EV battery. The paper investigates how the following charging strategies affect battery degradation; cable charging (i.e., conductive charging), smart charging including vehicle-to-grid (V2G), battery swapping, mobile charging, and wireless charging (i.e., inductive charging). The aim of this paper is to provide an overview of EV charging strategies and battery degradation, based on published scientific literature. The motivation for this review paper is to contribute to filling identified research gaps on how EV batteries are degraded, today and in the future, due to different charging strategies. Previous review papers mainly focus on only charging strategies, e.g., [3], or battery degradation, e.g., [4]. In contrast, this review paper contributes to analyzing recent scientific research on both aspects and how they may affect each other. There is a need to investigate EV battery degradation and EV charging strategies

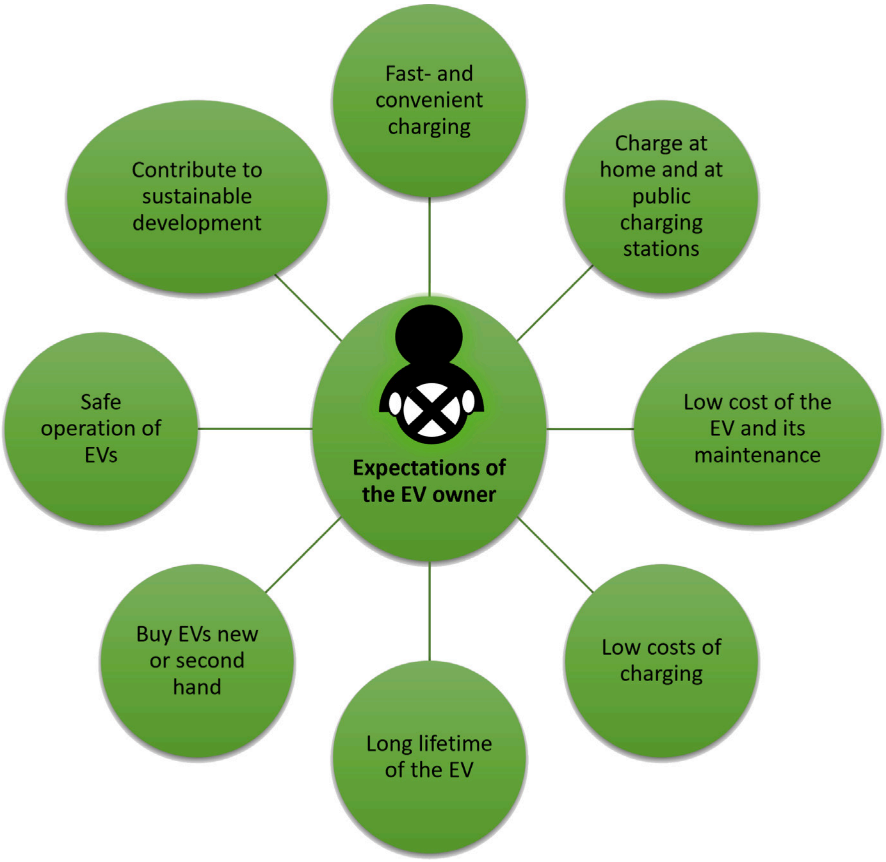


Fig. 1. An overview of the potential expectations from an EV owner on e.g., the vehicle and the access to charging infrastructure.

due to the rapid development of e.g., EVs, batteries, charging infrastructure, and charging strategies. There are several uncertainties and challenges in understanding how EV batteries can be degraded under different EV charging strategies. However, an improved understanding of the interrelation between charging and battery ageing can provide opportunities, such as new business models and potentially longer life of the EV. The focus of this paper is technical, but it also includes a discussion on e.g., new business models and sustainability aspects. Contributing to the knowledge of how EV batteries age during different charging scenarios is important as there are significant costs and resources related to the EV batteries and charging infrastructure. The paper is limited to studying only recent scientific literature from 2019 and onwards, focusing on fully battery electric vehicles with a main focus on the lithium-ion battery (LIB). Studies published before 2019 were excluded from this review paper, to focus on the recent scientific literature in the area. The international scientific literature was found in relevant databases, e.g., ScienceDirect.com, Scopus.com, and IEEE Xplore. The search phrases used included keywords such as "electric vehicle", "charging", "battery degradation" and "battery ageing", with a focus on technical aspects. This review article could support policymakers in planning and decision-making concerning electrified transportation systems.

The review paper is structured as follows; Section 2 provides a background to charging standards for cable charging, Section 3 describes the different ageing mechanisms for lithium-ion batteries in vehicles, and Section 4 describes different charging strategies and their effects on the vehicle battery. In Section 5, additional approaches to handling the battery degradation are discussed. In Section 6, the results are summarized and discussed. Finally, the conclusions from the in-depth literature review are presented in Section 7.

2. Charging standards

The time it takes to charge an EV relates to the power level of the charging and the capacity of the EV battery. Typically, high-power charging strategies with DC charging take less time than charging at lower power levels with AC charging. The charging rate (C-rate) describes how fast the battery will be discharged, where 1C means that the battery will be discharged in one hour with the current used [5]. For faster charging, the C-rate is higher. The opportunity to charge at different power levels and places is useful to meet the varied preferences of EV owners. The charging patterns for a group of battery electric vehicle (BEV) owners and plug-in hybrid electric vehicle (PHEV) owners during a week in the US were investigated with a survey in [6], concluding that the charging mainly occurred at home. But also, it was found that almost 38% of the respondents with a BEV charged at more than one place, such as at home, at the workplace, and a public fast charging station. Also, the power levels for the charging varied over the week.

Social, technical, and financial aspects are important to consider and affect the opportunity to buy and own an EV. The high cost of EVs relates to e.g., the battery size and battery technology, as the battery is an expensive part of the vehicle. Placement, cost, and access to charging infrastructure relate to aspects of justice and social equity, on being able to purchase and own an EV today [7]. Charging infrastructures are costly investments. However, if charging stations were available to a larger extent in society, providing fast and reliable charging, the EV batteries could perhaps become smaller and the EVs could potentially be reduced in price [8]. Therefore, investments in charging infrastructure for cost-effective access to fast and reliable charging and new business models to support the transition could affect the EV manufacturing process and perhaps reduce the interest in large and expensive EVs with big batteries, in favor for cheaper EVs, and thereby accelerating the deployment of EVs and the CET of the transportation sector [8]. On the other hand, the smaller EV batteries may require higher C-rates, which could lead to enhanced battery degradation and a shorter EV life, as discussed in [9], and enhanced fast charging infrastructure could be costly for society. Access to available and fully functional charging infrastructure where the charging is needed is important to meet the demands of the EV owners. The charging infrastructure needs to be operated with safety in focus, e.g., due to the high power levels of the electrical systems, potential risks of fire, and issues regarding data security during the charging sessions [3]. Future trends and technological innovations in charging infrastructure include e.g., combining the charging infrastructure with renewable energy sources, and designing and developing the fast charging infrastructure, to meet the demand for shorter charging times and effectively charge different types of EVs [3].

From an international perspective, there are different charging standards for EV charging with a cable. As described in [10], the International Electrotechnical Commission (IEC) standards are used in Europe [11], the SAE standards are used in the United States [12], and the GB/T standards are used in China [13]. These standards include information on e.g., safety during charging and the connector type for conductive charging. The connector types include e.g., Mennekes, CHAdeMO, and Combined Charging System (CCS) [10]. Moreover, the charging standards relate to different power levels for the charging, relating to the time it takes to charge an EV. Some more information on the different cable charging standards is provided here, based on data from [10]. For the IEC charging standard, Level 1 (AC) is specified to 16 A, 250 V for one phase and 480 V for three phases, 4–7.5 kW. Level 2 (AC) charging includes up to 32 A, 250 V for one phase, and 480 V for three phases, 8–15 kW, and Level 3 (AC) charging provides up to 250 A, 480 V, and 60–120 kW. For DC charging, the IEC standard includes Level 4 with off-board charging (max 400 A, 500 V, and 1000–2000 kW) [10]. The SAE charging standard includes two AC charging levels, namely Level 1, with charging power up to 1.9 kW, and Level 2, up to 19.2 kW [10]. Also, the SAE charging standard includes three DC levels, Level 1–3, providing 40–240 kW. The GB/T standard includes three AC levels, Level 1–3, with the power level of 27.7 kW and 8 A, 16 A, and 32 A current, and one DC level, Level 4, providing 250 kW [10]. Therefore, the higher charging levels of the IEC-, GB/T- and SAE charging standards all have higher power levels and shorter charging times. The lowest charging level (AC, Level 1) for the different charging standards may take around 7 h. The IEC- and the GB/T charging standards have one level for DC fast charging (Level 4), whereas the SAE charging standard, in comparison, has three different levels for DC charging (Level 1–3) [10], and the charging time for DC charging is around a couple of minutes. Access to cost-effective and reliable charging infrastructure is a major contributor to wide EV adoption.

3. Battery ageing

3.1. Calendar ageing and cycle ageing for vehicle batteries

The functionality of the EV battery will differ to some extent during the battery lifetime. Battery ageing related to calendar ageing is ageing when the battery is not in use, and where no current is passed through the battery [14]. Battery ageing based on calendar ageing occurs when stored batteries may be affected by temperature, time, and state-of-charge (SOC), and calendar ageing was modeled in [15]. Therefore, calendar ageing may occur at the manufacturer or in the shop, where the battery can degrade due to long storage time and possible extreme temperatures [16]. In contrast, battery ageing due to cycle ageing is when the battery is used, for example when the EV is being charged and discharged [17]. The cycle aging of a battery relates to e.g., the depth of charge, depth-of-discharge (DoD), temperature, and C-rate [16]. A review on battery aging during a battery life cycle was presented in [4], including an overview of aging due to internal- and external aspects, design, manufacturing, and aging on cell level or battery pack level. Both calendar aging and cycling aging typically occur for a battery used in an electric car [18].

The battery is estimated to have a certain lifespan, including a remaining useful life (RUL), until the battery reaches its End-of-life (EOL) [16]. The battery capacity degrades faster when the battery reaches its EOL [19]. The capacity of a battery is described as the specific energy in ampere-hours (Ah) [20]. The SOC is the rate between the remaining capacity and the nominal (i.e., maximum) capacity of the EV battery [21,22]. The EV SOC may be seen differently from the EV user perspective and from the technical side of the battery, where the user often sees a lower SOC range presented, around 20%–90% of the real battery SOC, to ensure safe operation and limited battery ageing [23]. Both the battery capacity can fade, meaning that the energy storage of the battery is lowered, and the battery power can fade, meaning that the power that the battery can provide is decreased due to degradation [24]. It was estimated that, after 6.5 years, the EV battery capacity was lowered by 10%. Also, it was estimated when 70%–80% of the rated battery capacity remains, the battery reaches its EOL [19]. At an initial stage, battery capacity fading is a rather slow process, whereas after a specific knee-point, the battery aging occurs much faster [25].

The popular LIBs, used widely in EVs, may have challenges regarding safety if parts of the system are malfunctioning [26]. This, in terms of e.g., thermal runway (TR), severe fire and damage. The safety issues imply that the vehicle batteries should be carefully investigated and monitored continuously. It is relevant to carefully monitor any thermal-, electrical- or mechanical damage, or battery ageing, such as due to charging or discharging at high power rates at either high- or low temperatures [26]. As the battery ages, the safety properties may change and the ageing is a non-linear process [26]. The work in [27] found e.g., that when it comes to calendar aging, high temperatures and medium SOC-level may lead to high battery capacity loss. Moreover, it was noted that the cycle aging was enhanced due to both very high- and low temperatures, high C-rates, or low charging currents together with high temperature, as this could result in longer charging periods in unfavorable temperatures [27]. In [16], it was also noted that batteries stored at high temperatures, at around 60 °C, showed both enhanced calendar aging and cycle aging.

A battery degradation model, based on estimations of both calendar- and cycling ageing of EVs, was proposed in [28], with calculations of calendar ageing based on storage temperature of the batteries, time, and SOC. Whereas, the parameters for calculating the cycle ageing included temperature during the cycling, C-rate during charging and discharging, DoD, and the charge throughput, meaning the amount of charge delivered by the battery (Ah). These are factors affecting the calendar- and cycle ageing, suitable to include as parameters when calculating and estimating the battery degradation, as presented in [28]. An overview of the aspects regarding EV battery degradation and several EV charging strategies and presented in Fig. 2. Previous studies concerning EV battery degradation and the EV battery lifetime observed that the EV battery degradation relates to both calendar- and cycle ageing. The variations in EV use, including e.g., differences in driving patterns and charging patterns, contribute to the complexity when estimating the battery ageing of an EV battery. A well-designed battery management system (BMS) and suitable charging- and discharging strategies are needed to manage the EV battery to ensure a long time before the EOL. Therefore, it is concluded that these aspects require more research, development, and experimental work to enhance the lifetime of future EVs.

3.2. Estimation of battery health

The BMS must make the correct estimation of the SOC value of the EV battery, as this otherwise could be a safety issue [21,22]. However, estimating the SOC, the knee-point, and the RUL of an EV battery is

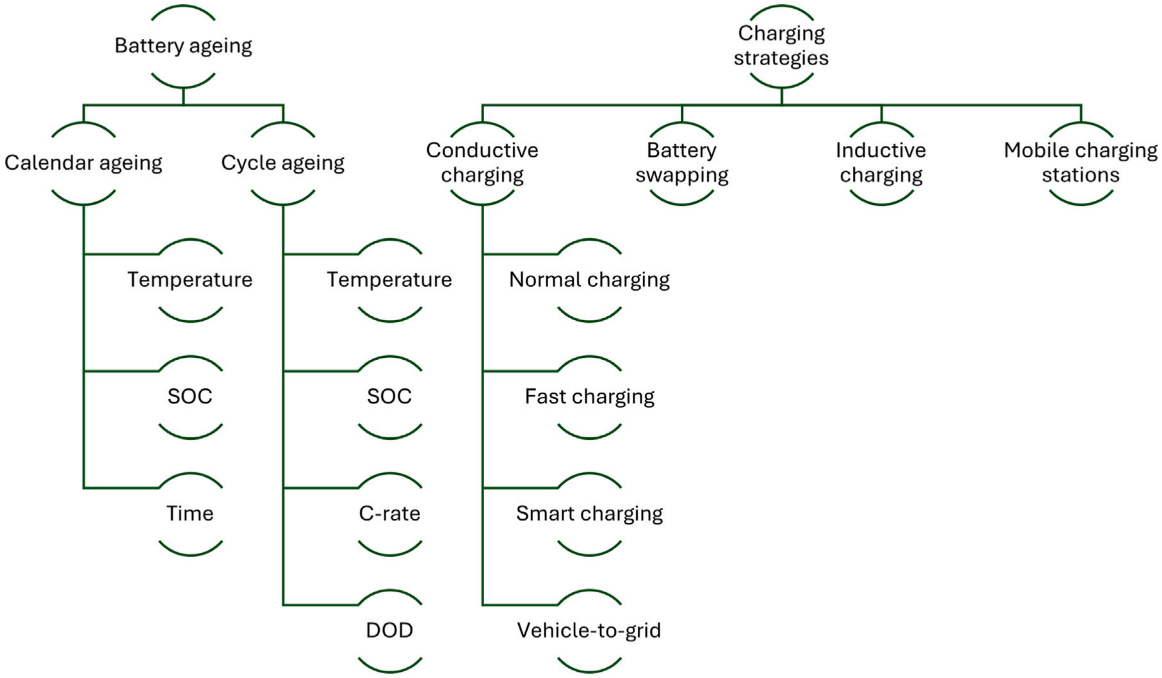


Fig. 2. Overview of aspects affecting battery degradation, including calendar- and cycle ageing [28], and an overview of different charging strategies [3].

complex, and several studies have investigated how this can be done. It was highlighted in [21], that four typical ways of estimating the SOC value are based on: (1) modeling of the battery, (2) utilizing data-driven methods, (3) ampere-hour integration, and (4) direct measuring [21]. Deep learning algorithms were used in [29] to model the capacity degradation of EVs on the road based on charging data, including e.g., information on SOC, current, voltage, and temperature. The battery behaves non-linear and the SOC needs to be estimated by the BMS avoid over-charging or over-discharging. In [30], the SOC was estimated using a so-called Coulomb counting-based unscented Kalman filter modeled in MATLAB. To estimate the SOC, as well as predicting the knee-point and the RUL, machine learning techniques were utilized and discussed in [25]. In [31], the RUL and the knee-point were estimated by investigating the SOC window of batteries from 80% to the cut-off voltage, when charged with constant current (CC) charging, with a method based on the Gaussian process regression (GPR). The battery health describes the battery capacity compared to what the battery is expected to perform at the initial stage of the battery lifetime. The state-of-health (SOH) is a measure of the remaining capacity of the battery in comparison to the initial battery capacity. The SOH value in percentage denotes the ratio between the current cycle's maximum available capacity and the rated battery capacity. SOH is also complex to estimate [32]. Both the SOC and SOH are relevant to carefully monitor to ensure a safe battery operation [21,32,33]. The state-of-everything (SOX) concept includes monitoring of SOC, SOH and state-of-energy (SOE). SOE includes information about the energy in the battery [34].

System measurements could support the estimations of the EV SOC. There is for example a relationship between the open circuit voltage (OCV) of the battery and the SOC of the battery, also affected by temperature and battery aging [22]. In [22], a specific temperature was chosen for measurements during charging and discharging to decrease the effects on SOC and OCV due to temperature variations. The OCV was estimated based on deep learning models in [35], to gain knowledge on battery health. The measurements of EV battery SOH can be done in a lab or during charging if the EV is in use [36]. There are more new techniques to identify how the battery is degraded. The charging data for a specific segment of the charging current for lithium-ion battery cells and information on the battery capacity were visualized as gray-scale images and analyzed with computer vision in [37], to identify patterns relating to battery capacity degradation. The aim was to support estimations of battery degradation with limited charging data. In [38], electrochemical impedance spectroscopy was utilized to identify ageing of LIB with nickel-manganese-cobalt (NMC) cathodes, for different cycling profiles.

To effectively measure the SOH of an EV could support the development of the second-hand EV market by estimating an appropriate value of the EV [27]. The second-hand market of EVs could contribute with several benefits such as cheaper EVs, improved resource management, and a more widespread EV adoption, contributing to the CET of the transportation sector. The EVs could be used longer if the second-hand market of EVs was expanded and new business models could support this development. Furthermore, the old EV batteries could also be used for other purposes and in other applications, e.g., as stationary energy storage in buildings or industries. It is important to estimate the battery health before using the old EV batteries in new applications. The SOH value was estimated experimentally for both battery cells and full EVs, by using incremental capacity analysis in [27]. The experiments included the identification of characteristic valleys and peaks in the resulting incremental capacity curves, related to different aging mechanisms of the battery. There are typically predefined voltage limits of the EV batteries that are defined by the manufacturer to ensure safe operation [27]. SOH forecast methods and analysis based on real data from several EVs were presented in [39]. The typical warranty levels for batteries are around 70%–80% SOH. Then, the ageing mechanism called lithium plating may enhance rapidly [40]. Prior studies have noted the importance of estimating the battery health and monitoring battery system functionality, especially due to the non-linear behavior of the battery degradation, to ensure that the EV works safely.

3.3. *Ageing mechanisms for vehicle batteries*

Battery degradation of the LIBs in EVs can occur due to several reasons, and there are many ageing mechanisms [41]. Table 1 provides an overview of the different battery ageing mechanisms and how they relate to several important features, such as temperatures and SOC-rate [23,40]. Batteries are probably the most expensive part of an EV and most other components in the vehicle may also have a longer

Table 1
Degradation of lithium-ion battery due to different stress factors, presented in [23,40].

Features	Battery ageing mechanisms
Temperature.	Higher SEI rate of growth, resulting in higher electrolyte usage, causing gas formation and dissolved metals from the positive electrode [23]. SEI growth from high temp. causes battery capacity fade and increased resistance, due to lack of available lithium, and may enhance lithium plating [40].
Low temperature (subzero ambient temperatures) or cooling.	No thermal preconditioning of battery (i.e., limited self-heating) decreases the functionality of the battery for e.g., fast charging [40].
High charging rates (and high SOC values or low temperatures).	Deposition of lithium on the carbon electrodes, affecting the battery cell, including aspects regarding the lithium and lower active material in electrode, causing reduced availability of battery energy [23], i.e., lithium plating [40].
High SOC	Not stable tri-metallic positive electrode structure, resulting in a low potential in comparison to the lithium on negative electrode, causing SEI growth. This results in higher electrolyte usage, causing gas formation and dissolved metals from the positive electrode [23].
High DOD (and high discharge current)	Particle fracturing [23].

lifetime than the battery [24]. When the battery degradation or SOC is varied due to charging or discharging, the battery cell changes volume with the swelling effect, resulting in a stack pressure inside the batteries, meaning that the cells swell and add pressure on the other cells, and this was estimated in [42]. Some different stress factors of batteries in EVs are cell temperature, SOC ranges, and the rate of charging or discharging, calling for reliable durability tests [23]. It is described in [43] that two issues affecting the battery aging are the charging current and the EV battery temperature, due to ambient temperature, cooling, and charging/discharging [43]. EVs can be charged at indoor- or outdoor charging stations, and it was found in [43] that the indoor alternative resulted in less EV battery aging and lower management costs.

It was described in [44] that the battery capacity decay of LIBs relates to several aspects; (1) loss of active material (LAM) relating to damage and loss of material based on dissolved parts of manganese and iron, (2) loss of lithium inventory (LLI) relating to the solid electrolyte interphase (SEI) layer growth and (3) ohmic resistance increment (ORI), based on loss of electrolyte, SEI film- and contact resistance. The ageing is due to the battery use, temperature, charging current, DoD, etc. [44]. The authors in [45] studied battery ageing in different SOC windows, finding that the degradation occurred faster for particularly high or low SOC values, with the worst degradation below 25% SOC due to LLI and LAM. Based on the study [45], the longest lifetime relates to cycling for SOC windows at around 35% to 55%.

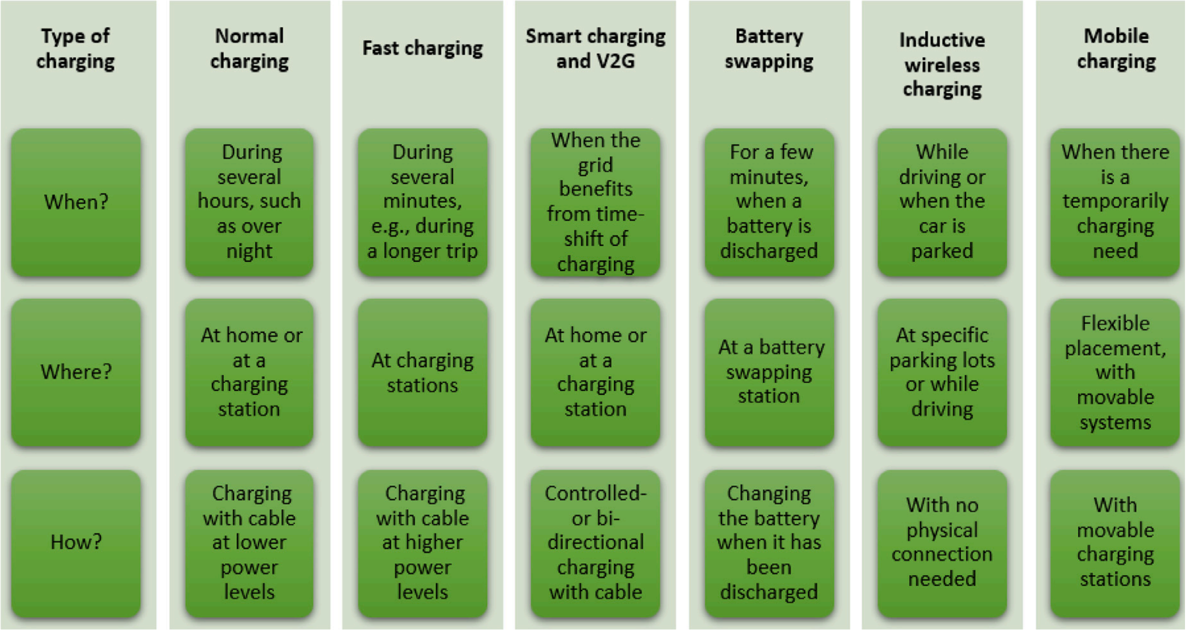
The LIBs are highly influenced by ageing due to the temperature. This is for example because of an enhanced SEI growth when the battery is under high temperatures, and lithium plating under low temperatures, suggesting that a temperature around 25 °C could be suitable for many batteries [18]. In [46], the battery degradation from long-term usage of EVs with LIBs was investigated, which could be useful to support decision-making in battery warranty, user charging- or driving behavior, costs of owning the vehicle, etc. There is a trade-off for the LIBs between high battery capacity and high charging power, and there is an interest in batteries adapted for both high energy and high power, without significant lithium plating [40]. Different battery cells were tested for degradation in [47], confirming e.g., that a high temperature increases the degradation for all the tested cells, but that the overall degradation is affected by battery cell chemistry. The literature on battery degradation has highlighted several degradation mechanisms, which are sometimes interrelated. A better understanding of battery degradation mechanisms can be of interest when the transportation sector is electrified, as the battery is an expensive part of the EV.

3.4. Safety of batteries in vehicles

Safety is of main concern when designing battery systems for EVs. The battery thermal management systems (BTMS) of the LIBs in EVs were analyzed in [48]. The author finds that the main benefits of LIBs are the high energy density and low costs and that the drawbacks relate mainly to thermal issues, especially too high temperatures during charging or discharging. Safety issues include TR, when the heat produced from the battery is enhanced so rapidly, due to a malfunction in the thermal-, electric- or mechanic parts of the system, that the battery cannot manage the heat dissipation properly, causing damage and potential temperatures of up to 200 °C [48]. The BTMS should designed for EVs used in both high and low temperatures. The low temperatures may lead to significantly lower power and energy of the battery system and potentially limited use of regenerative braking. The higher temperatures may cause an effect on the charging and discharging of the batteries, and managing temperature variability was discussed in [48].

Different problems with EV battery safety were summarized in [49] to internal- and external short circuits, overheating, overcharging, over-discharging, and cell inconsistency. To identify battery issues, the authors in [49] propose a model based on identifying abnormal battery voltages for an integrated battery model. The batteries of the EVs can be affected by mechanical damage, thermal failure including TR or overheating, or electrical damage including internal short-circuiting (ISC), overcharging, if the current and voltage are higher than the safety level, and over-discharging, also related to the safety level [50].

A fault diagnosis method could be applied to identify errors in the LIB used in an EV. In [51], the authors propose and experimentally test a fault diagnosis tool used during charging, based on the terminal voltage of the battery cells, to identify any of the following issues of the battery pack: low SOC, a low cell capacity, faults concerning the internal resistance, and external short circuits. The accidents related to ISC during battery charging, including float charging, can be severe and there are studies focused on early identification of ISC [52]. The ISC faults can co-exist and correlate with battery ageing, with potential risks of TR. Therefore, the identification of the overall battery health relates to being able to diagnose both the ISC faults and the battery ageing during charging or discharging, as presented in [53], where the ISC faults may relate to enhanced leakage currents. Overall, these studies highlight the need for more research on battery control and monitoring, especially during EV charging or discharging, due to the risks of TR or fire.



Type of charging	Normal charging	Fast charging	Smart charging and V2G	Battery swapping	Inductive wireless charging	Mobile charging
When?	During several hours, such as over night	During several minutes, e.g., during a longer trip	When the grid benefits from time-shift of charging	For a few minutes, when a battery is discharged	While driving or when the car is parked	When there is a temporarily charging need
Where?	At home or at a charging station	At charging stations	At home or at a charging station	At a battery swapping station	At specific parking lots or while driving	Flexible placement, with movable systems
How?	Charging with cable at lower power levels	Charging with cable at higher power levels	Controlled- or bi-directional charging with cable	Changing the battery when it has been discharged	With no physical connection needed	With movable charging stations

Fig. 3. An overview of different charging strategies and some aspects concerning time, place, and the overall system.

4. Different charging strategies and battery ageing

4.1. Normal charging and battery ageing

A short summary of different charging strategies, and aspects regarding time, place and the overall systems, are presented in Fig. 3. Charging with a lower power level is sometimes called normal charging, and can occur e.g., at a service station or at home. If a lower power level is used for the charging, the battery ageing is slower than if a higher power level is used, but the charging time takes longer. The difference in charging time can be significant. The charging time for a personally owned EV could be 7 h with normal charging, in contrast to DC fast charging, which could take up to around 30 min [10]. The typical EV is parked mostly, often connected to a charging pile. Charging overnight could take several hours. The battery degradation relevant for a parked car with overnight charging was analyzed in [54] for different outdoor temperatures and lower power levels, with a C-rate below 1. It was concluded that the most favorable charging curve for slow charging relates to a suitable temperature and battery states.

It is noted that an EV owner often changes between different charging protocols, i.e., charging levels, for the same vehicle, from normal charging to fast charging, and that the EVs are seldom used for charging/discharging from 0%–100%, resulting in additional charging cycles contributing to battery degradation [55]. In [55], different charging protocols were evaluated concerning battery ageing; a pulse charging protocol, a constant-current constant-voltage (CC-CV) charging protocol, and two types of multistage constant-current (CC) protocols. The pulse charging protocol resulted in the lowest battery degradation in the test [55]. Together, the studies indicate that while normal charging takes a long time, this charging strategy could result in limited EV battery degradation.

4.2. Fast charging and battery ageing

The public charging infrastructure could be useful for EV owners without access to charging points at home or needing to charge at different locations during longer trips. In a comprehensive study on public charging stations [1], a need to improve the understanding of e.g., time and travel patterns concerning public charging and payment methods for charging were identified. How suitable a specific location is for the charging infrastructure, such as public charging stations for fast charging, depends for example on the size of the system and the availability and strength of the local electric grid [56]. Public charging stations are often providing fast charging and shorter charging times.

To go from 10% battery capacity to 80% in only 15 min for a BEV is a significant challenge, especially while also ensuring a long battery lifetime and no TRs [40]. The C-rate for fast charging could be at least 2C [57]. Too high charging currents may cause lithium plating, and too high charging temperatures can lead to SEI growth, lowering the available lithium and leading to lower capacity and higher resistance [40]. Furthermore, the SEI growth could enhance lithium plating. It is noted that temperature, SOC, and SOH should be monitored and controlled, especially in fast charging sessions to ensure safe battery use [40]. Different charging sequences have been investigated to improve fast charging and battery longevity. However, there is a problem with investigating fast charging when the operation conditions change during the charging session [40]. In [40], a fast charging strategy is proposed and adapted based on real SOH, SOC, and temperature. This charging strategy was compared to the more commonly used CC charging cycle. It was concluded that fast charging should be used carefully and only to a certain degree, to limit battery degradation. SEI growth is described in [58] as one of the more predominant factors causing the ageing of LIBs with graphite anodes. A charging strategy model, including constraints e.g., in terms of voltage- and temperature levels, was presented in [58] and validated based on experimental data, to consider charging and battery ageing based on SEI growth, lithium plating, and loss of active material.

Extreme fast charging (XFC) is suggested to ensure that the charging time is limited to a maximum of 15 min to reach 80% SOC, without significant degradation of the battery [59]. However, as noted by the authors of [59], the fast charging will require development and research in LIBs as the charge rate is enhanced resulting in lithium plating which degrades the batteries. Design strategies for handling the lithium plating in batteries are e.g., managing the heat, or redesigning electrolytes, electrodes, or charging protocols [59]. A thermal strategy, where the cooling of and heating from the battery is adjusted during the charging event, was proposed in [59]. The charging infrastructure and the power electronics inside the vehicle rated for higher power levels, such as for XFC, are expected to be more expensive than for lower charging rates [46]. It was found in [46], that for a specific case of modeling an EV, the DC fast charging, with 60 kW, affected the battery lifetime in ten years, resulting in 67% battery capacity left after ten years. While the Level 1-charging, with 1.8 kW would result in 86% of battery capacity left after ten years of usage. As highlighted in [23], the charging of EVs affects the battery ageing based on the charging power level and the charging frequency. High charging power may cause particle fracturing, formation of lithium metal on the negative electrodes, and gathering of lithium in different parts of the battery. If the charging is done at high power rates, low temperatures, or high SOC values, the negative processes for the EV battery are enhanced. The difference between normal- and fast charging concerning thermal effects on the battery pack was investigated in [60]. The authors found e.g., that a high ambient temperature together with fast charging, such as charging at 50, kW, 175 kW, or 350 kW, and a limited time to cool off the system again, may lead to battery faults based on thermal issues, especially for some types of drive cycles [60].

As highlighted in [57], the risk of failures increases with fast charging strategies of EVs, suggesting that the enhanced battery aging, based on e.g., enhanced SEI growth and lithium plating, needs to be carefully monitored with active diagnosis. Experiments performed in [26] were done to investigate safety at high power rates, due to fast charging, for charging and discharging of LIB batteries. The authors described that the ageing process had three steps: (1) SEI growth, (2) SEI growth and loss of active material, and (3) SEI decomposition generation, loss of active material, and lithium plating. It was noted that aged batteries, charged or discharged at high rates, may be more likely to cause severe and outspread TR [26].

Therefore, charging the EV battery includes managing the two problems that contradict each other: charging fast enough, with a high C-rate, to ensure a convenient user experience, and providing a longer battery lifetime. The battery lifetime could be lowered due to high C-rates and high temperatures during the charging sessions [61]. Thus, a charging profile must be carefully chosen and the BMS has to control the charging process. In [61] the study includes a reinforcement learning method for the trade-off between high charging current and high battery temperature, to ensure that a LIB of the EV is not overheated by keeping the temperature below a certain limit, while still charging the battery quite fast. Several different steps relating to battery degradation in fast charging sessions were identified in voltage curves and categorized to find a general pattern for battery aging during fast charging in [62], based on fast charging protocols from [63]. Furthermore, the way that the EV is driven in different parts of the world affects the lifetime of the battery, and the combination of several driving profiles with starts and stops, various terrains, and charging strategies may together affect the degradation of the vehicle battery [64]. It was found that fast charging in EU, USA, and Australia may result in a more rapid battery degradation than in e.g., Japan, due to the local traffic situation and driving profiles [64]. The battery degradation depends on the ambient temperature as well as where the charging occurs. Charging the EV in a cold climate, with lower surrounding temperatures, significantly lowers the battery capacity. This enhances the battery aging, especially for higher charging rates [20]. The battery aging is enhanced when charging in low temperatures mainly due to a loss of active material, enhanced internal resistance, and a loss of lithium inventory [20]. Based on earlier research, the battery degradation due to temperature is the lowest around 25 °C [20]. The fast charging is convenient for the EV user, and more infrastructure for fast charging is being implemented. To date, several studies have linked faster charging with faster battery degradation, indicating that the lifetime of the EV could be reduced if fast charging is the preferred strategy. The advantages of fast charging are that the charging time is reduced and more EVs can be served at a charging station during a certain period, enhancing the revenues from EV charging stations. However, the disadvantages of fast charging are the enhanced battery degradation and the enhanced power peaks for the electric grid, due to the high power needed for a short period. If the EV charging occurs outdoors, a seasonal charging scheme is recommended, to plan the EV charging and only use fast charging during seasons with moderate outdoor temperatures, to limit the battery degradation.

4.3. *Smart charging and battery ageing*

Controlled charging to balance the grid or charge when the electricity price is low can be called smart charging, and can add flexibility to the electric grid [65]. There are questions regarding how to estimate the cost of the related battery degradation and the degradation can lower the revenues from using an EV to support grid flexibility [65]. In [14], a model is designed to analyze four different charging strategies; (i) a standard charging strategy where the EV is charged as soon as it is connected to the charging pile, (ii) a time-shift charging strategy where the EV has a delayed start of the charging time, (iii) a smart charging strategy where the charging starts at a low electricity price level, and (iv) a V2G strategy, where both charging and discharging to the grid occurs. It is concluded from the simulation study that the battery degradation modeled can be up to 5% lower if a smart charging strategy is utilized and that the calendar ageing can be significantly reduced with V2G as it reduces battery idle time [14]. These studies suggest that EV battery degradation could be reduced if the EV charging is planned and controlled in time, and also, that smart charging strategies could contribute to the overall flexibility of the energy systems.

4.3.1. *Vehicle-to-grid and battery ageing*

The concept of V2G is expected to either age the EV more or less, than when only utilizing the EV for driving, depending on the specific charging and discharging conditions during V2G. The estimated economic revenues from V2G can relate to selling electricity back to the grid. The EV can also contribute to different grid services. This can be compared to the economic drawbacks of potential additional battery ageing [66]. In [66], the cost of the EV battery ageing was modeled and estimated for V2G operation. The authors found that the more the battery is discharged, by using V2G, the higher the costs for the battery degradation for the EV owner, while an aggregator could benefit financially from V2G. However, the authors identify a need for deeper investigations on cycle- and calendar aging for V2G. This resembles the conclusions found in other research articles e.g., [67], where a need for enhanced analysis on bidirectional charging and battery degradation was identified. It was discussed in [68], that while countries such as Norway have a significant amount of EVs and the V2G technology is ready, V2G is not yet widespread. The decision of when to charge and discharge can be decided centralized or decentralized. A decentralized V2G charging strategy was suggested in [69], and modeled with data on prices for the French electricity market, taking into account information on the surrounding temperature and SOC limits to provide a longer lifetime of the battery while using V2G.

A review of V2G was presented in [67], highlighting the need for more research when it comes to V2G and battery ageing. In [70], a deep reinforcement learning strategy was utilized to model different charging strategies including V2G, taking into account both the effects on the electric grid and the vehicle battery degradation by estimating a cost for the battery degradation when modeling V2G charging. In [71], the authors model regular charging, smart charging where the EV charging is controlled in time (i.e., V1G), and smart charging including V2G capabilities, utilizing the Rainflow Counting method for different commuting distances for EV owners. The authors found e.g., that the V2G charging strategy could better support grid balancing services while keeping a similar battery lifetime because of similar DoD-values as a smart charging strategy based on V1G. However, V2G was expected to degrade the battery more due to the additional cycling, and larger commuting ranges would also degrade the EV battery more due to enhanced DoD levels. The EV owner may want to contribute to V2G, but only with limited SOC and DoD levels, to ensure a long battery lifetime [71]. Therefore, it is concluded that V2G could be used to support grid flexibility if the charging strategy is carefully designed, aiming for low battery degradation.

Creating a V2G charging schedule aimed to limit ageing of the vehicle battery, when the EV was charged and discharged to a microgrid powered by renewable energy systems, was discussed in [72].

Table 2
Estimated battery degradation rates for the charging strategies modeled in [28]. For more detailed information, see [28].

Estimation based on	Charging strategy	Estimated yearly degradation
Calendar- and cycle ageing, and intensive driving		
	1. Standard	11.55%
	2. Controlled in time, delayed start	9.83%
	3. Controlled with V1G based on SOC-value	9.83%
	4. Controlled with V2G based on SOC-value	10.33%
	5. Controlled with V1G and V2G based on SOC-value	10.13%

Batteries used for V2G were modeled for Li-ion NMC batteries, utilizing thermal models, electrical models and estimations for ageing [17]. It is argued that the calendar ageing, as well as the rate of charging and discharging, should be considered when investigating the pros and cons of V2G from a battery perspective [73]. In [73], blockchains were used to estimate if a certain EV would benefit from providing a V2G service based on economics, where the ageing from the EV was included in the analysis. EV charging and battery degradation was modeled in [28] for five different charging strategies including V1G and V2G; (1) standard charging, to charge as soon as the EV reaches the charging pile, (2) delayed start of the charging, (3) smart charging with V1G and to charge the EV when the SOC is at a suitable value to limit battery degradation, (4) to utilize V2G and adapting the start of the charging process with a suitable SOC value, to limit battery degradation, and (5) to change between V1G and V2G to limit battery degradation. While it is challenging to estimate EV battery degradation, the battery degradation rates for the five different charging strategies from [28] are summarized in Table 2. The authors concluded that the estimated battery degradation will not be enhanced by utilizing V1G and V2G charging strategies, compared to the modeled standard charging [28].

Vehicle-to-everything (V2X) is a concept related to charging and discharging from the EV battery to any other system with bi-directional charging. Also, the concept V2X is related to communication between an EV and for example the road infrastructure, another vehicle, or nearby pedestrians [74]. The concept V2X for bi-directional charging includes V2G, vehicle-to-building (V2B), and vehicle-to-home (V2H), meaning charging and discharging to the grid, to a building, or to the household, to support with more electricity. In the study of V2X in [74], the authors note that V2X charging strategies may not significantly reduce the lifetime of the EV battery. In some cases, a V2X charging strategy could even extend the battery life. It is concluded that V2X could be useful if the charging control strategy is well-designed to limit EV battery degradation. Together, these studies indicate an ongoing trend in research and development of V2G, V2H, and V2X, and in investigations on using V2G to contribute to grid flexibility and gain additional revenues. As presented in [28], the bidirectional smart charging could improve the lifetime of the EV battery if the V2G strategy is well-designed. This is interesting, as V2G could contribute to grid flexibility and support the electric grid when more variable renewable energy sources are utilized for sustainable electricity production. However, V2G includes a more complex charging scenario, and additional research and experimental work on V2G are needed to fully investigate any advantages and disadvantages of the bidirectional charging strategy.

4.4. *Battery swapping*

Swapping the used battery to a fully charged battery in a swapping station has gained attention lately, reducing the charging time. It is highlighted that the battery swapping may only take a few minutes, while fast charging may take around 30 min, and that the EV owners can buy a cheaper vehicle without a battery, and do not need to think about battery aging or battery maintenance as this is taken care for centrally at the swapping station [75]. Some challenges of such a battery swapping service include aspects of managing available and charged batteries at all times to meet the customer needs, meeting standardization when it comes to different types of batteries and vehicles, as well as ensuring safe installations of the batteries, as highlighted in [76]. There may also be costs related to the infrastructure for storing and maintaining all batteries, electricity costs for charging the batteries, as well as how often the battery is swapped and the battery ageing during storage [76]. An EV could be bought without the battery, limiting vehicle costs and opening for hiring (leasing) a battery from a battery swapping service instead [75,76]. The batteries in the battery swapping station could also be available for grid services with battery-to-grid (B2G) [75]. Some design considerations for EV batteries adapted for battery swapping are providing a specific standard, size, and weight of the battery for vehicle installation, and storing and charging the batteries at the battery swapping station. In [77], a model of a battery swapping station with PV generation for charging the batteries is presented, including an estimation of battery degradation. In [78], a model of a battery swapping station was presented taking into account potential battery damage and degradation. Battery swapping was compared to home charging as soon as the EV reaches home, and home charging controlled in time, in [2]. The results indicate that battery swapping and home charging that is controlled in time could be more beneficial than unplanned home charging, because of the potential to utilize the battery systems for enhanced flexibility to the grid and energy storage. The battery swapping technology has several advantages, including the opportunity to purchase an EV without the same concern for battery degradation, as the old or damaged battery could be removed from the EV and a new battery could be inserted instead. Also, battery swapping can support new business models, e.g., a leasing battery model, or using swapped batteries for other applications such as stationary energy storage. Therefore, there is a strong interest in the battery swapping technology.

4.5. *Inductive wireless charging*

Wireless charging, or inductive power transfer (IPT), is an emerging technology [79]. The wireless charging would not require the EV user to connect the vehicle with a large cable to a charging pile. Therefore, wireless charging could be a convenient and fast strategy. This can also result in charging while driving and it is suggested that this could support EVs with smaller battery systems, limiting battery costs. The possibility of charging wireless with constant power level with IPT was discussed in [79]. The reliability of a wireless charging system was estimated in [80], noting that if a separate part of the wireless charging system is malfunctioning, the full system could be down. Wireless power transfer (WPT) for EVs was discussed in [81], taking non-linear battery behaviors into account. While this could be a convenient charging strategy for the EV driver, the wireless charging systems may relate to large costs for the charging infrastructure. In [9], the authors find that wireless charging could be beneficial, and not enhance battery degradation. However, this is the case if the EV battery is of a suitable size, and not too small, as a small EV battery may result in higher C-rates and deeper discharging cycles, indicating that small batteries in EVs may need to be changed more often [9]. Battery degradation followed by wireless EV charging is not yet fully investigated, and more in-depth research and experimental work in this area is recommended.

4.6. Mobile charging stations

There are fixed charging stations (FCS) at certain locations. However, the mobile charging stations (MCS) can be moved to and from a suitable location to enable EV charging. The mobile charging stations could consist of a battery system at a truck that the EVs could charge from [82]. The MCS could be useful if there is a temporarily enhanced need for EV charging, for example, due to seasonal tourism. The MCS may contribute to enhanced flexibility, limited congestion at a charging station, and reduced range anxiety. A model of an MCS service was presented in [82]. Battery degradation of a mobile energy storage system was considered in [83], where the system was mainly proposed for an electric grid to enhance resilience. A novel system including a mobile trailer with a battery pack for battery swapping, charged at stations including solar PV systems, was described in [84] and the battery bank trailers were investigated for EVs in South Africa. More recent attention has focused on the provision for flexibility and accessibility when it comes to charging infrastructure for EVs, suggesting that mobile charging stations could be useful in society to meet the varying charging needs of EV users.

5. New approaches to mitigate battery aging

It is highlighted in [4] that the battery ageing should be considered from the very beginning of the design process of a battery, including design decisions affecting battery degradation at different levels: material-, electrode-, cell, and system level. One main advantage of focusing on the battery degradation from the initial stage of the design process is to limit the risks of TR, fire, and battery failures that may come from rapid battery degradation. However, the specific focus on battery degradation in the design process could require additional time and costs for the battery developer. To ensure a long lifetime of the EV battery, a strategy could be adopted to use the battery at a lower level than possible or within a limited span, in terms of e.g., current, voltage, power, temperature, SOC, or SOH [85]. Limiting for example the SOC-span, the power level (i.e., the C-rate), and the temperatures may provide a safer and less degraded battery system, if adapted properly for the specific type of battery [85]. However, this will also limit the system's performance. Therefore, the main advantage of this approach is a safer use of the EV battery and an estimated longer lifetime, whereas the main disadvantages include using the system at a lower performance level than it was initially designed for. To overcome the drawbacks of the limited charging strategies, these could be used mainly when there is no requirement from the EV owner for a faster charging process, such as to charge the EV for several hours if it is anyway parked during the night, or to charge the EV if there is an option to charge at a garage instead of outdoor at very low or high temperatures.

There are opportunities to design the energy system to limit the ageing of the EV batteries. A supercapacitor to accompany the battery has been proposed, to provide electricity to the electric motor of the EV [86]. This configuration is suggested due to the supercapacitor's possibility to give high power in short periods, beneficial for driving in areas with many starts or stops, and the EV battery would only contribute with lower current pulses parts of the time [86]. The authors suggest battery ageing could decrease if the battery charging current is limited [86]. Thus, a supercapacitor could contribute to a high-performance system, however, the disadvantage is the additional costs, and maintenance that come with adding a component to the EV.

To utilize a LIB and a supercapacitor in a hybrid energy storage system for an EV, and to control the system with a so-called imitation Q-learning energy management system, were discussed in [87]. Another type of hybrid system, including a vehicle with a battery, a fuel cell, and a supercapacitor, was reviewed in [88] mentioning the opportunity to limit energy storage degradation with a controlled hybrid system. The hybrid systems could benefit the operation of the EV, to better protect the EV battery. However, additional systems for the hybrid energy storage systems are costly and could enhance the maintenance needs.

The second life of the EV batteries includes, for example, to use old EV batteries in residential buildings, industries, or as backup power. Another alternative to second life application is to recycle the used EV batteries appropriately [36]. The SOC of retired EV batteries, i.e., EV batteries with SOC below 80%, were estimated for different temperatures and types of degradation in [89] to support reuse of retired batteries in other applications. The main advantage of second life applications for EV batteries includes improved resource management of the energy systems. However, the disadvantages are related to the complexity of estimating the battery degradation during EV usage, the need for data-sharing between the different users, and the uncertainty of for how long the system can continue to function safely in the second life application. To overcome these drawbacks, more research on monitoring and estimating the EV battery degradation continuously is suggested.

Charging with a constant current (CC) or a constant voltage (CV) is common. However, there have been investigations on charging with constant power (CP) instead, especially for fast charging, to limit the charging current and the related battery aging that relates to higher currents [79]. The commonly used CCCV charging scheme means that the battery is first charged with a constant current and an increasing voltage, and then a constant voltage at a certain level as the current decreases [37]. While the new charging schemes could potentially limit EV battery degradation, the drawbacks are that these are less tested than the established charging schemes, and any risks are not fully identified yet. To overcome these drawbacks, additional experimental work and research could be needed.

The battery system and the EV can be preheated in cold environments to limit the degradation due to charging at low temperatures [20]. The battery heating can either be external heating, such as air-, fluid- or electric heating, or internal heating, such as AC heating or pulse current heating [90]. The pulse current (PC) heating was investigated and modeled in [90] to preheat a vehicle battery from low temperatures. Preheating of the EV battery could limit the battery degradation, however, this requires more advanced thermal control systems in the EV and perhaps additional system costs for the manufacturer and EV owner.

Charging fleets of EVs can be modeled and controlled to plan for a charging strategy that e.g., limits battery degradation of the fleet [91]. To design charging protocols that are unique for each EV with reinforcement learning, based on the behavior of the EV driver and EV battery degradation, was described in [92]. The battery size can be modeled and redesigned to limit battery degradation for a passenger EV, as described in [93]. AI tools can be utilized to improve the manufacturing process of batteries and the management of battery health, to ensure batteries with long life and safety of the systems [94]. To summarize, the new approaches to mitigate battery ageing are e.g., to plan for the battery ageing at an early stage of the battery design process, to use the EV batteries at a lower performance level than needed, to add new components to the EV in a hybrid energy system, to try new charging schemes and to carefully plan and monitor the charging process. New approaches to mitigate battery ageing are continuously being developed, and the main advantage is possibly a longer lifetime of the EV battery. However, these approaches may result in more expensive or complex systems, requiring a significant data need and more in-depth testing before being utilized in the EVs.

6. Discussion and review results

The results from the literature review on different charging strategies and battery ageing are presented in Table 3, including an overview of opportunities and challenges with the charging strategies. The colors in the table indicate the severity of the estimated battery ageing (green:

Table 3
An overview of the different charging strategies and the potential effects on the battery (green: no major issues for the battery, yellow: potential issues for the battery, red: possibly major issues for the battery).

Charging strategy	Battery aspects	Opportunities	Challenges	Design proposals
Charging at low power level	Low battery degradation.	Limited degradation of the battery. Low costs and an opportunity to charge at home.	Long charging time.	Stop the charging at a certain SOC-level. Ensure charging at home over night.
Charging at high power level (fast-charging)	Lithium plating. Higher battery degradation.	Reduced charging time, fully charged battery when needed.	Enhanced power level may affect battery lifetime.	Thermal preconditioning is recommended if low ambient temperatures. Do not overuse the charging strategy.
Extreme fast charging (XFC)	May cause severe battery degradation and TR.	Less than 15 min. charging time.	Enhanced power level may affect battery lifetime. Risk for thermal running if not protected properly.	Careful monitoring, not use in extreme temperature. Do not over-use the charging strategy.
Fast-charging in high temperatures	May cause severe battery degradation and overheating of the system.	Reduced charging time.	Enhanced power level may affect battery lifetime.	Utilize a cooling system. Monitor the charging carefully and do not over-use the charging strategy.
Fast- charging in low temperatures	May cause severe battery degradation.	Reduced charging time.	Enhanced power level may affect battery lifetime.	Pre-heat the battery, and use lower currents before the battery is warmed up. Monitor the charging carefully and do not over-use it.
Smart charging or controlled charging, including V2G and V2H	Depends on the e.g., the charging rate, the temperature and DoD. Could either support the battery lifetime, or reduce it.	Contribute to self-sufficiency at the household, and flexibility for the electric grid.	Additional charging cycles due to stop and start adapted to the electricity price. Challenges in cold climates.	Design a smart charging protocol that takes battery ageing into account, utilizing lower power levels when possible and to limit the DoD.
Battery swapping	Store and maintain quality of several batteries.	Short time to swap batteries. Charge the batteries at low charging rate during the night.	Standardization is required. Calendar aging due to storage. Costs related to battery purchase.	Careful planning in storage, and standardization of the battery systems.
Inductive wireless charging	Smaller (cheaper) batteries, unclear battery degradation. Charging instants depend on where the transmitters are located.	Charging while driving. Could allow for smaller batteries.	Costs for road infrastructure. Unclear battery degradation of smaller batteries.	Investigate the opportunity to use smaller batteries, could result in cheaper EVs. More research is needed.
Mobile charging stations (MCS)	Depends on how the mobile charging stations are used and charged. Possibly low battery degradation.	The mobile system can be charged slowly during the night and discharged fast to the EV when needed.	Cost of system and cost of charging and discharging. Decisions and planning on locations for the MCS.	Analyze the specific environment where the mobile system is to be used and dimension the system based on the estimated charging need.

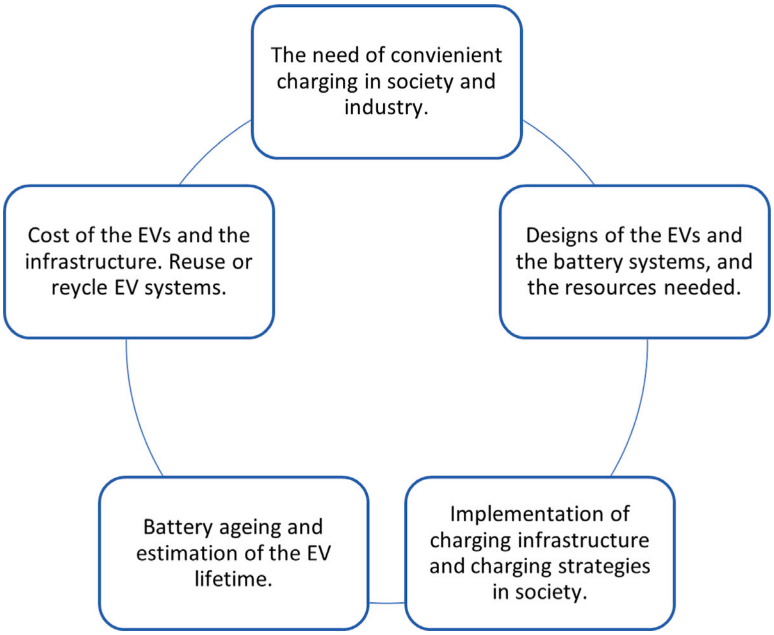


Fig. 4. An overview of aspects relevant for analyzing EV charging and battery ageing.

low, yellow: moderate, and red: severe). An overview of the relation between different aspects to consider for EV charging and battery ageing is visualized in Fig. 4.

Development of new EV batteries and charging strategies will likely relate to meeting different goals on convenient charging and battery ageing. Two contradicting goals regarding EV charging are: (1) to enhance the fast charging infrastructure to limit range anxiety and to provide a fully charged EV battery in only a few minutes, and (2) to ensure a long battery lifetime, limiting the battery degradation, often related to charging at lower power levels to make the LIBs and the EVs last longer. Therefore, there is a trade-off between the goals of faster charging and a longer battery lifetime to consider. Also, there is ongoing research and development towards V2G. Meanwhile, the additional battery use from bidirectional charging could either benefit or challenge the battery lifetime, based on the conditions for the charging and discharging. Furthermore, there is a strong interest in EVs in cold climates, such as in the Nordic countries during winter, and future EVs and EV batteries need to be designed and adapted to meet seasonal changes. If the ambient temperature is very low, the battery should be preheated before the fast charging sessions or the fast charging should be avoided. Due to the complexity of the cycle ageing, its relation to TR, and the potential severity of TR of LIB batteries, the EV charging sessions should be carefully monitored. The scientific literature indicates that the LIB in the EV could benefit from the limited use of fast charging strategies to ensure long battery life. However, the EV user may find fast charging convenient and necessary, especially for longer trips. There is a strong interest in developing the fast charging infrastructure in many countries for personally owned- and heavy-duty EVs. Significant development of fast charging infrastructure may result in societal costs, but this could also benefit the development of future, potentially cheaper, EVs with smaller battery systems, needing less material and resources for the batteries. Battery degradation is a highly non-linear process, and an exact figure of how much an EV battery will be degraded each year, with e.g., fast- or normal charging, cannot be specified with certainty. Also, the literature review highlights that it is complex to estimate battery degradation, but that the estimation of the battery capacity is important to mitigate risks for TR.

Fig. 4 highlights that several aspects are important to consider for planners and policymakers. This relates to societal perspectives, including the societal need to limit pollution in cities and to contribute to sustainable development, the charging need of the EV owner, and the EV owner's interest in ensuring a long life of the EV. Also, the research relates to technical- and industrial perspectives regarding the design of the batteries, the EVs, and the charging systems. Furthermore, it relates to environmental aspects regarding the resources needed to produce new systems such as the materials for the battery systems, and the land required for charging infrastructure, electricity generation, and the electric grid. There are economic perspectives on EV charging, regarding e.g., charging infrastructure investments, the cost of the battery system, and the cost of purchasing a new or preowned EV. A systems approach is needed to ensure that the electrification of the transportation sector contributes to a more sustainable energy system. The policymakers would need to carefully plan the implementation of charging infrastructure in society, to meet the needs of EV users, and to be aware that the available charging strategy affects the longevity of the EV batteries. Politicians would need to plan for investments for installing and maintaining charging stations. Also, to consider equal opportunities to buy and use an EV in society. Thus, the presented research in the field is relevant for policymakers, industry, and politicians to e.g., plan and manage resource use and to ensure sustainability. The following are examples of aspects to consider in the decision-making processes to enhance sustainability and support a sustainable energy system:

- Social sustainability: Improve access to available charging infrastructure to reduce range anxiety. Create incentives for manufacturing cheaper EVs, such as new EVs with smaller batteries, to enhance the opportunity to buy an EV, or consider providing financial support for EV buyers.
- Environmental sustainability: Enhance the electricity generated from renewable energy sources to the grid, to provide for EV charging. Limit the waste of resources from battery manufacturing. Support initiatives of a second-hand EV market, reuse the EV batteries if possible, and recycle the EVs.
- Economic sustainability: Support the development of cheaper EVs, and invest in cost-effective charging infrastructure. Industries will develop new business models for future charging strategies, and several new actors will contribute to the CET of the transportation sector.

Table 4

Overview of suggested scientific literature in the field for more information about battery degradation and EV charging.

Reference	Overview of content	Review paper?
[3]	Charging strategies	Yes
[10]	Fast charging	Yes
[4]	Battery degradation	Yes
[23]	Stress factors for EV batteries	No
[48]	Battery safety	Yes
[65]	Smart charging	No
[67]	V2G	Yes
[75]	Battery swapping	Yes
[79]	Inductive charging	No
[82]	Mobile charging	No

The charging strategy used by an EV owner may affect the second-hand market price of the EV, where significant use of home charging could be an argument for a longer expected lifetime of the EV battery. In the coming years, EV batteries could be reused in second-life applications, e.g., for energy storage in buildings, or the batteries could be recycled. To ensure a safe environment for the EV owner and a careful management of the batteries, other charging strategies, such as battery swapping at specific battery swapping stations, may be of interest. However, battery swapping stations may relate to high costs and be subjected to calendar aging of the batteries, enhanced by high temperatures and a long time in storage. The recent scientific literature highlights several correlated battery ageing mechanisms for LIBs in EVs relating to charging or discharging at high or low temperatures, high SOC, or high DoD. While the battery lifetime is reduced with enhanced battery ageing, the most severe events relating to EV battery ageing are TR and fire. A significant amount of literature highlights the need to improve the monitoring of the EV battery and estimating the SOH, for example during the charging session, and many techniques are proposed and developed. Knowing how well the battery is functioning improves the system safety, and the correct pricing of EVs on the second-hand market, and may encourage wider EV adoption. Charging strategies and battery systems need to be designed in the future to limit the risk of TR and severe accidents, not least during the charging sessions. Other battery chemistry may be useful for future EVs. The research on how the EV battery is affected by different charging strategies is relevant in both society and industry, to support decision-making and planning of implementation of charging infrastructure, and analyzing the resource-use and design of EV batteries and charging systems. An overview of interesting scientific literature has been summarized in Table 4, as suggested extra reading to provide deeper knowledge on EV charging and battery degradation.

The scientific papers reviewed have authors with affiliations from different parts of the world. Investigating the papers studied in this literature review, it is shown that author affiliations in only China represents around 15% of the papers. This is followed by author affiliations in only USA (for around 14% of the papers), in only India (for around 8% of the papers) and in only the UK (for around 5% of the papers). Some of the research papers have author affiliations from several different countries (approximately 25% of the papers), highlighting the significance of international research collaborations, out of which authors affiliations in China or USA are included in several of the papers. A majority of the reviewed scientific literature in this literature review was published in 2023 (around 62% of the papers). The most common journal publishing the scientific papers analyzed in this literature review is Journal of Energy Storage (almost 17% of all papers), followed by Journal of Power Sources (around 9% of the papers) and Energy (around 8% of the papers). The review paper highlights that while research is ongoing in many different countries globally, most of the research in this literature review comes from researchers with affiliations in China, USA, India and the UK, and that there are many collaborations in this research area.

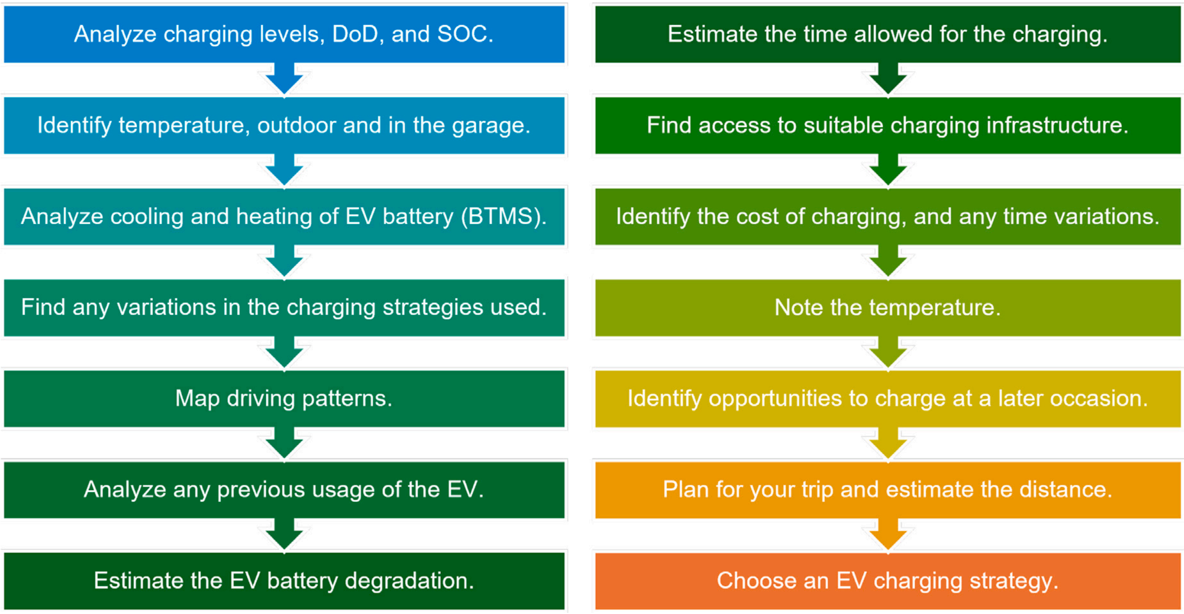


Fig. 5. Different aspects for an EV owner to consider when deciding the EV charging strategy and estimating the EV battery degradation.

The charging infrastructure investments and the cost of EV batteries are significant. Investments in the development of EVs and the charging infrastructure are interrelated. Access to charging infrastructure and knowledge about how the EV batteries are aged affects the willingness among car owners to purchase an EV, and thereby the personal opportunity to contribute to the CET of the transportation sector. The payment of EV charging could be developed and simplified to provide a better user experience. The coming EV charging strategies open for new business models. Possible future business models of different charging strategies are for example; (1) charging with V1G controlled by an aggregator to ensure charging at a low electricity price for the EV owner and provide grid flexibility, with related financial compensation for the service, (2) charging with V2G opens for purchasing electricity from the grid when the price is low and selling electricity back to grid when the price is high, providing flexibility to the grid while being compensated financially for the additional use of the EV for grid storage, (3) battery swapping services can provide opportunities to purchase EVs without the battery installed and instead lease the batteries, (4) battery swapping stations could provide additional services to the electric grid by utilizing the batteries in the swapping stations for local energy storage, when not used in the EVs, (5) improved battery technology and battery management can ensure a longer lifetime and go hand-in-hand with development of the second-hand market of the EVs and second-life applications of the EV batteries, and (6) battery recycling can create business opportunities for buying and selling battery material from used EVs. There are many aspects to consider for an EV owner, when planning for a suitable charging strategy and estimating the life of the EV battery. Suggestions on some aspects to consider are summarized in Fig. 5.

The findings of this study suggest that future research directions should include e.g., more experimental work, analyzing real data on EV charging and battery degradation, and investigating battery safety during charging. Furthermore, more interdisciplinary research collaborations would contribute to a deeper understanding of interrelated challenges regarding battery chemistry and electrical aspects of EV charging. This area could also benefit from future research on the technical- and economic perspectives on new charging strategies and their effects on different EV components, and with international perspective when the EV is used in regions and at varying temperatures. Emerging trends in the area that require additional research are e.g., bidirectional charging with V2G, new applications for old EV batteries, and battery swapping for EVs. It is concluded that good access to charging infrastructure supports the EV market, and that if V2G is planned properly, it may contribute to enhanced flexibility in the electric grid without significantly degrading the EV batteries, supporting the CET. However, more research in bidirectional charging and EV battery degradation is recommended. Overall, this study strengthens the idea that future research on the CET of the transportation sector is needed continuously

7. Conclusions

This literature review provides an overview of charging strategies for electric cars and the related battery aspects, in terms of battery ageing, concerning the current or future type of charging. The work is based on scientific literature published from 2019 to 2024. It is concluded that fast charging strategies may degrade the EV batteries the most, especially if fast charging is done at very high or low temperatures without the proper thermal management. Battery degradation is a non-linear process and the battery capacity of an EV is difficult to estimate. The BMS plays a crucial role in ensuring safe charging. The future EV batteries and charging strategies will likely be designed to meet the need for fast and convenient charging, and a long battery lifetime and safe EV operation.

One main finding is that there is a trade-off between faster charging and a longer lifetime of EV batteries. This relates to environmental, economic, and societal sustainability aspects. Faster charging may result in wider EV adoption and thereby support the CET of the transportation sector. However, the fast degradation of EV batteries comes with an enhanced need for more battery materials. Also, there is a need for more research on bidirectional charging with V2G, and battery ageing. V2G may contribute to grid flexibility, which is important when including more renewable energy sources. Therefore, the trade-off between battery degradation and V2G is important to analyze, and interdisciplinary research is recommended. Policymakers should investigate the trade-off between the preferred charging strategies for EVs and battery degradation, and analyze any compromises needed for the future energy system. This should be considered when planning for new charging infrastructure and in decision-making on EV infrastructure and grid investments. New business models will be developed with the new charging strategies and batteries. This study has identified that more research is needed on battery degradation and charging, due to the amount of new charging strategies being developed, the related costs of infrastructure investments, and the potential risks with damaged EV batteries.

The CET and sustainable development rely on decarbonized transportation, which includes electrification of the transportation sector. The energy policy for EVs needs to be developed to support wide EV adoption while maintaining the long life of EV batteries. More in-depth studies on how the charging strategies affect EV battery ageing are recommended. A key message is to identify the advantages and disadvantages of different charging strategies and analyze how the charging strategy would affect the vehicle battery, before investing in infrastructure. Improving access to cost-effective charging infrastructure by investing in available charging infrastructure is recommended to support EV adoption. Enhanced electrification of the transportation sector will reduce the use of fossil fuels, contributing to sustainable development.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jennifer Leijon reports financial support was provided by Swedish Energy Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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