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Enabling large-scale integration of electric bus fleets in harsh environments: Possibilities, potentials, and challenges

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ABSTRACT

This paper presents a comprehensive and detailed investigation of electric bus transit systems, focusing on their feasibility in harsh environmental areas. The aspects that combine economics, operation, long-term performance, and reliability are all addressed and discussed in both short and long-term horizons. This work covers most of the "important to consider" criteria, compares the strategies applied in E-bus energy management, and recommends the best practices to follow in the presence of many system variables. Due to the significant impact of the ambient temperature, characterizing the battery performance under hot ambient temperatures is performed considering the existing Li-ion battery technologies. Moreover, the grid impact of large-scale charging systems is identified and classified by identifying the factors affecting the grid hosting capacity and permissible interaction levels. This work includes developing a comprehensive picture of the state of the art, emphasizing the gaps found in the literature, and proposing new venues for future research that help address the identified issues to enable reliable E-transportation plans.

1. Introduction

Globally, many projects are replacing fuel-based transportation systems with electric-based systems. Their environmental needs and technology readiness increase their potential. Transitioning public bus fleets into electric is a great step toward a clean energy transportation system. Electric buses (E-buses) have the potential to minimize carbon emissions and enhance air quality, leading to a better eco-friendly future. However, it has been discovered that optimal placement and capacity sizing of charging systems in large-scale electrified public transportation is still in the early stages [1]. This, in turn, requires more attention for future research to develop advanced grid planning and operation systems. Transportation electrification has become a requirement in some countries and will be in the rest of the globe as some environmental mandates should be met.

It is important to mention the hazard associated with fuel-based mobility where carbon dioxide (CO_2) emission from fuel transit buses is about 10 kg for a 100 km trip [1]. This is a major source of pollution and global warming dilemma. Fig. 1 compares the most recent sources of CO_2 emissions where the conventional transportation system is the second major contributor to the overall emissions.

Medium- and heavy-duty vehicles are categorized according to their weight, with medium-duty vehicles typically falling within the weight range of 5–12 tons [2]. Examples of medium-duty vehicles include trucks and shuttle buses. In contrast, heavy-duty vehicles exceed 12 tons in weight, and city transit buses are classified within the heavy-duty category [2]. It has been calculated that a heavy-duty E-bus bus consumes 40 % less energy compared to a conventional diesel bus.

It is anticipated that the driving cycles for transit vehicles will lead to more significant battery discharges in comparison to Light-Duty electric vehicles (EVs), which can

potentially reduce the overall lifespan of the batteries. Furthermore, the faster charging rates for these batteries also have an impact on their cycle life. Recharging E-buses demands significant power compared to the current fast charging of small EVs. Fig. 2 depicts the yielded consumption profiles of both types [2].

The 2023 global EV outlook of the International Energy Agency (IEA) exposed that around 27 countries committed to selling only zero-emission vehicle buses and trucks by 2040.

US and EU have both proposed stricter emission regulations for heavy-duty vehicles [3]. Moreover, the study showed that more than sixty thousand E-buses were sold worldwide in 2022, reaching about 5

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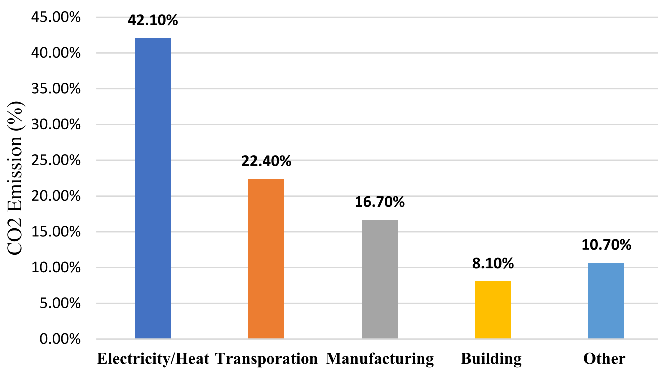


Fig. 1. Sector-wise global CO_2 emissions in 2023 [1].

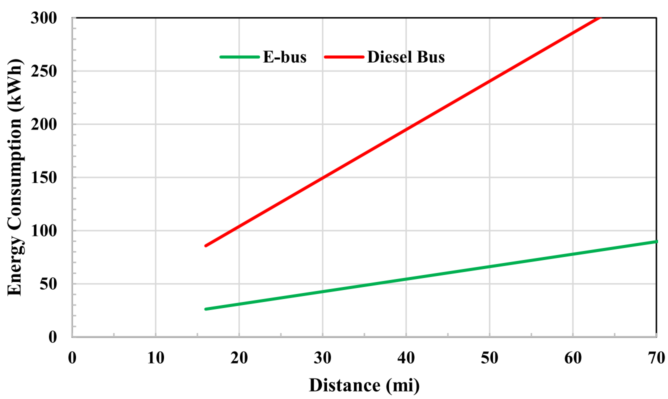


Fig. 2. Energy consumption for E-bus compared to fuel bus [2].

% of bus sales [3,4]. The size of the E-bus market size in USD with future projections until 2030 is depicted in Fig. 3 [5]. The E-bus market distribution in recent years is shown in Fig. 4 with the Chinese biggest market share [6].

Despite the widespread use of this technology, an electrified transportation system poses several challenges, particularly when integrating E-buses as heavy-duty vehicles into the existing power grid. Consequently, power networks would not be able to support the globally accelerated electrification processes without appropriate planning, regulatory reforms, and dedicating massive investments to upgrade the power networks. Additionally, with the widespread of E-bus transit systems, fast charging technology is likely to be the dominant EV charging method. In this regard, this work primarily aims to emphasize the use of this technology as a viable solution for next-generation electric transit systems (ETS), enhancing the transformation by enabling fast charging technologies.

The incremental power demand and the significant grid capacity upgrade are both among the major challenges encountered in electrification. On top of that, the economic and environmental needs to integrate renewables would increase the complexity and constraints on the

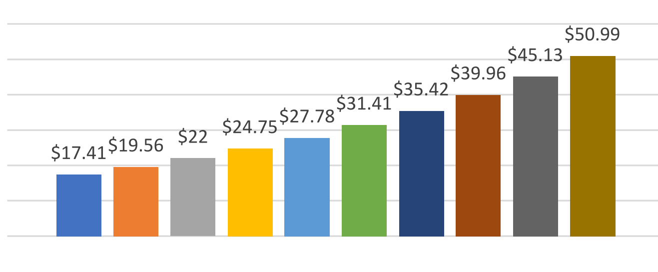


Fig. 3. E-bus market size 2021–2030 ($ Billion) [5].

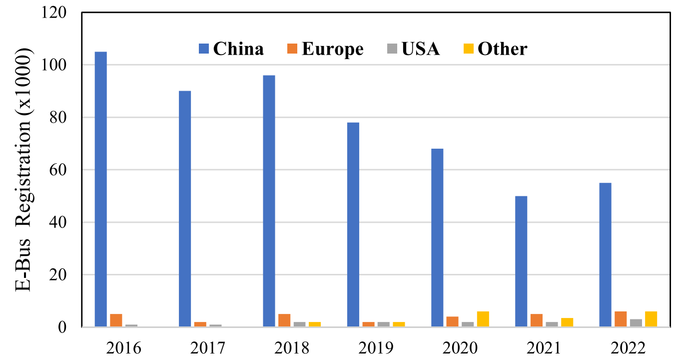


Fig. 4. E-bus registrations and sales by region, 2016–2022 [6].

required transformation [7–10]. By employing appropriate solutions, such as grid upgrades, smart charging, and demand response, seamless integration of E-buses can be successfully realized. Therefore, optimal planning, deploying, and operating of public E-bus fleets is of interest and must be carefully investigated.

Among the technical aspects that justify the urge implementation of fast charging E-bus systems include; **(i)** fast charging, unlike slow in-depot charging, allows for charging at any time during the day. **(ii)** When connected to a renewable source like a photovoltaic (PV) system, the daytime energy generation minimizes the fast-charging high-grid imported power, thereby maintaining power system adequacy. In essence, fast charging takes advantage of efficient PV self-consumption, which primarily happens during the day hours. **(iii)** Fast charging schedules are less constrained and offer more flexibility compared to slow charging. **(iv)** Furthermore, transit E-bus, compared to light-duty EVs, enforces the need for extra fast charging rates to meet the larger battery size and driving cycle. Thus, this research focuses on facilitating fast charging technology to distribute and reduce the impact of aggregated charging loads on the utility grid.

2. Problem statement, contributions, and article structure

Over the past decade, there have been many pieces of research concerning transportation electrification including the impact of EVs on utility grids. These studies have primarily focused on aspects such as trip ranges, battery size, grid compatibility, and line congestion, where the studies were primarily on light-duty EVs. Furthermore, the majority of the existing literature assumes that EVs operate optimally under normal driving conditions. However, when operating E-buses under abnormal temperatures, (i.e., less than 8 °C and greater than 35 °C), their performance experiences significant degradation. This degradation is primarily caused by additional energy requirements for thermal management purposes, besides, temperature-caused capacity loss. Consequently, the battery capacity reduces under such ambient temperatures.

The following contributions provide valuable insights into the complex issues affecting the transportation electrification pathway in adverse weather conditions.

- **Investigating E-bus grid integration:** This paper offers an extensive examination of the integration of E-bus into the grid, with a specific focus on how they perform in harsh weather conditions and their impact on power grids.
- **Characterizing the impact on distribution network hosting capacity:** The investigations include potential challenges to grid stability, shifts in demand patterns, and implications for the electrical infrastructure. A study of existing literature concerning the broader effects of ETS on the power grid is conducted. Moreover, definitions and standards related to EV charging, power networks, and power quality are also discussed.

- **Investigating the weather-related consequences on E-bus.** The consequences are categorized into:
  - Battery Performance: The study explores how harsh environments affect the functionality of batteries. This includes an in-depth review of Li-ion batteries, covering their operational principles, electro-chemical properties, battery health considerations, and performance characteristics in different ambient temperatures. Moreover, real and lab test pieces of evidence are reported and analyzed.
  - Trip range: The effects of unusual weather conditions on the overall travel distance and efficiency are evaluated. This work particularly examines how high temperatures affect various vehicle-level factors, including the reduction in travel distance, the energy needed for cooling, and charging duration.
- **Investigating battery thermal management systems for harsh environments:** detailed examinations of useful mechanisms used to alleviate the difficulties associated with batteries in harsh environments are performed.

Fig. 5 shows the structure of the article according to the addressed topics.

3. The challenges facing the electrification plan and charging infrastructure

Public transit buses are a class of heavy-duty vehicles that require significant power consumption rates to electrify [11]. Therefore, the major challenges encountered E-mobility transition include; **(i)** increased unpredictable electricity demand. The increased electricity demand is hazardous and requires upgrades to the utility grid infrastructure to handle the extra-large loadings added to the grid [12]. Adding the charging load of E-buses to the existing utility grid results in grid congestion, risking grid reliability. **(ii)** Establishment of new charging infrastructure. **(iii)** Grid stability and power quality; the integration of large-scale charging stations into the grid leads to fluctuations in power supply, impacting grid voltage and frequency profiles [13,14]. **(iv)** In big cities, where the E-bus is economically feasible, the increased power demand and the difficulty of incorporating renewables, amplifies the encountered challenges. **(v)** The lack of infrastructure and the required makeover in many urban cities. **(vi)** The battery size of a typical E-bus ranges from about 5 to 10 times the sedan EV battery size [15]. **(vii)** IEEE-1547 and IEC-61000-3-2:2018 standards have established strict limitations on the allowable harmonic content and DC offset currents into the grid, and EV chargers must adhere to these standards in their design and operation [16].

Due to the aforementioned reasons, it is very crucial to coordinate and optimize all the parameters involved in the transformation plan. Therefore, alleviating the challenges and maximizing the benefits can be reasonably achieved.

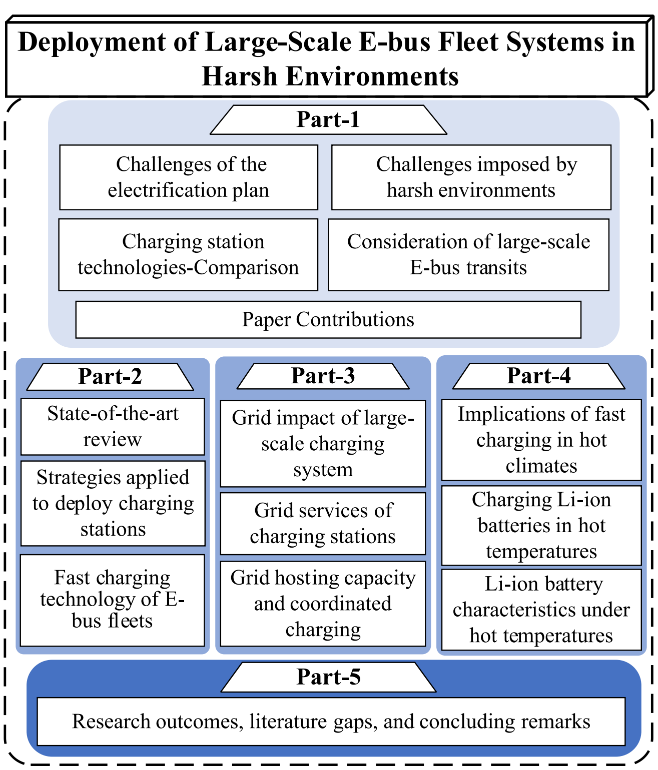


Fig. 5. The structure of the article.

4. Optimal planning strategies of E-bus public fleets

Many frameworks and strategies have been proposed for optimally deploying charging infrastructure while accounting for grid stability, achieving economic benefits, and reducing carbon emissions. In Ref. [9], the study examined the most suitable charging system to minimize both grid impact and overall cost. It was revealed that truncated fast charging followed by cooldown intervals is feasible and helps mitigate battery heat generation caused by high charging rates. In Ref. [10], a mathematical model was presented to improve the reliability of a power grid with huge E-bus charging loads. The focus was to minimize voltage drop by placing the charging infrastructure with a PV source installed.

In [17,18], the authors reviewed different approaches proposed for optimal EV charging planning and their impact on power grids. In Refs. [19,20,21,and21]] the work focused on the thermal management system as an integrated parameter in the optimal charging of Li-ion batteries. Different schemes were studied to obtain their effect on the optimal driving range of EVs. The authors in Ref. [22] developed a dual-level optimization framework to manage an EV fleet in a power system with multiple types of energy sources. The paper focused on scheduling the EV fleet according to variable energy costs. Therefore, the optimization was tuned according to the selected route, time, and energy cost.

In [23], the researchers considered the IEEE 39-bus system with high EV charging demand distributed all over the network. The work was directed toward the feasible operation of the E-bus fleet in the open wholesale electricity market where the V2G cost-minimization approach was investigated. The researchers implemented the distributional robust optimization method (DRO) to account for the high variability and uncertainty level of the input variables in the framework. In Ref. [24], a comprehensive analysis of the optimal deployment of fast-charging infrastructure was made. The work discussed the urban and rural deployment considering renewable integration to minimize the grid impact. Moreover, the work discussed the business model and the payback period of different infrastructure models when additional storage and PV systems are attached. Globally, Shenzhen city in China is the first complete E-bus city.

The authors in Ref. [25] considered this city to design an optimal approach to meet the charging demand and the grid capability. A planning strategy was made to deploy the charging stations in a way to serve the buses and distribute the loadings among the grid nodes. The study made in Ref. [26] showed that the feasibility study of electrifying public bus fleets should consider the power of the charging, consumed energy, and lifespan prices. Simulations were established to assess E-buses under different operating conditions, considering bus configuration, charging methods, and operating routes. In Ref. [27], a scheduling optimization was proposed to minimize the number of E-buses in a heterogeneous fleet by determining the optimum number of bus types and sizes.

An optimal selection of charging technology for urban transport was made in Ref. [28]. The work revealed that overnight charging provides acceptable performance with no significant impact on the grid. The shorter charging time that can be achieved using fast charging would impact the service quality. In Ref. [29], a configuration was proposed to determine the number of E-buses and battery capacities to meet the E-bus predefined schedule with opportunity and depot chargers. The design included charger and battery capacities. The results showed that large fleets should be heterogeneous, where different battery sizes lead to better short and long-term benefits. Compared to the work performed in Ref. [29], an additional variable was incorporated in optimizing the charging infrastructure considered in Ref. [30] where the impact of different Li-ion battery technologies on designing the E-bus fleet was conducted. The results revealed that coordination between Li-ion battery chemistry, charging technology, and battery capacity leads to a more optimized system. In particular, it was shown that according to the different characteristics of the chemistries, opportunity fast charging using Lithium Nickel Cobalt Manganese Oxide (NMC) and Lithium Titanate (LTO) chemistries, and slow in-depot charging with Lithium Iron Phosphate (LFP) chemistry yield feasible charging schemes. The findings indicated that achieving optimal system performance depends on coordination among Li-ion chemistries, charging technology, and battery capacity.

Depot and opportunity charging schemes of the city E-bus transit system were investigated in Ref. [31] to determine the optimal strategy. The study found that the regenerative braking recaptures 15–40 % of the energy. Moreover, it was found the 18 m E-bus consumes less energy which is about 33 % more than the 8.9 m E-bus. Table 1 summarizes the study fundings and Fig. 6 compares the consumption rates of the E-buses used in public transportation. It can be seen that the energy efficiency of the 18 m E-bus is better than the other model as it only consumes 33.4 % energy more than the 8.9 m E-bus with double passenger capacity.

In [32], the authors investigated the impact of charging infrastructure versatility and interoperability on cost reduction. The investigations revealed that charging stations can be used by different E-bus brands to optimize the cost. However, the existence of different standards and communication protocols impedes interoperability. The work performed in Ref. [33] considered establishing a power reserve to minimize the cost and optimize the charging. The charging location was also variable and can be determined according to the grid status. Another optimization was proposed in Ref. [34] where a two-stage problem was formulated to first minimize the trip time of the E-bus and second to reduce the charging cost. In Ref. [35], the work introduced an approach for addressing the challenging task of locating charging stations within a transportation network. Optimizing charging station placement was performed by utilizing self-avoiding random steps and a probabilistic rule to achieve comprehensive network coverage with the fewest number of charging stations.

In [36], the research utilized a multi-objective optimization, which incorporated a "brute force" Monte Carlo simulation. The objective was to find the most efficient combination of chargers and charging power that minimizes the total cost of fleet operation while minimizing grid impact. Similar to the work done in Ref. [24], the study in Ref. [37] aimed to find the optimal energy and power capacity for battery storage to support charging scenarios for E-buses. It used a Mixed Integer Linear Program (MILP) to determine the storage battery power and energy ratings for a configuration involving depot and en-route charging stations. It was found that the storage battery was able to reduce the peak demand and cost by minimizing operational expenses. In Ref. [38], the problem of EV charging was addressed using an optimal power flow (OPF) to account for network constraints at various charging locations on the IEEE 14 bus system. The study employed a nested optimization approach based on valley filling and peak shaving of the charging demand.

Table 1
The electrical specifications of the most deployed public E-buses.

Parameter	8.9 m E-Bus	12 m E-Bus	18 m E-bus
Battery (kWh)	160	160	240
HVAC consumption (kW)	24	24	48
Electric boiler (kW)	25	25	37.5
Energy Consumption of the drivetrain (%)	100 %	101.7 %	133.4 %

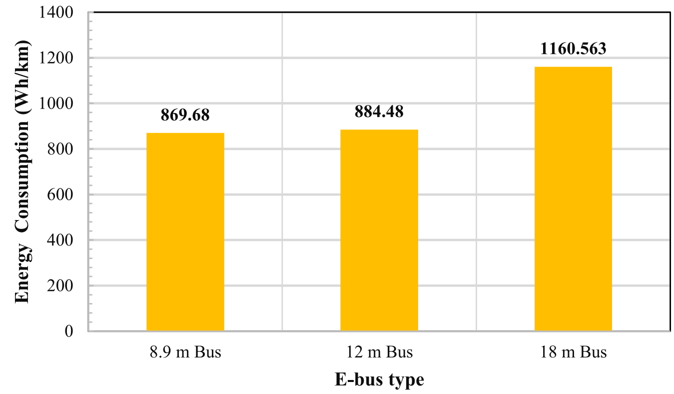


Fig. 6. Energy consumption of different E-bus models [31].

The battery-swapping technique was proposed in Refs. [39,40,41]]. The authors introduced an optimization model for efficient scheduling of battery swapping stations in an E-bus transit system. The swapping aimed to minimize operational costs by charging during low electricity price periods and providing grid ancillary services. Even though the technique provides a certain paid grid service, large additional investment cost was incurred which minimized the feasibility of the proposed technique.

The study conducted in Ref. [42] optimized charging infrastructure and battery capacity for E-bus public transit using a MILP. The article presented in Ref. [43] proposed a method to minimize the total cost of ownership (TCO) in an E-bus fleet. The target was to optimize battery size, the amount of chargers, and power ratings based on the prepared schedule. Battery customization was able to reduce the cost; however, it adds extra cost to manufacturing. To enhance EV resilience [44], discussed the optimization of EV battery size to reduce peak load and supply power during grid outages by imposing a penalty during peak intervals.

The framework presented in Ref. [45] demonstrated the potential of EVs in both G2V and V2G modes. It was revealed that the existing power network can accommodate a certain number of EVs. However, the fleet size handling capability increases when EVs participate in a V2G market. This suggests that the integration of V2G ancillary service could effectively enhance the capacity of current power networks to handle larger numbers of EVs. In Ref. [46], storage batteries were involved in optimizing the operation of E-bus charging stations, similar to the work presented in Refs. [24,37]. The research incorporated factors like battery price, capacity charge, and electricity price arbitrage to reduce peak charging loads and electricity purchase costs.

Fig. 7 depicts a mesh diagram illustrating the major challenges facing the deployment of E-bus fleet systems and the relations among the variables associated with the bus electrification plan. The mesh aims to link the factors influencing the operation of E-transportation systems. The diagram provides a comprehensive view of the complexities involved in managing a battery-based E-bus fleet system, highlighting the need for a balanced approach to address concerns while optimizing variables and efforts. These variables and efforts are interconnected and can influence each other. They all contribute to the overall cost, which is a crucial aspect to consider in the implementation and operation of E-bus fleet systems.

Table 2 is introduced to summarize the findings related to review articles on public E-transportation systems. This Table serves to describe the extent of these reviews and offers insight into the subjects covered.

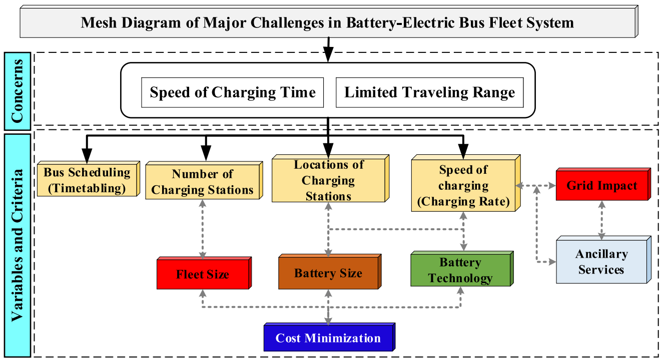


Fig. 7. Mesh diagram showing the relation between bus electrification plan associated variables.

Furthermore, Table 3 is designed to present a comprehensive overview of global initiatives, along with reports from completed projects and devised strategic roadmaps in the field.

5. The considerations of large-scale E-bus fleet systems

This section aims to assess the potential of E-transit systems and sheds light on the viability of electrifying public mobility systems. It investigates numerous technical criteria and aspects, including: (i) charging technologies and infrastructure, (ii) battery performance under extreme ambient temperature conditions, and (iii) considerations of battery capacity, type, and weight. The discussion explores cutting-edge strategies that have implemented various energy management schemes for E-bus fleets. It also emphasizes the research gaps by outlining the specific aspects considered in system development and realization.

Public transportation buses are ideal for electrification due to their predefined routes and the cost-effectiveness of their operations compared to diesel buses. Moreover, Public buses are ideal for electrification due to their certain trip, fixed routes, and cost-effective operation compared to light-duty private vehicles. However, on large-scale fleets, bus depots require substantial electricity to charge the fleet, which often occurs overnight, potentially drawing 25–100 kW per bus, totalling 200–400 kWh per day [61]. A depot serving 100 buses might need up to 10 MW of service for charging [60,62].

One key parameter in the optimal integration of E-Bus fleet systems is the charging strategy that directly affects the system's performance

Table 2
Summary and comparison of state-of-the-art review papers on E-bus Fleet systems.

[Ref] Year	Review Scope	EV Type	Grid Impact	Renewable Energy Source	Comparing Different Charging Technologies	Impact of Harsh Environment	Remark (Paper Highlight and Topics)
[11] Year:2022	Waiting Time, bus scheduling, placements of fast chargers	E-Bus	✓	×	✓	×	The focus is evenly distributed on the criteria considered with literature comparisons
[16] Year:2023	Charging methodologies and topologies, control algorithms, Grid impact of the topologies	Light Duty & E-Bus	✓	×	Fast Charging Only	×	Focused on the power converter topologies
[47] Year: 2022	EV charging planning considering distribution networks	Light Duty Vehicle	✓	×	✓	×	Focused on the integrated planning strategies with the distribution networks, positioning the charging stations according to the technology
[48] Year: 2021	Sizing of energy storage, energy management and modeling, and charging schedules.	E-Bus	✓	×	×	×	Focused on powertrain and motor drive
[49] Year: 2013	Operations of E-bus. Study the critical aspects (trip range and charging time)	E-Bus	×	×	✓	×	Focused on lessons learned from previously deployed systems worldwide
[50] Year: 2016	Comparative review of hybrid, fuel cell, and battery-based bus	E-Bus	×	×	×	×	Focused on the comparison includes economic, operating, energy, and environmental aspects
[51] Year: 2022	Planning and scheduling of E-bus	E-Bus	✓	×	✓	×	Focused on investment in E-bus, charging infrastructure, placement of chargers, and scheduling
[52] Year: 2022	Mapping of the methods, trends, and gaps of the field E-bus	E-Bus	✓	×	✓	×	–
[53] Year: 2021	EV powertrain modeling and general charging methods	Light Duty Vehicle	✓	✓	×	×	Focused on EV and Hybrid EV models and operation
[54] Year: 2021	E-Bus battery, Power Management, and Charging Scheduling	E-Bus	×	×	×	×	Sizing of battery, types of powertrains and motors, and control schemes
[55] Year:2023	EV charging stations with PV Considering techno-economic Implications	Light Duty Vehicle	✓	✓	✓	×	The EV market, technical requirements, and infrastructure. Control strategies. Review of connection standards.
[56] Year:2021	Converters architecture and International standards for EV charging stations	Light Duty Vehicle	×	×	✓	×	Detailed analysis and comparison of the power converters used in different charging technologies
Proposed	Public E-bus fast charging infrastructure in harsh environments	E-Bus	✓	✓	✓	✓	Investigation of energy management aspects, grid impact, renewable integration, Li-ion battery performance under hot climates.

✓: Considered/Included in the paper, ×: not considered.

Table 3
International studies and funded projects on E-bus transportation systems.

[Ref] Year	Project Name	Country	Deliverables and Scope
[2] 2020	"Medium- and Heavy-Duty Vehicle Electrification, An Assessment of Technology and Knowledge Gaps"	USA	- Leveraging medium- and heavy-duty EV information to evaluate the commercialization of EVs. - Assessment of current E-bus electrification architectures. - Identification of E-bus technologies.
[3] Year:2023	"Global EV Outlook 2023, Catching up with climate ambitions"	International (International Energy Agency)	- Integration of historical analysis and projections to 2030, covering EV deployment, charging infrastructure, battery demand, emissions reduction, and policy advancements. - Guide policymakers and stakeholders in strategies for EV adoption. - Examines the financial performance of EV-related investments.
[24] Year: 2017	"Considerations for Corridor and Community DC Fast Charging Complex System Design"	USA	- Focus on DCFC chargers for convenient charging. - Lesson learned from past DCFC and data collection from many EV brands. - Considerations for designing and enhancing DCFC infrastructure. - Cost estimation of high-power DCFC.
[57] Year:2023	"FLOW- Flexible energy systems Leveraging the Optimal integration of EVs deployment Wave"	EU	- Investigation of V2G definitions and terminologies for both EVs and electric vehicle supply equipment (EVSE)
[58] Year:2022	"U.S. Virgin Islands transportation Electrification roadmap"	USA	- Fostering the expedited proliferation of EVs across the Virgin Islands to enhance EV dependability, - Improve air quality, and enable a more resilient power grid.
[59] Year:2018	"Electric Buses in Cities, driving towards cleaner air and lower CO_2 "	EU	- Investigation of E-bus barriers, financing, and TCO, - Review of Li-ion battery market
[60] Year:2021	"Electrification of Public transport, A Case Study of the Shenzhen Bus Group"	Shenzhen, China	- Analysis of the Policies and Infrastructure of Shenzhen E-Bus Group. - Analysis of the business model. - Assessment of the TCO and the overall benefits
[61] Year:2020	"Electric Vehicle Charging Infrastructure"	India	- EV growth scenarios - EV charging infrastructure technologies - Key considerations for Public transit buses - Review of existing efforts in rolling out public charging stations
[62] Year:2023	"Decarbonising Transport: What Does It Mean for India?"	India	- Investigation of India's transport sector emissions - Investigation of the potential of EV technology pathway

and cost. In large-scale systems, the interaction with the utility grid is critical when the energy transacted from the grid induces frequency instability and voltage regulation issues at the distribution system level. Therefore, many approaches were proposed to establish feasible planning frameworks. A reliability-based deployment for large-scale charging stations is a considered solution for safe grid and charging system operation. In this approach, power system reliability indices can be employed for the optimal allocation of charging stations [63].

The charging technologies are mainly featured by their charging rates and voltage levels. These technologies are categorized and classified according to the power levels as presented in Table 4, and according to voltage levels as presented in Table 5. The classification made in Table 4 shows the impact of each charging technology on the battery charging time and lifecycle, whereas Table 5 presents the technology's standardized level according to the utility voltage and power ratings. Slow charging is typically related to a more cost-effective charging infrastructure and larger batteries.

On the other hand, opportunity charging using a Pantograph has a higher initial infrastructure cost but smaller battery packs with overall feasible operation in a fully electric fleet system [65]. A practical challenge that faces the deployment of fast chargers lies in the need for a much larger power transformer rating, where it has been determined that opportunity chargers require very large power transformers [65].

Typical operational requirements for E-buses involve covering an average distance of 150 km over 15 h, with 6 h dedicated to depot charging at a rate of 100 kW. Currently, most commercially available DC fast charging (DCFC) stations typically provide a power capacity in the range of 300–600 kW. However, the trend of increasing charging power ratings is significant. This development aligns with the growing demand for faster charging times and the need to support higher-capacity batteries.

6. Strategies applied to deploy charging stations

Optimizing E-bus charging systems is important to enable sustainable and cost-effective solutions. At the same time, the interaction level

Table 4
State-of-the-art charging technologies of battery E-bus [11,31,32].

Charging Strategy	Features	Comment
Fast Charging (Opportunity/ Flash)	Fast charger with a large intermittent and variable charging profile, its efficiency depends on a high C-rate which in turn, induces a rough grid interface.	Short average battery lifetime (Around 4–5 years)
Slow Charging (In-depot)	Parking charger/slow, flat charging profile, seamless interaction with the grid	Long average lifetime (Around 12–14 years)
Swapping Charging	Vary in size, the charging profile is controllable	Expensive capital cost
Wireless Charging	Easy and safe charging-contactless	Expensive capital cost

Table 5
Charging power levels in compliance with IEC-61851 standard [64].

Technology Level	Supply Voltage (V)	Current (A)	Charging Power (kW)	Charging time of 50 kWh battery (hr)
Level-1 (AC)	230 − 1φ	16	3.7	13.6
	230 − 1φ	32	7.4	6.8
	400 − 3φ	16	11	4.5
	400 − 3φ	32	22	2.3
Level-2 (AC)	400 − 3φ	63	44	1.1
Level-3 (DC)	400	125	50	1.0
Level-3 (DC-Fast)	400	375	150	0.3 (20 min)
Level-3 (DC-Ultra Fast)	800	$<$437	350	1.1 (9 min)

with the utility grid should be established such that the interaction is risk-free. In typical EV-charging stations, an agent-based locating strategy can be effectively used to determine the location of the charging station that considers the scattered patterns of charging behaviors and can meet the convenience level of the agents [66]. However, in E-bus charging stations, the locating process is more restricted to transportation networks and power distribution networks. In this regard, intersection-based and traffic-based strategies can be adopted [67]. In a junction-based locating strategy, the charging station can be deployed at bus stops (route-end) that intersect with other routes [67].

This should maximize the served buses where this type is favorable in city (urban) fleets. On a traffic-based locating strategy, the aim is to locate the chargers at the routes with higher traffic. This plan is considered to maximize the utilization level of the chargers and to serve the fleets with long trips at divergent locations. This strategy, indeed, distributes the demand seen by the power distribution network (PDN) and vividly serves the inter-city fleets [68].

Many studies revealed that charging slowly (at depots) necessitates a larger onboard battery. On the other hand, fast charging en-route (at stops and terminals) can reduce the required battery capacity by approximately two-thirds [66–68]. Furthermore, the energy consumption of the bus was decreased to 90 % due to a reduction in bus weight [67,69]. However, the strategy of fast opportunist charging for large-scale fleets can lead to risky interactions with the grid. As a result, implementing coordinated fast charging strategies (non-opportunist) and utilizing renewable energy sources seems to be an optimal solution to the charging problem. This approach not only addresses the issue of charging speed but also promotes the use of renewable energy, making it a comprehensive solution.

The comprehensive literature survey conducted in this study encompasses state-of-the-art strategies and optimizations, providing a thorough overview of the field. In addition to surveying the review papers presented in Table 2, an analytical Table (i.e., Table 6) has been created to present the merits of the reviews and to display the criteria considered in the proposed frameworks. This allows for a deeper understanding of the advancements in the field and helps identify existing technological gaps.

Table 6 illustrates the strategies adopted in planning and optimizing E-bus transit systems all over the world. The Table highlights the main objectives and the mathematical tools employed to conclude the outcomes. It's important to note that a significant percentage of the literature has conducted research under the assumption of normal ambient temperatures. However, the presence of severe ambient temperatures can have a substantial effect on optimization processes. This highlights the need for future studies to consider the influence of a wider range of ambient temperatures to ensure the robustness and reliability of their findings.

While the basic principles of electrification apply to both heavy-duty and light-duty EVs, the differences in scale, energy demands, and operational profiles necessitate tailored solutions and considerations for each category. When considering the E-bus transportation systems compared to light-duty EVs, several distinctions arise. E-buses require significantly larger and more powerful batteries to accommodate the higher energy demands of their larger size and heavier loads. Light-duty EVs have smaller batteries tailored to meet the energy needs of individual consumers. The widespread adoption of E-bus systems and EVs affects the electrical grid and charging infrastructure. The impact and requirements may lead to compulsory grid upgrades. To ensure consistent conclusions about the technical aspects of charging technologies when applied to large-scale systems, Table 7 is constructed. This Table serves to illustrate and contrast the features of each technology from a business model perspective.

According to the primary features of each charging technology and considering the associated advantages and disadvantages discussed earlier and outlined in previous Tables, Pugh matrix is constructed in Table 8. This matrix offers a fair methodological way of comparing the technologies, supported by recent facts and features. It facilitates the analysis of different options to identify the optimal technology for a specific application. The results of the Table reveal that even though fast charging technology scores the minimum regarding grid impact that has the largest weight (i.e., 15 points), it scores the highest with 82 points among other technologies. The battery swapping technique scores the second highest with 78 points which gives it great potential as battery storage system price decreases.

Results Discussion: The requirement for slow charging necessitates a larger battery size capable of supporting multiple trips. This, in turn, results in a battery that is not only large but also heavy. Consequently, the bus carrying this battery must also be larger and heavier. In conclusion, considering future transportation, which is likely to be dominated by EVs, there is a demanding need to advance fast charging rates and expand the network of charging stations while adhering to grid quality constraints [85]. This approach aims to reduce charging time and battery capacity. It is a strategic move that will facilitate the fast transition to complete E-transportation systems. Key takeaways include the requirement for fast chargers that prioritize charging speed without being opportunistic, with the ability to operate during off-peak hours. Additionally, fast-distributed chargers provide potential solutions that are not only efficient but also have a minimal impact on the grid, have lower power ratings, and are reliable.

7. The impact of transportation electrification on grid hosting capacity

The accelerated transition toward E-mobility systems is a demanding issue that risks the adequacy of power networks to meet the incremental demand. In recent surveys conducted by European Commission agencies, it was shown that the growth rate of battery E-buses increased by 50 % on average in most of the union countries in the last two years [86].

Moreover, the trend of this transition is expected to accelerate more with an additional 20 % growth by 2027 [11,86]. This, in turn, adds hundreds of *TWh* demand on power networks. At the same time, the level of grid flexibility to accommodate the unpredictable power production coming from renewable sources and heavy-consuming loads (like ETS) is another concern to be considered.

Grid-supporting services were proposed in different pieces of literature. Renewable energy and storage systems were proposed to shave the peak load caused by fast charging facilities [87–89]. Integrating an energy storage system was proposed in Ref. [87] to minimize the grid impact and meet the high charging rates in a large-scale E-bus transit system. In Ref. [65], it was shown that the load factor (LF) of the fast chargers is very low compared to the depot charger. From a power system perspective, this value represents a poor load profile where the ratio between the average and maximum load is small. However, from an optimal operation perspective, this means that fast charger utilization of the transformer is small and can be easily shaped by shifting and coordinating the charging process of the whole fleet of buses. Table 9

Table 6
Comparison of fast charging schemes dedicated for battery E-bus fleet systems (from 2015 till 2023).

[Ref] Year:	Developed Framework	Objective Function	Problem Formulation	(Region) Climate/ Temperature
[39] Year:2023	Optimization of MW-scale battery storage swapping stations	Minimizing the running costs of the BSS by exploiting the low electricity prices, and utilizing the BSS in the provision of grid reserve.	Saving cost index (SCI) based Pyomo abstract model	(Ontario, CA) Min = −11 °C Max = 27 °C
[42] 2017	Optimization of the trade-off between charging stations and battery size	Cost-minimizing by reducing the number of chargers and battery sizing	Deterministic optimization/MILP	(Germany) Min = −15 °C Max = 30 °C
[70] Year:2018	Determination of charging station locations considering battery degradation	Cost-minimizing including battery aging function	Deterministic optimization/MILP with several periods	(German city) Min = −1 °C Max = 26 °C
[71] Year:2018	Locating charging stations considering energy consumption uncertainty using affinely adjustable robust counterpart approach	Cost-minimizing with set-based RO function	Deterministic optimization/robust MILP	(USA/Utah) Min = −3 °C Max = 32 °C
[72] Year:2019	Locating charging stations considering high electricity demand charges	Minimizing the total cost of EV batteries and electricity cost	MILP	(USA/Utah) Min = −3 °C Max = 32 °C
[73] Year:2019	Locating charging stations based on a multi-objective techno-economic optimization framework	Minimizing the total cost of ownership	Matlab-based iterative approach	(Spain) Min = 7 °C Max = 24 °C
[74] Year:2019	Locating large-scale charging stations based on multistage planning considering transportation and power networks	A spatial-temporal model that finds the locations and capacities of E-bus charging stations, and strategies for multiple stages of infrastructure planning	MI second-order cone programming	(China) Min = 11 °C Max = 32 °C
[75] Year:2020	A bi-objective optimization framework for efficient scheduling considering the limited driving range with chargers installed at terminal stations	Minimize the total number of EVs and chargers	Hybrid Lexicographic and max-flow solution methodology	(Singapore) Min = 20 °C Max = 33 °C
[76] Year:2020	Two incorporated stages of optimization: (1st): estimation of energy consumption (2nd): optimizing the placement of the chargers	Optimal sites for charging infrastructure based on routes, energy consumption profiles, and running costs	Enhanced heuristic descent gradient and Voronoi diagram framework (graphical representation)	(Toronto, CA)/ Cold Min = −7 °C Max = 27 °C
[77] Year:2021	A bi-level programming framework: (1st): find the charging station location (2nd): calculate user cost	To optimize the costs of the useres and operators	Modified genetic algorithm	(Zurich, Switzerland) Min = −1 °C Max = 25 °C
[78] Year:2021	Location planning model including bus operation and distribution networks	To minimize the total cost of the construction, operation and maintenance, travel, and the power loss	Affinity Propagation method and e Binary Particle Swarm Optimization a	(Yangjiang, China) Min = 12 °C Max = 32 °C
[79] Year:2022	Locating opportunity charging infrastructure, sensitivity of E-bus fleets under both optimization of charging stations and trip schedules	Optimizes the charging stations and E-bus trip schedules	variable neighborhood search metaheuristic approach suited for large-scale problem	(Germany) NA
[80] Year:2022	Locating and scheduling chargers at bus stops and considering variable electricity prices	Optimizes the total cost of charging, chargers price, battery price, and penalty cost due to waiting time and trip delay.	Deterministic model linearized to be solved using MILP	(Sydney, Australia) Min = 8 °C Max = 26 °C
[81] Year:2022	Optimization of charger placements and fleet scheduling for E-buses with time-varying ridership, dwelling time, and travel time with opportunity charging	Optimizes the battery capacity, bus fleet size, and charger locations at stops and terminals to minimize the total costs.	MI-Nonlinear Programming	(Oslo, Norway) Min = −5 °C Max = 23 °C
[82] Year:2023	Cooperative optimization of E-bus trips and charging timetabling including sensitivity analysis of the impact of charging technology on cost	Minimize the charging cost	Integrated adaptive large neighborhood searching and branch and bound (ALNS–BB)	(Shenzhen, China) Min = 11 °C Max = 32 °C
[83] Year:2023	Optimal placement and sizing that maximize the returns of a swap station: (1st): E-Bus consumption model formulation. (2nd): battery model for profit maximization.	Maximizing income from swapping, minimizing charging costs, and regulating service	Constraint-based iterative solution approach	(Berlin, Germany) Min = −2 °C Max = 24 °C

presents a comparison between the positive and negative impacts of deploying large-scale E-bus charging systems on the utility grid.

When the charging station is connected to distribution transformers under hot temperatures, their performance becomes critical due to the excessive heating of the internal windings caused by the injected harmonics. Under heavy charging loadings, a critical winding temperature of more than 200^0C can be reached [90]. This leads to quick transformer aging and reduced grid reliability. In this regard, the work presented in Refs. [90,91] showed that applying controllable-coordinated charging scenarios can significantly reduce the transformer rating requirements and reduce the thermal stresses. A mixture of overnight (depot) and opportunity (fast) charging is also proposed to ensure that buses start their operations fully charged, allowing for top-ups. For overnight charging, medium-voltage charging using standard slow charging was employed, achieving power levels similar to light EVs. However, the charging process for E-buses takes longer due to their larger battery capacity, which is approximately 10 times that of light-duty EVs.

Since depot charging occurs overnight, it has reduced grid impact. This is a conservative assumption as the actual grid impact depends on the number of E-buses that are charging simultaneously and harmonic distortion levels. Fast charging is more expensive compared to depot charging. Nevertheless [92], indicated that deploying a fully electric fleet can lead to smaller battery sizes, resulting in a lower TCO, which includes battery replacement and retirement costs. Fig. 8 summarizes

Table 7
Existing E-bus charging strategies [84].

Charging Strategy	Battery Size		Capital Cost	Overall System Cost		Applicability in Large-Scales	
Slow (Depot)	**Big**	For overnight charging, larger capacities are required for batteries.	Low	**Average**	Battery prices are expensive. However, if reduced night tariffs are applied, charging will be economic.	**Average**	(i) With large-scale systems, overnight incurs serious problems in bus queuing, number of chargers, and grid impact. (ii)Large batteries and heavy-weight issues
Fast (Opportunity)	**Small**	Buses can top up at terminals in a relatively fast manner, battery packs are small.	Medium	**Average**	The higher cost of the fast charging system is met by a small battery size.	**High**	(i) With large-scale systems, it is applicable in terms of charging time, queuing, and battery size. (ii) Indirectly, distributes the charging demand.
Fast (wireless/ Pantograph)	**Small**	There is no need for a big battery (en-route charging).	High	**Expensive**	(i)Wireless charging is expensive. (ii)Dedicated to a single route (limited feasibility).	**High**	(i)Pantograph charging is being implemented worldwide. (ii) System cost reduction is proportional to the increased number of buses

Table 8
Pugh matrix of large-scale deployment of E-bus transit systems.

Category	Maximum Weight	Fast Charging	Slow charging	Battery Swapping	Wireless
1. Capital Investment	**(15)**	12[a]	14	7	8
2. Grid Impact	**(15)**	10	15	15	12
3. Charging Time	**(10)**	10	5	9	6
4. Efficiency	**(8)**	7	4	6	5[b]
5. Restrictions on Station Location	**(7)**	5	3	6	2
6. Ease of deployment	**(6)**	4	4	4	3
7. Compatibility with other EV charging	**(5)**	4	4	0	0[c]
8. Quality of service (queue, availability)	**(6)**	6	4	6	4
9. Timetabling and Bus Scheduling	**(6)**	6	4	5	4
10. Grid Service Capability	**(6)**	5	4	6	3
11. Charging System Reliability	**(6)**	5	5	6	3
12. Compliance with grid codes/standards	**(6)**	4	6	6	5
13. Requirement of upgrading grid infrastructure	**(4)**	4	2	2	2
	Total (100)	**82**	**70**	**78**	**57**

[a] Expensive charging infrastructure with cheaper and small-size batteries.
[b] Poor Power coupling and transfer.
[c] Dedicated for certain bus charger configurations.

Table 9
The grid impact aspects of large-scale transportation electrification.

Positive Grid Impact *Ancillary services (Bus-to-Grid)*	Negative Grid Impact
Power Reserve	Violation of Voltage Drop Limit
Peak Shaving	Violation of Frequency Drop
Electricity Trade	Power Quality Deterioration
Power Quality (Harmonic Compensation)	Power Imbalance
Transmission Line Congestion Relief	Increased Power Loss
Voltage Regulation	Transformer and Lines Overloading
Frequency Regulation	Forming Peak Load Demand
Load Factor Enhancement of lightly loaded lines (Improves the utilization factor-valley filling)	Overheating Distribution transformers (Harmonic currents interactions)

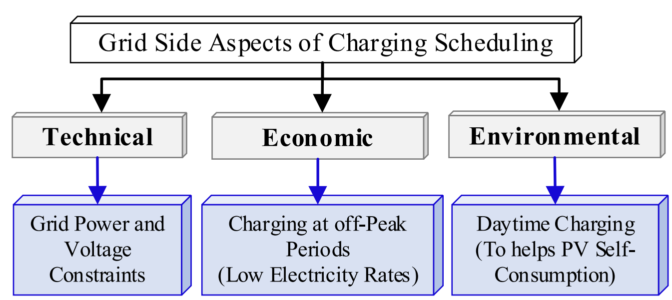


Fig. 8. The aspects associated with optimal charging scheduling.

the essential criteria necessary for optimal charging scheduling. It highlights the necessity of holistically considering technical, economic, and environmental factors, particularly when scheduling for fast-charging where the grid impact is significant. It is crucial to emphasize that the level and nature of grid interaction are influenced not only by techno-economic factors but also by environmental considerations. It indirectly facilitates the integration of larger renewable systems with the grid.

8. Ancillary services and grid codes

The ancillary services are vital for ensuring the stability and functionality of the power grid. Ancillary services include services outside of primary power generation and are subject to specific requirements [93]. Most grid codes necessitate the capability to provide reactive power and power reserve as major ancillary services [93]. The requirements aim to guarantee that generating units can provide these services promptly upon request, particularly during emergencies. According to the latest grid code revisions, EV charging stations are now obligated to meet specific requirements. These requirements include power quality, voltage support, demand response capabilities, anti-islanding measures, and the ability to withstand grid conditions, including fault ride-through (FRT). Furthermore, advanced network codes differentiate EVs based on their roles as either demand (V1G) or generation (V2G) entities. The specific ancillary services offered by large-scale charging stations depend on the technology and capabilities integrated into the charging infrastructure. Moreover, advancements in smart charging and V2G technologies continue to expand the potential contributions of charging infrastructure to the overall stability and efficiency of the power system [93,94].

Large-scale E-bus charging stations can contribute to grid ancillary services. Charging stations can contribute according to demand response agreements. By adjusting the charging tariffs according to grid conditions, they can help balance electricity supply and demand, especially during peak periods. Moreover, they can provide voltage support and reactive power control to help maintain power quality on the grid. This is particularly relevant as charging can lead to voltage drop, and the charging stations can manage the charging to compensate for the resultant drop. If the charging infrastructure supports V2G technology, E-bus can feed surplus energy back into the grid during high-demand periods [95]. This bidirectional flow of electricity can be a valuable asset for grid balancing. E-bus charging stations can align their charging schedules with renewable energy generation patterns, helping to absorb excess renewable energy during peak production times and providing flexibility to the grid.

Unlike medium or high-voltage grids, the low-voltage parameters are characterized by less strict criteria, and there is currently no obligation to provide voltage support [93]. Table 10 compares several grid aspects of fast charging systems that have been discussed in the literature.

9. The coordination between E-bus transit systems and distribution grid

As EVs and their charging stations proliferate, power quality becomes increasingly vital in electric networks due to their non-linear voltage and current profiles. Numerous studies investigate the effects of transportation electrification on the utility grid, especially on the distribution networks. This includes aspects such as substation overloading, harmonics, voltage drops, poor load factor, and unbalanced loadings [109]. Therefore, comprehending the impact of charging stations on power quality is of utmost importance [110]. Other studies focused on the impacts on power grid reliability and stability with the augmented charging demand that maximizes power network loadings. Moreover, grid stability is majorly concerned with the on/off switching of large charging infrastructures and their impacts on system frequency [111,112].

Ensuring adequate power quality is one of the utility's important responsibilities and is typically governed by grid codes (i.e., IEEE 519, IEC 61000). The power quality issues in the presence of power electronics chargers depend on charger type, converter topology, and charger capacity. The hosting capacity (HC) of a given network establishes the maximum load that can be connected while maintaining power quality within acceptable limits. Due to the nonlinear charging power, utility companies are concerned about exceeding the HC of power networks. This concern arises because a poor power quality profile degrades the HC of the networks besides overloading the power transformers and lines [113,114]. Consequently, deploying more charging infrastructures leads to power quality issues. Fig. 9 shows a block diagram of implications associated with the large-scale E-transportation on power grid hosting capacity.

On a large scale, charging stations have a significant impact on power quality where the large impact of harmonic distortion is generated by the multiple chargers, accumulatively. Harmonic distortion can pose issues when the cumulative harmonic signals surpass predefined thresholds, transformers and lines heating losses, and instrumentation malfunction. Several factors determine the impact of harmonics. These factors include the penetration level of chargers and converter topology [115–117]. A significant degradation in grid power quality was observed when a heavy fast charging occurred due to the presence of 3rd and 11th order harmonic currents, and a large drop in voltage and frequency [118,119]. The studies conducted in Refs. [120,121] revealed that the main concern for fast charging stations is the high THD_i, rather than the overloading of power transformers. The research demonstrated that the number of chargers that can be installed without exceeding the harmonic limits is restricted by the grid code. Deploying the charging stations in higher voltage substations would help compliance with the grid code [122].

When considering a network with both charging stations and inverter-based DG (I-DG), both can contribute common harmonics to the grid. However, if I-DG and charging stations are appropriately sized and located, they can help reduce harmonics by canceling out each other's harmonics [123]. Idaho National Lab (INL) researched EV compatibility with the grid and has published the results of testing the grid impact of level-2 charging [124]. The results show that low-order harmonics contaminate the grid at low-charging power, as shown in Fig. 10(a)-(b). Also, the results show that charging efficiency is enhanced at higher power rates, as shown in Fig. 10(c).

The studies in Refs. [113,125,126,and126]] revealed that at extremely low temperatures (i.e., $\leq 0\,^{0}C$), THDi exceeds the acceptable limits. This is attributed to the fact that charging at low temperatures is a low-power process due to the Li-ion electrode plating phenomenon, resulting in a minimal fundamental current flow. As a result, total demand distortion (TDD) can be used to compare charging profiles at various temperatures, as per the IEEE Std 519–2022, which states that the maximum TDD should be 5 % [122]. In Ref. [127], it was observed that charging a cold battery took at least two times the room temperature charging. Interestingly, the study showed that the TDD was within the permissible range throughout all charging processes.

Charging infrastructure must be designed to accommodate the specific requirements of battery chemistry used for each charging technology. Compared to nickel-metal hydride (NiMH) and solid-state batteries, the most commercial battery type used in the EV industry is Li-ion batteries [128]. Besides the cost of the battery, important criteria affect the adoption of the charging technology.

These criteria mainly depend on the battery's chemistry, including battery lifespan and number of cycles, maximum charging rate that is affected by the thermal sensitivity of the battery, and cell voltage requirements [128,129]. The literature agrees that Li-ion batteries support faster charging compared to other battery types. Solid-state batteries have the potential to offer even faster charging speeds due to their unique characteristics. However, no broad commercial production exists so far. Furthermore, Li-ion batteries have a lower voltage range and can handle high currents, which is suitable for fast charging technology compared to NiMH, which has a poor thermal coefficient. In Ref. [129], the authors compared three Li-ion chemistries (namely; LFP, NMC, and LTO) used in E-bus regarding the impact of fast charging rate, battery size, and lifespan. The results showed that LTO exhibits the minimum impact on battery lifespan at higher charging rates with a 1.5 % yearly degradation. On the other side, the NMC battery loses more than 20 % of its capacity with fast charging schemes. Furthermore, it was revealed that all chemistries benefit from the increased capacity where the degradation rate decreases proportionally. The results inferred a stable operation of the LFP battery at different charging rates.

10. The battery performance in harsh climates

As of 2022, the prevailing battery chemistry in the market was lithium nickel manganese cobalt oxide (NMC), constituting a significant 60 % market share [3]. Following closely behind was lithium iron phosphate (LFP), with a market share just shy of 30 %, and nickel cobalt aluminum oxide (NCA) with a market share of approximately 8 % [130]. As the volumetric (Wh/L) and gravimetric (Wh/kg) energy densities of Li-ion are much higher than other technologies, they become more mature and widespread [131]. Table 11 presents the specifications of several Lithium-based batteries and their thermal characteristics for industrial applications.

Similar to cold weather operation conditions of Li-ion batteries, hot

Table 10
Comparison between state-of-the-art studies on grid impact of large-scale fast-charging infrastructures.

[Ref]	Developed Scheme-Problem	Grid impact Aspect	System Size (kW)
[96]	A joint optimization of transit network and power grid using a spatial-temporal model to locate sites and sizes of e-bus charging stations-	Power loss and voltage drop minimization	110 kV lines 30 E-bus 250 km routes
[97]	2020-Warsaw-Poland Pantograph exemplary model of a bus station with charging infrastructure	Power quality (THDv)	1st: Sparta'nsk-200 kW 2nd: Wilanów-2x400kW
[98] (Depot)	maximizing profit bus of depot operator and grid stability enhancement with PV and energy storage	Peak power limits	50 kW, 100 kW PV 500 kWh ESS
[99]	Grid code compliance and grid impact details of Fast charging stations considering the power quality	Voltage fluctuation Harmonic resonant Harmonic distortion	50 kW DCFC
[69]	investigates the performance of different locations and sizes of chargers	estimation of the benefits of PV to reduce impacts on the utility	100 kW–1200 kW
[100]	Bi-level Distribution locational marginal price-based optimization algorithm for E-bus grid interaction	Managing load congestion as a demand response service	51.5 kW 112 kWh (charge-G2V)
[101]	Optimize the charging schedule to minimize the charging costs and the grid impact	Dynamic charging according to variable grid tariff	47 batteries of 240 kWh each (47 chargers with a charging power of 50 kW)
[92]	Impact of fast-charging solution of battery E-bus on distribution networks of two solutions: 1. Pantograph, 2. Slow-charging	Power quality/Harmonic distortion in current and voltages	Fast-chargers (350 kW) using pantograph and slow-chargers (50 kW)
[65]	Technical-based feasibility study of Battery Electric Buses with utility impact measures	Distribution transformers lifetime, and grid overloading. voltage regulation	250 kW-fast 200 kW-depot
[102]	grid impact evaluation of 3 charging methods: - Every Station Charging: more intermittent charging power and transformer tapping, - End Station Charging: Less intermittent charging power and transformer tapping - Overnight Charging: continuous charging power and less transformer tapping considering PV and LV grid.	- Power/current Overloading - Voltage drops (The overnight charging is grid-protecting and predictable. However, requires a very large battery (700 kWh)).	From 300 kW to 600 kW
[103]	Replacement of the passive diode rectifier with an active front-end converter in the charging station	Power quality/harmonic distortion (THDv), Flickering	120 kW
[104]	Interaction between an bus aggregator and grid operator	Power/current Overloading	–
[90]	Study on the determination of the safe level of EV penetration according to transformer loadings	Impact of higher order harmonics on distrbution transformers' temperatures	160 kW
[91]	Strategic placement of charging stations considering network capacity and future forecast.	Transformer Overloading and load shifting	600 kW
[85]	Study of the Impact of EV Harmonic Currents on Transformers in the presence of PV system.	The harmonic currents of PV to cancel the injected charging station harmonics	–
[105]	Practices used to minimize congestion impact of fast charging grid.	Congestion and power quality	600 kW (ultra-fast)
[106]	Role of E-bus charging in regulating renewable source production to smooth the impact on power demand. A V2G E-bus smart charging is compared to opportunity charging	Smart charging with PV increases the self-consumption of renewable systems by using E-transportation infrastructure as a buffer stage	80-kWh buses. (Daily total net bus charging MWh = 188.36)
[107]	PSO optimization considers the charging model including optimal power flow, degree of satisfaction, and the power grid cost.	Voltage adjustment of 10 kV On-load-tap-changer (OLTC)	–
[108]	To study the effect of harmonics injected by EV charging stations with a high level of PV penetration	Host capacity degradation as a result of low-order harmonics	–

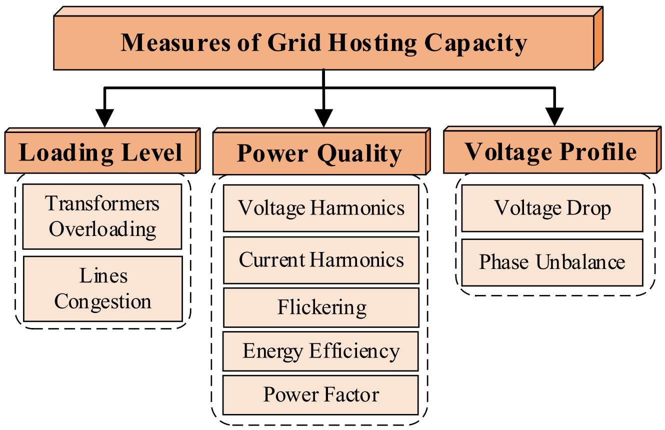
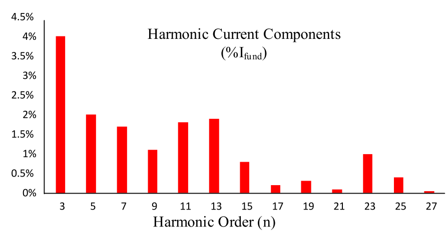
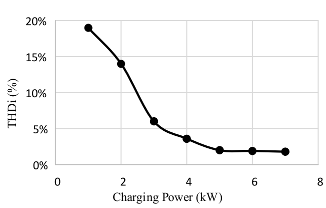


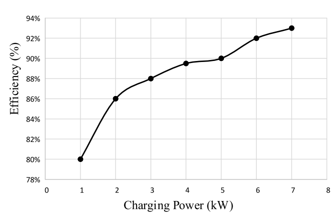
Fig. 9. Criteria affect grid hosting capacity.



(a) The current harmonics



(b) The current THD



(c) The charging efficiency

Fig. 10. EV charging and grid compatibility test [124].

ambient temperatures significantly impact Li-ion batteries. Hot temperatures cause unwanted internal reactions that work to deplete and break down the composite bonds. Hot temperatures also cause the capacity to fade, reducing lifespan and safety [132]. Therefore, temperature effects must be considered in Li-ion battery design and operation for EVs. It's important to note that while high temperatures can initially boost the performance of Li-ion batteries by quickly facilitating the reactions, the long-term effects are harmful, leading to a reduced lifespan and potential safety risks. Therefore, it's crucial to manage the temperature conditions of Li-ion batteries effectively [132].

Roundtrip efficiency of the battery operating under a high temperature for a long time will be significantly reduced. Prolonged exposure to elevated temperatures accelerates the degradation of the battery, leading to a permanent loss of capacity over time. This can result in reduced driving range. This is because the internal temperature is an important aging accelerator that influences the battery capacity and power characteristics. Moreover, optimal battery capacity is typically achieved around 21 °C, but it significantly decreases when temperatures exceed 35 °C [132,133]. Consequently, running Li-ion EVs outside the normal range incurs more charging cycles to maintain similar trip distances.

11. Implications of fast charging in hot climates

Due to changes in the electro-chemical properties of Li-ion batteries under different temperatures, non-linear response yields to represent the battery model. This non-linearity adds a layer of complexity to the battery mathematical modeling and the estimation of SOC and state-of-health (SOH) [134]. SOC is essentially a measure of the current energy level in a battery as a percentage of its maximum chargeable energy. SOH, on the other hand, is a long-term indicator of the battery's aging process and represents the ratio between the maximum chargeable energy and its full capacity. While the battery operating temperature increases, its non-linear behavior becomes more pronounced [135]. This increased non-linearity at high temperatures complicates battery modeling and analysis, leading to more complicated management systems for E-bus systems [136].

Long-term exposure to high temperatures can lead to significant damage to cells. As depicted in Fig. 11, an increase in temperature results in a greater degree of capacity fading. High temperatures cause the electrolyte layer to gradually deteriorate and dissolve into the electrolyte. This exposes part of the anode's active material to the electrolyte again, triggering side reactions. Consequently, intercalation at the anode

Table 11
Thermal specifications of most common Lithium batteries.

Battery Chemistry	Heat Tolerance Capability (Overheating)-Thermal Stability	Main Features	Safety Under Fast Charging	Generalized Evaluation[a]
1. Lithium Iron Phosphate (LFP)	Good thermal stability	Lower Energy Density, (larger and heavier for the same energy capacity)	Most Safe	83 %
2. Lithium Titanate (LTO)	Exceptional thermal stability	Lower Energy Density (Long cycle life)	Safe	75 %
3. Lithium Nickel Cobalt Manganese Oxide (NMC)	Moderate thermal stability, degrades in high-temperatures	Good balance of energy and power	Used in most of hybrid EV	79 %
4. Lithium Cobalt Oxide (LCO)	Sensitive to high temperatures, which can lead to capacity loss	High Energy Density	Safe	66 %
5. Lithium Nickle Cobalt Oxide (NCA)	Sensitive to high temperatures	High Energy Density	Safe- used in cell phones	71 %
6. Lithium Manganese Oxide (LMO)	Excellent thermal stability	Moderate Energy Density	less prone to thermal runaway	66 %

[a] The evaluation is made by evenly scoring the main features:(Cost, Lifespan, Performance, Thermal Stability, Specific Power, Specific Energy).

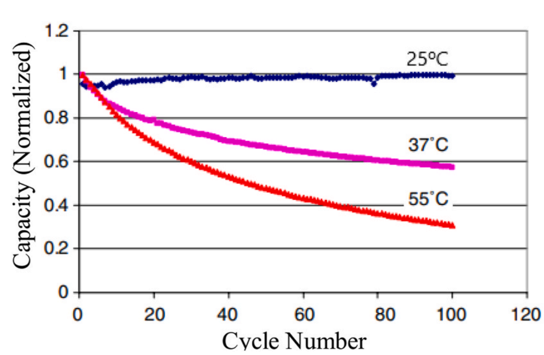


Fig. 11. The accelerated capacity fading due to high temperatures [137].

becomes more challenging, and ionic conductivity decreases [136]. Fig. 12 shows the impact of the fast charging rates (i.e., C-rate>1) on increasing the internal temperature of the battery where a significant increase occurs. This increase would impede the fast charging rates at high ambient temperatures if no efficient thermal extraction mechanism is employed. Detailed comparisons between the impact of different charging rates (C-rate) are performed in Ref. [135].

According to many experimental validations, it has been proven that the optimal operating temperature of an EV Li-ion battery pack is in the range of 15 ^{O}C to 35 ^{O}C [138–140]. Hence, the degradation is influenced by abnormal temperatures. Higher temperatures cause electrolytes to break down and increase the self-discharge rate of the battery leading to a shorter lifespan [141,142]. To comprehend the degradation behavior of batteries under different temperatures, it's essential to devise modeling methods that accurately represent the electrochemistry degradation [143,144]. Ensuring the safe operation of Li-ion batteries is a significant concern due to the large energy density and inflammable electrolytes.

It is crucial to implement safety measures to prevent thermal runaway as Li-ion batteries become unsafe at high temperatures, leading to uncontrolled electro-chemical reactions and thermal runaway. This can result in battery destruction, increasing the risk of fire and explosion [138]. Table 12 summarizes the major attributes associated with untypical operating temperatures of Li-ion batteries.

Most of Lithium battery types used in E-transportation have been surveyed to address the temperature effect on battery performance. The experimental research performed in Ref. [145] showed that a higher C-rate generates additional heat due to the increased cathode resistance. Therefore, fast charging augments the harsh environmental conditions. In Ref. [146], the authors experimented with the battery lifecycle under 30, 40, and 50^{o}C. It was shown that working with 50^{o}C shrinks the lifespan by about 3 times. In the experiments, the results showed that lifecycle decreases dramatically when the ambient temperature goes above 45^{o}C.

The authors in Ref. [147] performed a practical comparison between EV Li-ion batteries based on their state of function (SOF), considering the degraded lifespan caused by high-temperature operating conditions. The SOF includes a comprehensive evaluation that incorporates various factors influencing the performance of a battery. These factors include the weight of the SOC, charging/discharging rates, environmental temperatures, and other degradation-influencing variables. The essence of SOF lies in its ability to articulate how well the battery performance aligns with the actual power demands during its service life [147]. A direct study on EV consumption and efficiency based on city local temperature was conducted in Ref. [148]. The study considered all US states where the temperature varies from −20 °C to 44 °C according to the state. It was shown the energy consumption of the EV increased significantly when the ambient temperature exceeded 30 °C.

In [149], a review article focused on the barriers faced by the adoption of EVs in Arab Gulf countries, including the high-temperature conditions. In Ref. [150], the authors experimentally investigated the

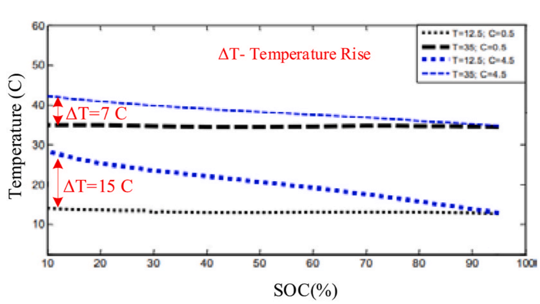


Fig. 12. The impact of fast charging rates on the internal temperature of the battery [136].

Table 12
The impacts of abnormal temperatures on Li-ion batteries.

Attribute	Hot Temperature Impacts	Cold Temperature Impacts
Temperature Range	T ≥ 35 °C	T ≤ 8 °C
Root Causes	Electrolyte breakdown Binder decomposition/ breakdown	Increased lithium plating Increased internal resistance
Chemical Side Effects	Decreased SOC	Decreased SOC
Electric Side Effects	[a]Decreased equivalent resistance (short-term). [a]Increased equivalent resistance (long-term).	Reduced conductivity. Increased equivalent resistance
Consequences on Battery	Quick capacity Fading. Complex thermal management system.	Higher Power loss
Consequences on EV	Higher cost, less age, more weight, less trip range, low charging/discharging rates, more charging stations, more power quality issues	
Long Term Impact	More	Less

[a] note: the internal resistance decreases with the temperature increase; however, with cycling increase, the resistance increases significantly at higher temperatures.

impact of summer ambient temperature in Kuwait on the EV trip range. It has been discovered that more than a 30 % reduction in the estimated travel range occurs due to high temperatures, and the temperature at the start of the trip should be as low as possible to reduce EV energy consumption. Matlab simulations performed in Ref. [151] revealed that the harsh ambient temperatures in some Moroccan cities increase the required number of charging stations. Moreover, it has been depicted that a 20 % increase in charging stations is required when the ambient temperature increases from 29 °C to 45 °C due to the reduction in the actual battery capacity. In Ref. [152], the authors proposed an adaptive thermal management system to cool the battery in harsh temperatures with minimal energy consumption.

The experimental results carried out in Ref. [153] found that fast charging rates of more than 2.0C worsen the degradation (i.e., degradation >0.015 % per cycle) of the battery, considering the cycle duration. Further, as the temperature increases, the degradation increases. In Ref. [154], the authors showed that V2G services can be restricted in high-temperature areas as the demand increases in proportion to ambient temperature. This would increase the cost of the service as it harms the long-term battery performance. Fig. 13 depicts the challenges that face the deployment of E-mobility in hot regions. The root causes and the consequences are highlighted to address the issue and enable

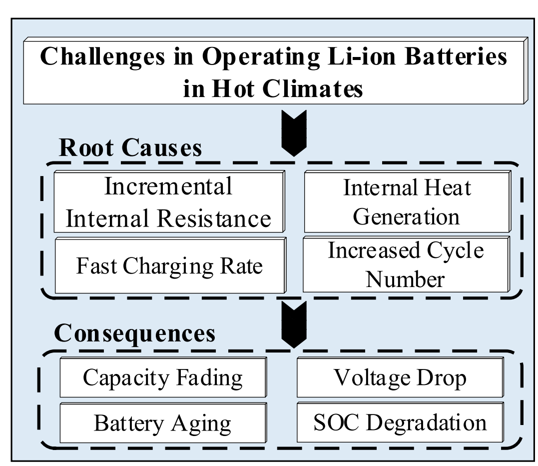


Fig. 13. Challenges imposed by hot climates on the performance of Li-ion batteries.

E-mobility in hot climate regions.

12. Thermal management systems of EV battery

The majority of operational difficulties encountered by operating heavy-duty EVs in high-temperature conditions are associated with the thermal impacts on the Li-ion batteries. As a result, precise representations of the batteries' thermal characteristics are necessary for the design of efficient battery thermal management systems. Active/passive air, fluid coolants, and phase-change materials (PCMs) are frequently used methods for battery cooling in different applications [147,152]. The initial method of heat management considered for high temperatures is air cooling. A battery pack is typically constructed with several parallel cells. This configuration makes air cooling systems a popular choice for heat management. Directing an airflow at the pack can effectively achieve the cooling effect.

In [155], the authors showed that thermal comfort inside an E-bus around 21°C in harsh conditions may increase heating, ventilation, and air conditioning (HVAC) energy consumption by 50 %. The comparison made in Ref. [19] affirmed that excessive capacity fading of Li-ion batteries occurs when the temperature exceeds 35 °C. The authors determined that LFP chemistry has the best evaluation among other chemistries, in addition to being the safest type. The work also discussed the thermal management systems used to cool battery packs. Another piece of research was reported in Ref. [20], where a detailed comparison between the thermal energy management of EV Li-ion batteries was made. The impact of cold and hot temperatures on capacity loss and battery size has been discussed and compared, where the review showed that the effect of hot temperatures (binder decomposition and electrolyte breakdown) is more dangerous than cold temperatures due to the unrecoverable characteristics and thermal explosion possibility. Due to the wide range of operating temperatures, heat pipe (HP) technology-based cooling systems were found to be more efficient than other water and PCM management systems. However, both reviews [19, 20] indicated the necessity for more investigations into heat extraction mechanisms for high charging rates at abnormal operating temperatures, including hybrid management systems for battery pack levels and real applications.

Increased temperatures can speed up reactions and boost charging/discharging power, but they also raise the risk of overheating. If the generated heat inside the battery is not removed fast enough, it can lead to a continuous temperature increase. Therefore, causing a thermal runaway. This is a situation where rising temperatures trigger conditions that lead to even more heat, which may result in battery destruction.

The thermal management system (TMS) of Li-ion batteries consists of active components, which include external and internal cooling sources, and passive systems. One of the key strategies to enhance the operation and lifespan of Li-ion batteries in E-bus under high temperatures is to reduce the internal heat generation within the batteries. The liquid (working fluid) cooling method is more prevalent due to its ease of implementation and lower technical complexity. However, PCM demonstrates superior performance in terms of the speed which can be utilized to cool down the battery [138].

The impact of high temperatures is more complicated compared to low temperatures due to the strong relation between heat generation, internal resistance, charging rate, and cycling [156]. Air cooling presents challenges due to air's low conductivity, making this method suitable for moderate temperatures and charging rates [138]. Both liquid and air-cooling systems are costly due to the need for a pump and ventilation system. As a result, PCMs have been introduced as advanced methods for EVs in low-temperature environments [157,158]. PCMs are substances that can store and release a significant amount of heat which provides an efficient heat transfer mechanism [140]. During the transformation of solid-liquid material, heat is either absorbed or released.

As shown in Table 13 where the cooling systems are compared, it's evident that each mechanism has its unique strengths and weaknesses, which are influenced by several factors. These include the specific chemistry of the battery, the temperature, and the driving cycle of the bus [159–162]. Generally, active cooling strategies are deemed more efficient in dissipating heat generated within the battery [163]. The efficiency of a specific TMS should be assessed based on an exact EV location, and its impact on battery long-term performance. Conversely, alternative strategies focus on developing battery components like the electrode and electrolyte to withstand broader ranges of temperatures [164]. According to the literature discussed before, it has been inferred that PCM provides an optimal thermal manager due to its satisfactory performance in addition to the major criteria like weight, energy consumption, and size.

In real-world tests, the researchers in Ref. [124] measured the SOC of different EV brands. The tests were conducted under freezing, typical, and hot ambient temperatures to capture the impact of the thermal management system on the battery performance. The results are given in Table 14 where it can be seen how installing an effective system is important in maintaining the battery capacity.

For a detailed analysis of the ambient temperature effect on EVs, Fig. 14 (a) and (b) show how severe ambient temperatures degrade the performance of the battery and the kilometers driven by an EV. This degradation occurs in many EV brands with some differences that exist according to the used TMS.

14. The research essential outcomes

It is not possible to optimally plan for large-scale E-transport networks without collaborating and preplanning with utility grid operators. The optimal solutions require coordinated charging systems whether including unidirectional or bidirectional power flow (i.e., G2B, B2G). The following points are highlighted in the study.

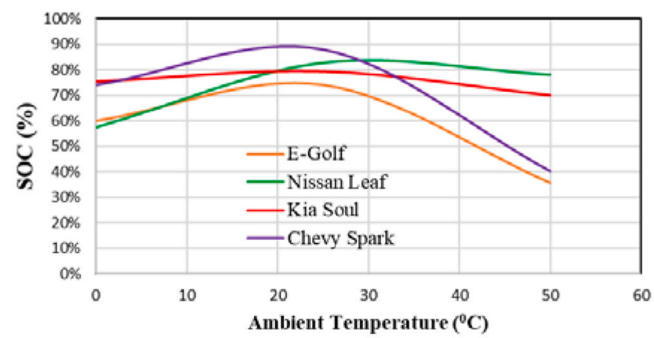
1. The paper conducted a detailed literature survey of the most relatively experimental-based articles that discuss the impact of harsh environmental conditions on battery performance, charging rates, and ancillary services. It has been shown that much of the existing literature has assumed that EVs operate under normal temperatures. However, EVs experience a range of temperatures in countries with abnormal climates, where transportation electrification is on the rise.
2. Operating E-bus in cold temperatures has been focused on in most of the literature as EVs are heavily integrated in many European and Canadian cities that have low temperatures. Therefore, the hot environment is focused on in this work to facilitate the deployment of E-bus in hot climate countries.
3. It is important to mention that many pieces of research found a significant discrepancy between the laboratory and field results of Li-ion battery characterization under different temperatures. Moreover,

Table 13
Main features of main thermal management strategies for EV batteries.

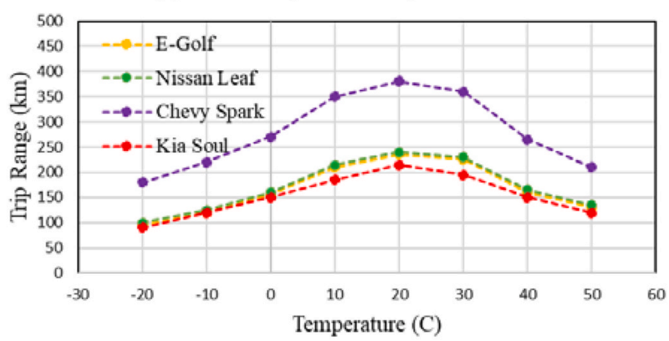
Cooling System	Advantages	Disadvantages
Air Cooling System (Passive, active)	Easy to implement, less technical complexity	Low heat transfer efficiency
Coolant Cooling System (Passive, active)	High heat transfer efficiency, effective in reducing temperature influence	High energy consumption, complexity, high heat transfer efficiency
Refrigerant Cooling System	Effective cooling power, good for high temperatures	Environmental impact, safety concerns
PCM-based Cooling System	High heat storage capacity, good for low temperatures	Less mature technology, expensive
Heat Pipe	High cooling power, efficient heat transfer, moderate complex design	High cost
Thermoelectric Cooling System	Direct conversion of temperature differences to electric voltage	Low efficiency at small temperature differences

Table 14
EV battery SOC measured values after 30 min at different ambient temperatures [124].

Make/Model	SOC at 0 °C	SOC at 25 °C	SOC at 50 °C	Cooling Mechanism
2015 E-Golf	60 %	74.2 %	35.6 %	Passive- Air (Radiator)
2013 Nissan Leaf	57.5 %	82.8 %	78.1 %	Passive- Air (Radiator)
2015 Mitsubishi i-MiEV	31.8 %	43.5 %	32 %	Active -Air (Air conditioning)
2015 Kia soul	75.4 %	79.3 %	70 %	Active-Air (Air conditioning)
2015 Chevy Spark	74.2 %	88.1 %	40.1 %	Active-Cooling liquid



(a) The temperature impact on the SOC



(b) the temperature impact on the EV trip range

Fig. 14. The behavior of SOC profiling and the ranges of different EVs at different temperatures [124].

it has been investigated that even though high temperature decreases the internal resistance of Li-ion batteries which, in turn, increases its Ah-capacity, binder decomposition and electrolyte breakdown cause fast aging. This would converse with the discussion made in Ref. [113] regarding hot temperature. In conclusion, three points should be carefully addressed to avoid the conflict:

(i) An increase in temperature correlates with a decrease in battery internal resistance,
(ii) the internal resistance tends to rise with an increased number of battery cycles, and
(iii) fast charging increases the internal temperature of the battery.

4. It is shown in this paper that the optimal solution that ensures reliable integration of fast-charging infrastructure can be achieved when the following aspects are holistically considered.
 - Proper coordination with grid operator including Bus-to-Grid service.
 - Enable short-term load forecasting, load shifting, and peak shaving.
 - Enabling demand response by establishing an incentive-based electricity market.
5. As discussed throughout the paper, there is no simple answer to optimal size, location, or charging system type. The work highlights all the factors that affect the reliability and feasibility of large-scale fast-charging systems.
6. Besides addressing the harmonic effect on the grid hosting capacity, research should look into the energy efficiency aspects of the harmonics. This is because the time horizon of the charging profile may conflict with the consequences of different THD levels. In other words, a long-term, low THD charging profile is worse than a short-term, High THD in terms of energy efficiency.
7. After analyzing several tests conducted by Idaho National Lab [124] on Level-2 (AC) and level-3 (DC) fast charging it has been concluded that the hot climate areas (40+ °C) have more potential to have feasible E-transportation systems compared to cold areas (0 °C) in many aspects. These aspects include the charging time, the round-trip efficiency, and capacity fading. However, the successful operation of fast charging E-bus systems in hot temperatures depends on adaptively coordinating an advanced thermal management system (as discussed in Refs. [19,20]) with adaptive charging/discharging rates and customized cooling mechanisms.
8. It has been concluded that fast charging rates increase the internal temperature of the battery. Therefore, deploying fast-charging infrastructure in hot ambient temperatures requires careful attention including shading and ventilation of the charging stations.

13. Li-ion battery cycling under high temperatures

High temperatures can have damaging effects on both the charging and discharging processes of Li-ion batteries. After a certain threshold, they can cause capacity degradation, thermal-safety issues, reduced efficiency, and overall diminished battery performance. Hence, it is crucial to assess the thermal efficacy of Li-ion batteries following a sufficient number of tests, as the impacts of many factors appear after a specific number of cycles and a considerable service duration. Table 15 compares the consequences between the two modes and their effects on the battery performance.

To further get insights into the effect of temperature on Li-ion batteries, Fig. 15 shows the testing results of an EV battery SOC profile and the corresponding battery temperature at different operating temperatures. It can be seen how the high temperature affects the charging time (i.e., 15 min more) and degrades the battery voltage which impedes the battery from reaching a higher SOC level (i.e., 27 % less).

In [165], the effectiveness of the power conversion of a fast charging system showed a slight reduction when the charging temperature was shifted from 25°C to 40°C where the efficiency decreased from 93 % to around 90 %. In Phoenix, AZ, E-bus route testing where summer temperatures touch the upper 40s (i.e., T > 40°C), it was revealed that hot climates extend the charging time of the E-buses due to uncontrolled heat generation. In addition, it was recommended to shade and air condition the charging stations to satisfy charging time [166].

This city is among very few hot climate cities that integrate E-bus services and shows the importance of shading and air conditioning the charging infrastructure itself which affects the economic aspects of such projects.

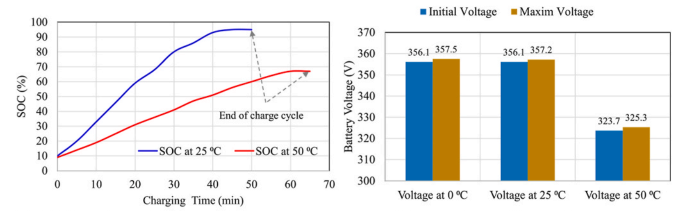
In [167], the authors have introduced statistical models for predicting battery charging durations based on ambient temperature. Using regression analysis, they have developed a formula that represents the relationship between the final SOC, charging duration, ambient temperature, and initial SOC. Notably, their empirical model demonstrates that as ambient temperature increases, the time required to achieve a high SOC decreases. However, the validation has only been conducted at temperatures of 0 °C and 25 °C which may not be valid for higher temperatures and limits the correctness of the results.

Given the importance of documenting the results of practical experiments related to the automotive industry, the charging profiles of two common EVs are depicted in Figs. 16 and 17. The figures

Table 15
The major aspects associated with the cycling of Li-ion batteries at high temperatures.

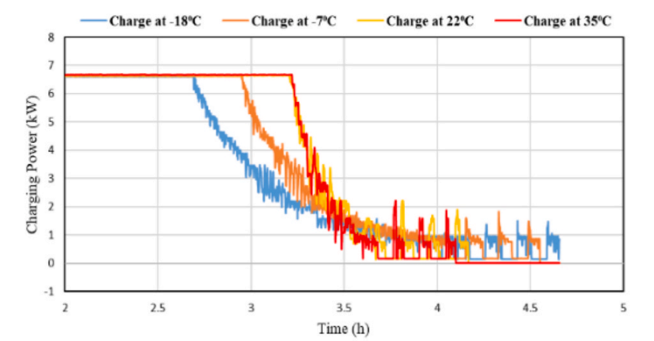
Charging Mode		Discharging Mode	
Challenge	Comment	Challenge	Comment
Increased Reaction Rate	Hot temperatures augment the reaction rate, resulting in an augmented power output. But, this increases heat dissipation which adds extra unwanted heat.	**Increased Power Output**	High temperatures can increase the power output of the battery.
Slow Heat Dissipation	If heat isn't dissipated faster than it's generated, the temperature will continue to rise, potentially leading to a thermal runaway situation.	**Electrolyte Transfer Speed**	As the temperature increases faster, the transfer rate of the electrolyte decreases.
Temperature Limits	The permissible charge temperature is between 0 °C and 45 °C. Good charge performance is ensured at high temperatures but it leads to shorter life.	**Performance Impact**	Lithium-ion batteries can handle an elevation in temperatures. However, keeping the battery discharging for long periods at higher temperatures may lead to gas generation.
Charging Restrictions	As the temperature goes high, the chemical balance can be destroyed and side reactions start.	**Voltage Drop**	The battery's internal resistance can cause a significant voltage drop during discharge, reducing the available power output.
Safety Concerns	Charging Li-ion batteries in high temperatures leads to partial breakdown and initiates thermal runaway	**Reduced Energy Efficiency**	High-temperature discharging is less energy-efficient. More of the energy is dissipated as heat due to increased internal resistance.
Reduced Capacity	The reactions that occur during charging are less efficient at elevated temperatures, resulting in a lower amount of charge stored.	**Shortened Lifespan**	Similar to charging, discharging a Li-ion battery at high temperatures can also negatively affect its lifespan. The accelerated chemical reactions at elevated temperatures can lead to quicker degradation of the battery's components.
Shortened Battery Lifespan	Prolonged charging at high temperatures can cause accelerated degradation of the battery. This can result in a shorter overall lifespan.		

demonstrate the effects of ambient temperatures on charging duration. For the temperatures considered in the test, the charger maintains a steady power output during the constant current phase until reaching a specific SOC. After that, constant voltage mode starts where the charging power begins to decrease gradually at higher SOCs. Several minutes longer charging time of high-temperature charging can be observed. Comparing the three charging profiles, it can be seen that the 35 °C profile takes a longer time to finish the charging cycle and the battery consumes more power required by the battery management

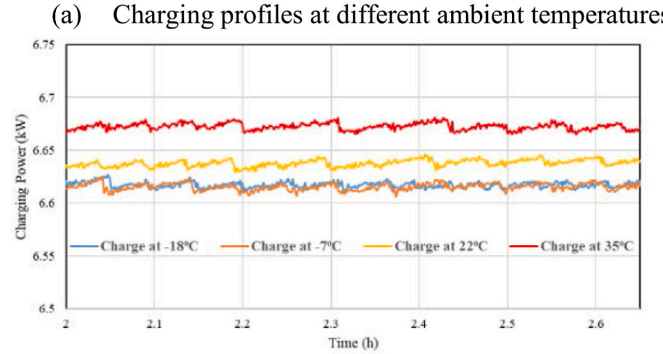


(a) SOC profiles at different temperatures (b)the corresponding voltages

Fig. 15. Complete charging cycle measurement of Li-ion 2015 E-Golf EV and the battery voltage.



(a) Charging profiles at different ambient temperatures



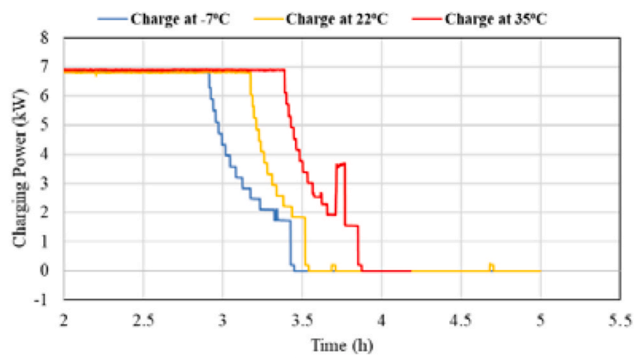
(b) Zoomed version during the constant current region

Fig. 16. Level- 2 charging profiles of Li-ion Nissan Leaf battery under different ambient temperatures [168].

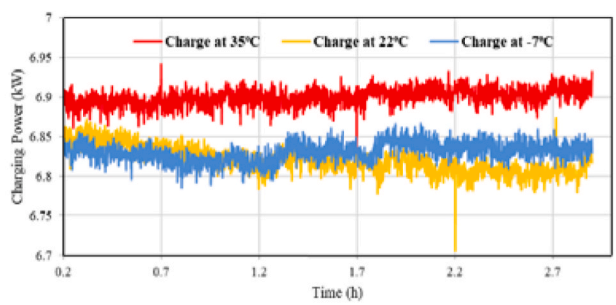
system.

The report made by the American Automobile Association (AAA) [169] showed that several tests have been made to show the impact of cold (-7 °C) and hot (35 °C) temperatures on the energy consumption of different EV brands. For the high-temperature operation, the comparison compared the normal 22 °C temperature to 35 °C where variations in ambient temperatures led to reductions in trip range. Moreover, the utilization of heating, ventilation, and air conditioning (HVAC) systems leads to substantial reductions in trip ranges and reduced fuel economy. These reductions are influenced by temperature-dependent factors and battery capacity. Normally, when the temperature reached 35 °C, it caused a 4 % reduction in driving range and a 5 % reduction in equivalent fuel efficiency referring to 24 °C test conditions, considering that HVAC was not running. After turning on the HVAC, substantial declines in trip range and fuel efficiency were observed. It is important to mention that the target of this paper is to address the consequences of temperatures higher than 35 °C, whose impacts are more significant and pronounced. However, to the best of the authors' knowledge, limited real automotive-related experimentations and resources are reported in the literature.

To quantify the impact of the HVAC on the trip range, Fig. 18 (a) and (b) present a bar graph of fuel consumption in Mi/Gallon values of different EVs before and after operating the HVAC system at three



(a) Charging profiles at different ambient temperatures



(b) Zoomed version during the constant current region

Fig. 17. Level- 2 charging profiles of Li-ion Ford Focus battery under different ambient temperatures [168].

different ambient temperatures. The values show the significant impact of the HVAC on the fuel economy of EVs. It can be concluded from Fig. 18 that both hot and cold ambient temperatures, caused a tangible decrease in trip range and efficiency. At low temperatures (−7 °C), a 12 % decrease in trip range occurs. At high temperatures (35°C), around a 5 % decrease in the trip range compared to the 24 °C operating climate. When HVAC is ON, −7 °C ambient temperature decreases the trip range by about 40 % whereas 35°C driving conditions decrease the range by almost 17 % compared to 24°C driving temperature [169]. Higher temperatures would lead to increased HVAC energy consumption.

A nonlinear degradation model presented in Eq. (1), can be used to accommodate the battery performance model in a more accurate way compared with many linear models. The model illustrates a specific case involving a temperature effect where the model parameters are denoted as β_0, β_1, and ρ. The average performance is characterized by a degradation model, $\mu(T, t)$. It's important to note that this model is semi-empirical in nature. Accordingly, the change in the degradation parameter is constrained by the availability of reactive materials. The final model can vary significantly according to the calculated parameters. Fig. 19 shows the resulting nonlinear model fit. The adverse effect of high temperature on increasing the resistance and thereby decreasing the capacity can be observed.

$$\mu(T,t) = \left[1 + e^{t(\beta_0+\beta_1/T)}\right]^{\rho} \tag{1}$$

The employed degradation model can be utilized to assess the average lifespan of a cell under specific ambient temperature conditions and predefined end-of-life (EOL) criteria. The determination of EOL criteria is contingent upon various factors encompassed within the life model. In instances where a solitary stress factor, such as temperature, and a performance metric of relative resistance are considered, the EOL criterion may be specified as a 30 % augmentation in degradation at a given temperature, denoted as $\mu(T_0, t) = 1.3$ at EOL. The relative resistance (i.e., battery resistance after a certain number of cycles divided by the initial resistance) is used as a performance measure to quantify the battery degradation. The measure is used as the internal impedance of the battery increases over time irrespective of ambient temperature.

Regarding the nonlinear degradation model delineated in Eq. (1), the resultant estimated lifetime, ($\hat{t}_{EOL}$), is expressed in Eq. (2), where parameters marked with the hat symbol ˆ represent values derived from nonlinear regression-based estimations. The resultant degradation model can predict the average lifespan of a cell under defined temperature conditions and EOL criteria. By employing the nonlinear degradation model presented in Eq. (2), the estimated lifetime can be computed using parameters acquired through nonlinear regression. Assuming an EOL criterion of 30 % rise in relative resistance at T_o = 30 °C, substituting the relevant parameters into Eq. (2) results in a calculated lifetime estimation of 12.0 years.

$$\hat{t}_{EOL} = \frac{\mu(T_0,t)^{\frac{1}{\hat{\rho}}} - 1}{e^{\left(\hat{\beta}_0 + \frac{\hat{\beta}_1}{T_0}\right)}} \tag{2}$$

The authors in Ref. [170] conducted a test on EVs to characterize the impact of hot climates under different charging modes. The concluded

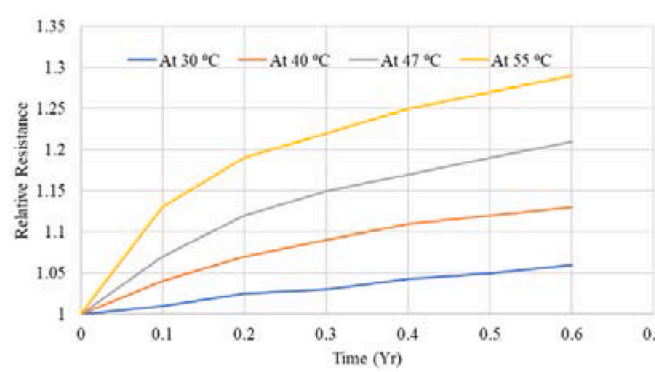
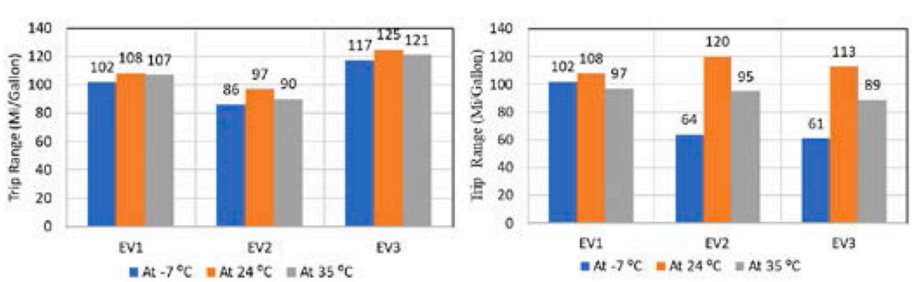


Fig. 19. Temperature-dependent fitted nonlinear model.



(a) before turning on the HVAC (b) after turning on the HVAC

Fig. 18. The ambient temperature impact on Li-ion EV with and without turning on the HVAC.

results are depicted in Fig. 20 where it can be seen that the fast charging causes additional heating to the battery. On top of that, the results show that there was a slightly greater reduction in battery capacity when being fast-charged. It's worth mentioning that higher ambient temperatures seemed to accelerate the capacity loss in all the E-buses in the study. Additionally, the same study revealed that fast charging, on average, raised the battery temperature by approximately 8°C. Fig. 21 shows the measured value of the internal resistance and its relation to the charging speed. This factor is very important to explain the decaying performance of EV batteries under both high temperatures and fast charging.

15. Research gaps

- Considering the grid impact when planning for fast charging systems is crucial and includes several technical aspects. Fast charging incurs extra risk and costs on the investment when charging during peak hours and high electricity rates. However, the majority of the conducted research focused on cost minimization without identifying realistic grid impacts.
- One of the research gaps found in the literature is the missing mathematical model and circuit model of Li-Ion batteries at high temperatures. After obtaining the experimental models, the existing models have been identified through several parameter identification techniques as performed in many pieces of research.
- Some discrepancies were found in the literature regarding the exact effect of high temperatures on the performance of Li-ion batteries. Therefore, concise and detailed analyses should be performed considering the application, size, charging speed, and actual conditions when comparing the results.
- Another research gap found in the literature is the very limited studies on E-bus systems performance in hot climates.

16. Conclusion

This paper investigates the optimal deployment of E-bus charging infrastructures in harsh climate cities. The investigations consider the impact of high temperatures, Li-ion battery performance and characteristics, fast charging rates, advantages and disadvantages of grid interaction, types of charging stations, and optimal approaches in planning, designing, and operating the charging infrastructure.

The substantial influence of high temperatures on Li-ion batteries is highlighted and discussed. The aspects include long-term performance, capacity deterioration, electro-chemical reactions, thermal management schemes, and safety. The effect of higher temperatures has been specified and compared to help alleviate the temperature effect on reliable deployment of E-bus transit systems in hot climate cities. The discussion highlighted a significant reduction in the driving range of EVs, with the decrease being further exacerbated by the increased energy consumption for HVAC. It negatively affects the performance of Li-ion batteries, leading to a reduced E-bus trip. High temperatures accelerate degradation, reducing the overall lifespan of the battery. This, in turn, can increase the cost of battery replacement or maintenance. High temperatures can lead to thermal runaway and potentially hazardous situations. Implementing efficient thermal management systems, utilizing cutting-edge technologies, and using standby and preconditioning techniques can all help regulate and maintain the battery's temperature within an ideal range in order to lessen the negative effects of temperature on Li-ion batteries. Solutions proposed in the literature focused on advanced cooling, battery oversizing, regulated charging, and deploying more charging stations.

The operation of Li-ion batteries in hot temperatures has great potential compared to cold weather operations with the existence of an efficient thermal management system. This would emphasize the high possibility of deploying E-buses in hot climate countries while ensuring a feasible, safe, and environmentally friendly transportation system.

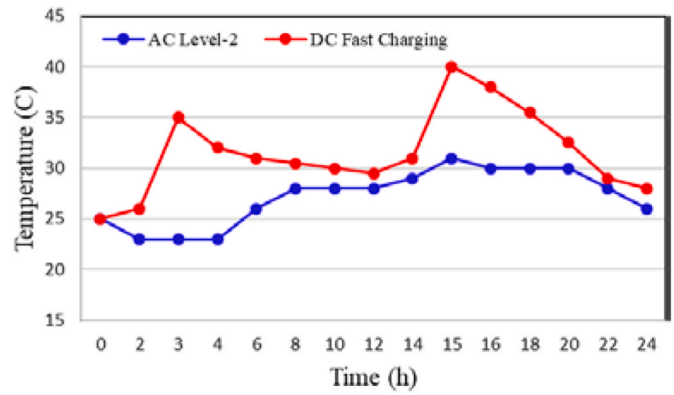


Fig. 20. Charging mode effect on battery temperature [170].

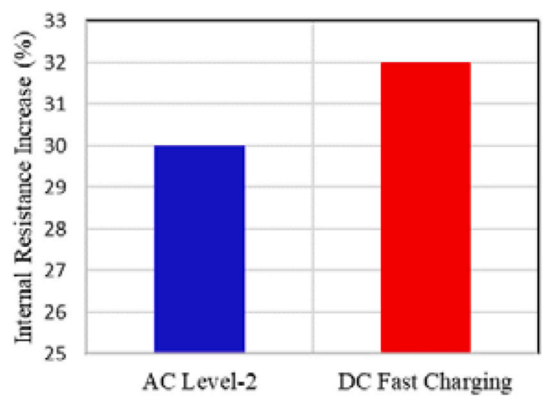


Fig. 21. Percentage increase of the battery internal resistance measured after 80, 000 km [170].

CRediT authorship contribution statement

Salman Harasis: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Irfan Khan:** Supervision, Validation, Writing – review & editing. **Ahmed Massoud:** Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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