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TOPICAL REVIEW

Electric Vehicles Under Low Temperatures: A Review on Battery Performance, Charging Needs, and Power Grid Impacts

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ABSTRACT Electric vehicles (EVs) are gaining mainstream adoption as more countries introduce net-zero carbon targets for the near future. Lithium-ion (Li-ion) batteries, the most commonly used energy storage technology in EVs, are temperature sensitive, and their performance degrades at low operating temperatures due to increased internal resistance. The existing literature on EV-power grid studies assumes that EVs are used under "perfect temperatures" (e.g. 21 Celsius) and temperature-related issues are ignored. In addition, most of the countries/regions with high EV penetration (e.g. Norway, Canada, northern parts of the US and China, etc.) experience harsh cold months, making it extremely critical to understand EV performance and consequently their impacts on the electrical power networks. In this paper, we present a systematic review of the literature that considers the combined investigation of Li-ion battery technology and power networks, focusing on their operation under suboptimal weather conditions. More specifically, we review: (i) the impact of low temperatures on the electrochemical performance of EV batteries in parking, charging and driving modes, (ii) the challenges experienced by EVs during charging and associated performance degradation, and (iii) the additional impacts of EV charging on the power networks. Our analysis shows that there are serious research gaps in literature and industry applications, which may hinder mass EV adoption and cause delays in charging station roll-out.

INDEX TERMS Electric vehicles, Li-ion battery, low temperatures, power grid impacts, power quality.

NOMENCLATURE

BMS	Battery Management System.
BTMS	Battery Thermal Management System.
CO_2	Carbon dioxide.
CC	Constant Current.
CV	Constant Voltage.
CENELEC	European Committee for Electrotechnical Standardization.
DSM	Demand Side Management.
DoD	Depth of Discharge.
EV	Electric Vehicle.
EVSE	Electrical Vehicle Supply Equipment.
EN	European Norm.
ESS	Energy Storage System.
FEC	Full Equivalent Cycles.
GHG	Greenhouse Gases.
HVAC	Heating, Ventilating and Air-Conditioning.
ICE	Internal Combustion Engine.
IEC	International Electrotechnical Commission.
Li-ion	Lithium-ion.
LV	Low Voltage.

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MV	Medium Voltage.
PCM	Phase Circuit Material.
PV	Photovoltaic.
SEI	Solid Electrolyte Interphase.
SoC	State of Charge.
SoH	State of Health.
SAE	Society of Automotive Engineers.
TDD	Total Demand Distortion.
THD	Total Harmonic Distortion.
V2G	Vehicle to Grid.

I. INTRODUCTION

A. CURRENT EV STATUS

Climate change is one of the world's critical environmental problems, threatening the sustainability of our planet. Anthropogenic carbon dioxide (CO_2) emissions and other greenhouse gases (GHG) are at the highest level in history. Transportation is a critical sector to decarbonise, as nearly one-fourth of global GHG emissions come from this sector. Light-duty transport vehicles contribute to almost three-quarters of these emissions due to using gasoline and diesel as primary fuels [1]. The importance of sustainable energy and decarbonisation became more important following the 2015 Paris Agreement. Governments of major economies began promoting the decarbonisation of certain sectors, but the main attention has been given to electricity and transportation. For instance, in 2019, it was reported that 21% and 27% of UK greenhouse gas emissions were attributed to the electricity supply and transportation sectors, respectively [2]. Therefore, to tackle climate-related issues, the UK government has set a goal to achieve net-zero emissions by the year 2050.

Electric vehicles (EVs) are essential in helping the transportation sector become carbon-neutral and achieve its carbon reduction goals. EVs significantly reduce emissions because their well-to-wheel emissions are half that of the internal combustion engine (ICE) vehicles when the electricity is also generated from low-carbon resources [4]. Therefore, many governments, including the UK Government, are targeting to end sales of cars powered by petrol and diesel by 2030 [2], [4]. The US government has declared that half of the vehicles sold in 2030 will be EVs [5], while the Norwegian Parliament has established a nationwide target for all new cars sold in Norway to be zero-emissions by 2025 [6]. Decarbonisation of the electricity sector continues to grow due to sharp declines in the per kWh energy generation cost of renewables. Most countries generate a significant fraction of their electricity through clean energy resources such as solar and wind, and have started to phase out coal and natural gas power plants. The global renewable generation capacity grew by over 9% in 2022, reaching 3372 GW [7]. The goals of selected countries related to electrification and the net-zero target are shown in Figure 1.

Currently, EVs represent a relatively small percentage of the current light-duty vehicle fleet and sales. There were 10 million EVs on the road worldwide at the end of 2020, and nearly 3 million were sold worldwide, representing a 4.6% market sales share [3]. EV sales were boosted due to factors such as price reductions, technological improvements in battery storage, incentives offered by the government, and vehicle manufacturers' strategic shift towards selling only EV models [8], [9], [10]. It is estimated that EVs will account for 30% of the global passenger vehicle fleet in 2032. Similarly, the EV fleet in the UK is expected to reach nearly 24 million, and the EV market in Norway will be around 90% by 2030 [11]. At the moment, China has by far the largest EV fleet in the world, with more than 4.5 million EVs and is expected to be a global leader in mass-EV adoption [3].

B. CHARGING INFRASTRUCTURE

The mainstream acceptance of EVs also depends on deploying sufficient EV charging infrastructure to meet diverse customer needs. The EV chargers could be broadly grouped into three categories as Level 1, Level 2 and Level 3/fast chargers [12]. These types represent the charging rates since they have different power outputs. Each charger has its own set of connections suited for low- or high-power applications and charging by AC or DC. Level 1 chargers, rated up to 3 kW, are commonly used for home charging using existing power outlets. Level 1 chargers are well suited for overnight charging, as filling up a typical EV battery takes long hours. Level 2 chargers are typically rated between 6.6 kW and 19.2 kW. If there is spare capacity, these chargers could be installed at homes. Nevertheless, their primary application is public parking spaces such as shopping malls, workplaces, and airports [13]. However, Level 3, or DC Fast Charge, uses an external power electronics unit, using higher peak outputs (up to 400kW) at typical charging rates of 50kW. The Society of Automotive Engineers (SAE) has defined different charging levels with the SAE J1772 standard for EVs, shown in Table 1, along with the characteristics of these levels. Notably, most European countries adopt IEC Standards, which are slightly different from the SAE standards due to different voltage levels shown in Table 1.

Charging power is delivered to the EVs via on-board or off-board charging systems. The former converts grid-supplied AC power into DC in the battery of the EV (inside the actual vehicle), generally used for Level 1 and Level 2 charging. The latter converts incoming AC power into DC in the charging station to charge the battery of the EV (outside the actual vehicle), used for DC fast charging. On-board chargers transfer less power and add another weight to the EV, but the battery heating problem is not a concern. In contrast, off-board chargers maintain higher power and remove weight on EVs, but the issue of battery heating needs to be addressed [14].

According to data from the Department for Transport for Great Britain [17], the UK had over 25,000 charging points as of October 2021. The most frequent charge points were for fast charging, accounting for over half the total. The number of public charging points has increased on average at an

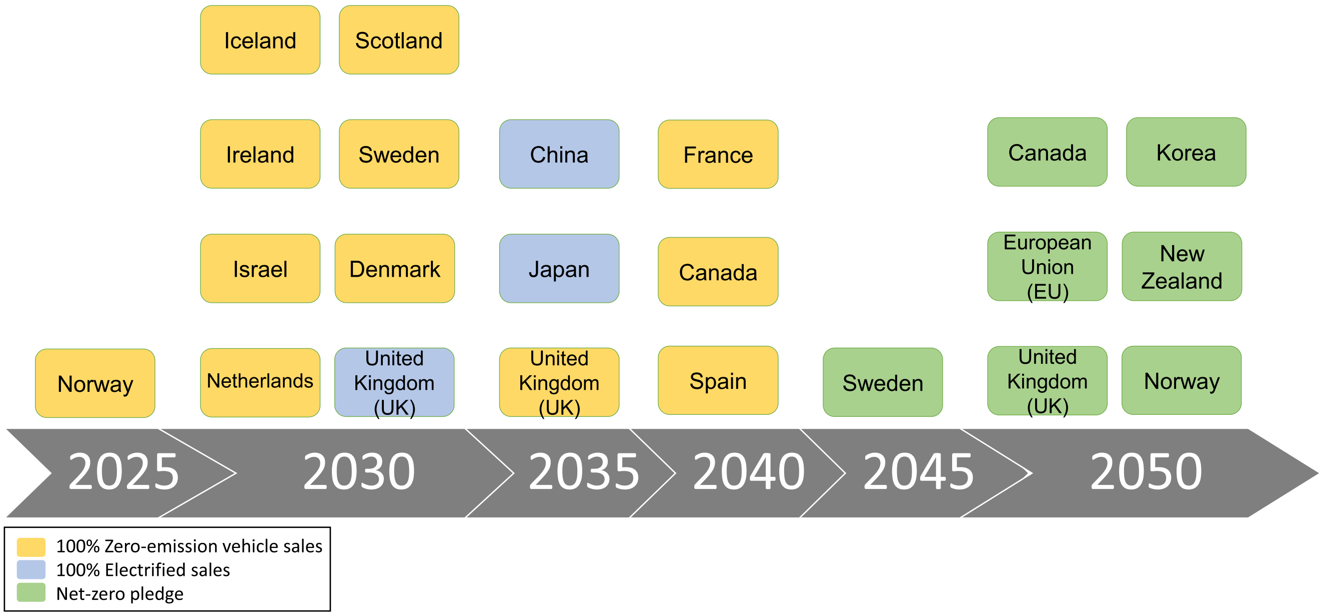

FIGURE 1. ICE bans, electrification and net-zero emission pledges for different countries [3].

TABLE 1. Characteristics of different EV power charging levels [15], [16].

	Level 1 (Slow)	Level 2 (Semi-fast)	Level 3 (Fast)
Current limits (A)	12 - 16	24 - 80	80 - 400
Voltage limits (V)	120 (AC)	208 - 240 (AC)	50 - 1000 (DC)
Max Power (kW)	1.44 - 1.92	5 - 19.2	80 - 400
Charging time (h)	4 - 12	2 - 6	0.2 - 1.0
Phase	1-phase	1-phase	3-phase
Charger location	On-board	On-board	Off-board
Installation of charger	Domestic	Domestic - Public	Public

annual rate of 9 per cent every quarter since 2015. Rapid charging devices grew more quickly, at 13% over the same time frame. Regarding electric car models, Tesla Model 3 was the best-selling electric car model globally in 2020 (365 out of 1,000 units) [18]. Although there are several models of this electric car, the standard model has 60 kWh of battery capacity [19]. This battery can fully charge in over 20 hours of slow charging, whereas it only takes about 1 hour of fast charging (e.g. 50 kW) under the optimum temperatures.

In 2020, nearly 386,000 public fast chargers were deployed worldwide, with over 80 per cent located in China. Similarly, there were 922,216 publicly accessible slow chargers (Level 1 and 2), with over 54% located in China [20]. In EV charging infrastructure planning, there is naturally the question: is there a golden ratio for EVs versus the number of public charging stations, such that steady growth of EV uptake is maintained? Answering that question is not straightforward and requires a regionally-specific framework, which considers factors like per cent home charging, driving time, battery type, weather conditions, and others into account as key inputs [21], [22]. For example, countries like China, Japan, and Singapore have higher proportions of multifamily housing compared to single-family homes. Thus, the share of faster charging points needed is substantially higher compared to other countries. The availability of parking garage charging reduced the demand for quick charging capacity on shorter day trips, especially in early market deployment. On the other hand, building in-home charging investments is also needed [23].

C. PROBLEM STATEMENT AND CONTRIBUTIONS

Over the last decade, there has been a growing amount of literature on EV grid impact studies that focus on power quality (e.g. voltage, harmonics), transmission congestion, and generation-side impacts [24]. On the other hand, existing literature assumes that EVs operate under optimal driving conditions, namely 21.5°C optimal temperature when they show their best performance. However, under low (e.g. less than 5°C) or high temperatures (e.g. more than 30°C), the performance of EVs significantly degrades as a sizable portion of the stored energy is used for heating (or cooling the battery) and the driver's cabin. Therefore, the battery used for traction reduces in line with the low ambient temperatures [25], [26].

In addition, EV charging durations are adversely affected by low-temperature conditions. Low temperatures influence EV battery's electrochemical structure [28]. As a result,

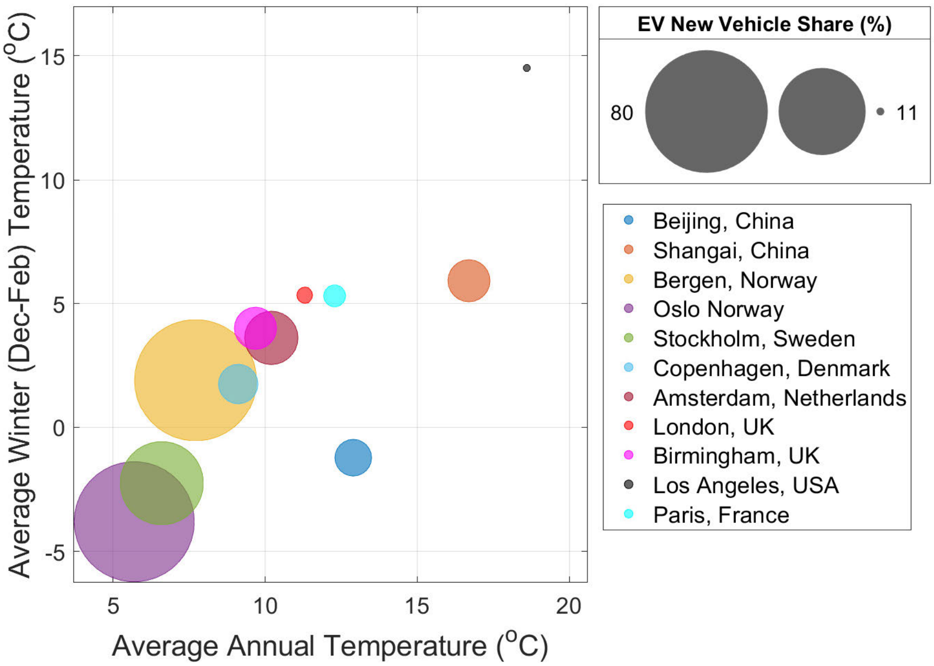

FIGURE 2. EV share and average temperature for some highly EV-integrated cities [27].

accelerated internal chemical reactions affect EV performance and safety. To maintain its safety, Battery Management System (BMS) limit the charging rate when the battery is cold [29]. Therefore, the charging rate of DC fast chargers is considerably reduced under low temperatures. The charging times could be doubled, thereby negatively impacting the schedule of EV drivers and EV fleets under low temperatures (less than -10°C) [30]. Another impact could be on the utilisation of public chargers. EV load profiles may shift to peak hours during winter owing to increased use of public chargers and prolonged charging times, which may cause long vehicle queues. Last but not least, range anxiety could be boosted in winter months, negatively impacting customer confidence in EVs [31].

The research gap between existing studies and actual impacts could be severe as the vast majority of the countries with high EV penetration are located in the Northern Hemisphere (e.g. China, Canada, Norway, and the UK) and have cold winter months. As shown in Figure 2, annual and winter temperature averages are very low in cities and countries with high EV penetration. The estimated EV demand could be higher in the winter months, the peak hours could be shifted, and additional power quality issues could arise as fast chargers operate below their rated capacity. To that end, the contributions of this paper can be enumerated below:

- This paper presents a compact survey of the EV grid integration under suboptimal weather conditions. The associated weather impacts are classified into three groups (i) the performance of batteries, (ii) EV driving experience, and (iii) the impact on power networks and the discussion of mitigation strategies as described below. These three groups are structured as follows.
- Firstly, battery-level impacts of low temperatures EV charging are investigated. A thorough literature review on Li-ion batteries, their working principles, electrochemical properties, health, and performance characteristics under varying ambient temperatures are presented. Empirical evidence on the ageing, degradation and energy demand under varying ambient temperatures are presented.
- Secondly, vehicle-level impacts such as all-electric range degradation, energy for preheating, and charging durations are presented. Both theoretical and empirical studies are analysed and presented to provide a holistic view of the existing literature.
- Thirdly, existing literature on EV-grid impacts is presented. The relevant definitions and standards on EV charging, power networks, and power quality are presented. Then, the additional impacts of low temperatures EV charging, apart from existing studies, on distribution networks and power generation are discussed. The implications on power harmonics are capitalized, as this has been an untouched area in the existing literature.
- Lastly, mitigation strategies to cushion low temperatures in EV charging are discussed in detail. In the last section, key research gaps and conclusions are presented.

A pictorial overview of the impacts of low temperatures on EV charging and the power networks is shown in Figure 3.

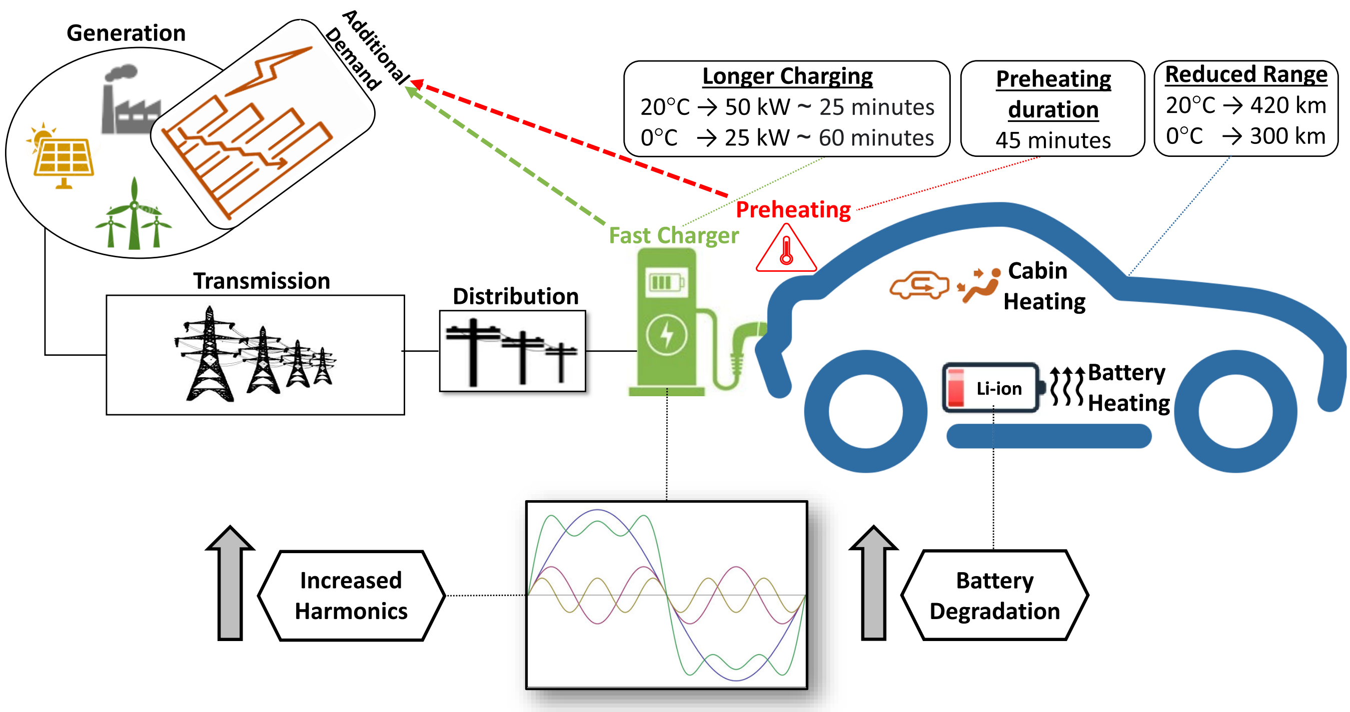

FIGURE 3. Impacts of fast charging on EVs and power distribution network under low temperatures.

While the paper presents a holistic literature review, special attention is given to highlighted challenges (battery degradation, reduced range, long charging times, increased harmonics, etc.) described in Figure 3.

It is noteworthy that EV batteries and charging sessions represent similar behaviour under high temperatures [32]. However, this study primarily focuses on the impacts of low temperatures because EV penetration is much higher in cold-climate countries, and we take a holistic review of the effects of low temperatures on EVs and power grids with case studies and mitigation strategies.

II. OVERVIEW OF EV BATTERY (LITHIUM-ION) TECHNOLOGY

A. BACKGROUND

Li-ion batteries are among the critical enabler technologies for EVs. This section provides an in-depth analysis of the underlying technology. The history of Li-ion batteries dates from the late 1950s, when the solubility of lithium was investigated in various non-aqueous electrolytes, such as inorganic lithium salts and insoluble salts dissolved in propylene carbonate. Formation of a passivation layer was observed, allowing for the ionic transport but also not allowing a direct chemical reaction between the lithium and electrolyte [33], [34]. These observations stimulated studies of Li-ion battery stability. Since the early 1960s, Li-ion (non-rechargeable) primary batteries have been available in the market. Further advances in understanding lithium's interaction with various materials have made the Li-ion secondary battery (rechargeable) a widespread option [35]. These batteries, which started being used commercially at the start of the 1990s, are the most common types of batteries used in a variety of applications, such as handheld electronics and, of course, in EV technologies [36].

The working principles of the Li-ion battery technology are presented next. A Li-ion battery is composed of an anode, a cathode, an electrolyte, current collectors (positive and negative), and a separator. Both anodes, made from graphitic carbon, and cathodes, made from lithium metal oxide, store lithium. The electrolyte, made from lithium salts dissolved in organic carbonate, is the liquid which acts as a lithium-ion transporter. Electrical current flows from an aluminium/copper collector across a device. Each current collector gets electrons from the external circuit, depending on if the battery is charging or discharging. A porous polymer separator allows the lithium ions to flow freely between the anode and cathode. It also blocks the flow of electrons within the battery. The structure of the Li-ion battery is shown in Figure 4. When the Li-ion battery is discharged, the lithium atoms stored in the anode are released into the cathode, becoming lithium ions via electrolytes and electrons via the outer circuit. During charging (plugging in a device), lithium atoms stored at the cathode are released to the anode as lithium ions through the electrolyte and electrons through the external circuit [37], [38], [39].

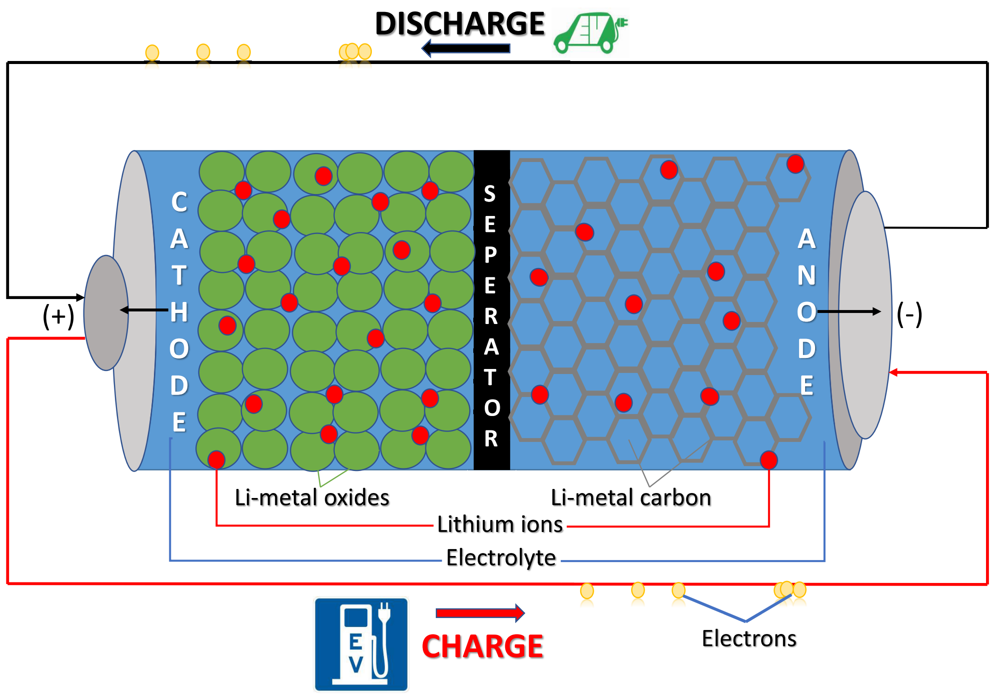

FIGURE 4. Schematic overview of a Li-ion battery during charging and discharging.

Li-ion battery technologies have been the dominant energy storage technology for the EV market. Li-ion batteries provide several advantages, including the ability to recharge, high energy density (75–200 Wh/kg), high power density (150–315 W/kg), high operating voltage (3.7 Volts), long cycle life (1000-10000 cycles), low self-discharge (0.1–0.3% per day), the fast response time (order of milliseconds), very high cycle efficiency (up to 97%), and reliability needed for end-users. Since Li-ion batteries have these benefits, they are lighter and smaller than other secondary batteries, namely, nickel-cadmium, nickel-metal hydride, and lead-acid batteries [40], [41], [42].

B. CHALLENGES WITH LITHIUM-ION BATTERIES

A few challenges are associated with the further widespread deployment of Li-ion batteries. These challenges include limited energy density, longevity, longer charging times, and technical barriers, such as high material cost, uncertainties in serviceability, and lack of maintenance and repair infrastructures for EV applications [42], [43], [44], [45]. Moreover, some of these issues are likely to be intensified in regions with low temperatures, which is another significant factor affecting the performance of EV batteries [32]. Therefore, it is essential to investigate the effects of low temperatures on EV batteries, as many studies today assume that EVs operate under optimum temperature conditions.

Battery modelling is also challenging due to complex electrochemical mechanisms, non-linear characteristics, variation across battery types, and limited data for availability, necessitating precise validation. Battery modelling refers to developing a mathematical representation of a battery's performance and behaviour. This may include various modelling aspects, such as the battery's electrical characteristics, thermal behaviour, and mechanical properties under different operating conditions, such as charging and discharging. Battery modelling aims to comprehend how a battery can perform under varying operating conditions and optimize its operation [46].

Modelling lithium-ion cells is critical in building BMS, ensuring battery pack safety and reliability. Common modelling techniques for Li-ion batteries are categorized as (i) circuit-based, which is founded on the electrical circuit of the battery; (ii) chemistry-based, which is based on battery chemistry and its electrochemical equations; and (iii) empirical models based on laboratory testing [47].

In circuit-based models, modelling of the battery is done using electrical components. With these components, the battery can be easily incorporated into the system modelling of the EV and is computationally inexpensive. The equivalent circuit model of the battery is shown in Figure 5. V_{OC} represents the open-circuit voltage, and it depends on the SoC of the battery. R_S represents the battery's internal resistance. R_P and C_P represent the battery's dynamic characteristics while charging and discharging [48], [49].

Chemistry-based models clearly reflect the chemical processes in the battery, in contrast to equivalent circuit modelling approaches. These models are the most accurate battery models since they extensively represent the battery processes. However, the highly detailed explanation also introduces considerable computational complexity. It can take many hours to simulate the charge-discharge cycle of this battery model [47], [50].

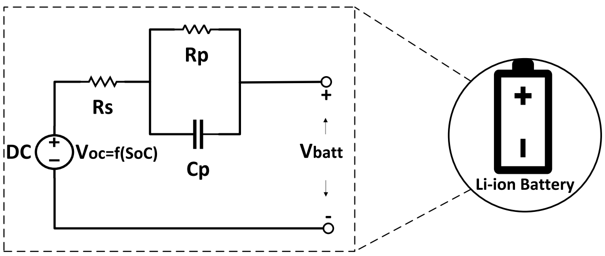

FIGURE 5. Battery equivalent circuit model [47].

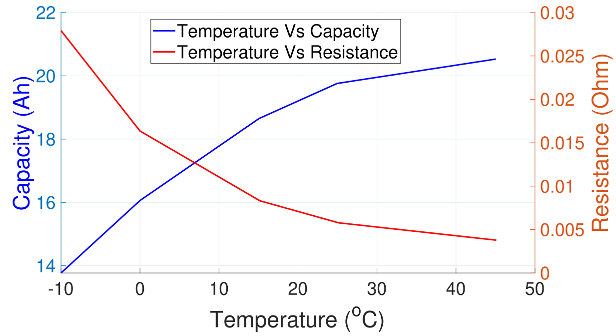

FIGURE 6. Li-ion cell characteristics at several ambient temperatures for capacity and resistance [56].

When an electrochemical model is unavailable, an empirical model is developed instead, which consists of general equations that reflect battery behaviour with parameters that match experimental data. Empirical models are low-cost in terms of time and data. They are primarily descriptive and easy to set up, but their computational outcomes are the least reliable, and they need to provide more information about the model's actual structure [51]. The following section will present some of the most common empirical and chemistry-based models to deliver the impacts of low temperatures on battery health and performance.

III. LOW TEMPERATURES IMPACTS ON BATTERIES

In this section, we present the impacts of low operating temperatures on EV batteries. Firstly, low temperatures can significantly impact Li-ion batteries used in EVs, affecting several aspects of their performance and behaviour. In terms of energy storage capability, low temperatures can reduce the amount of energy stored for propulsion. Secondly, low operating temperatures increase the battery's internal resistance, making it more difficult for the lithium ions to move through the electrolyte. Consequently, the battery power's charging and discharging rate is significantly limited.

Thirdly, we present state of charge (SoC) and state of health (SoH) models, which can provide valuable insights into how low temperatures affect Li-ion batteries for EVs. By creating a mathematical representation of the battery's behaviour and performance under different conditions, battery models can help predict how it will behave and optimise its performance. Fourthly, we present that battery degradation under low temperatures can also contribute to battery degradation and ageing. At low temperatures, the battery's rate of degradation increases, leading to a shorter lifespan and reduced overall performance.

Finally, low temperatures can also impact battery safety, potentially reducing performance, overheating, and even battery failure. As such, it is crucial to consider the effects of low temperatures when designing, modelling, and operating Li-ion batteries for EVs.

A. BATTERY CAPACITY

Battery capacity is the total amount of electricity that can be stored via electrochemical reactions. This generated electricity is stored in the battery over time and measured in Ampere hours (Ah). Alternatively, battery energy is described as the product of the battery capacity and the nominal voltage and measured in Watt-hour (Wh). The battery capacity is a significant parameter for an EV, and it depends on several factors, including the battery's chemistry, current, and temperature. The diffusion rates of the solid electrodes, the conductivity of the electrolyte, and the solid-electrolyte interphase layer (SEI) are reduced by lowering the temperature, resulting in increased internal resistance. Then, the capacity loss increases as a consequence of increasing incremental impedance [28], [52], [53]. The impact of temperature on battery resistance and capacity is shown in Figure 6. It is evident that Li-ion battery performance can significantly reduce under low temperatures. For example, it has been found that the usable energy of Li-ion cells at -10° C is 75% of the room-temperature (25° C) value for the same current (50A) [54]. According to [55], the battery capacity is at its maximum when the temperature is around 21°C, and the capacity significantly reduces when the temperature goes below 0°C. This suggests that electric cars in colder climates require charging more often in order to travel similar distances.

Unbalanced capacity is another issue with the capacity loss for an EV due to temperature and non-homogeneous heat distribution. Although not directly related to low temperatures, this is still something that needs to be considered in the battery design as a battery bank is made up of a lot of distributed Li-ion cells which are not in a uniform manner across an EV. As a result, these cells are distributed in various ways in the car, which results in some cells operating at a temperature that is different from others [57]. As previously stated, due to slower electrochemical kinetics and increased battery polarization, the battery is more likely to lose adequate capacity at low temperatures [58]. The battery operating conditions, whose energy capacity is already reduced at low temperatures, may be further limited by low-capacity cells contained in it for protection against overcharging and discharge [59].

B. BATTERY POWER

The ability of the battery to deliver high current over short periods (a few seconds) is directly related to its power capabilities [10]. Since batteries are electrochemical devices, they rely on both electrical and chemical processes, which should ideally co-occur, but this is not always the case. This time difference for Li-ion batteries is determined by the lithium-ion diffusion rate in the electrolytes, electrodes and SEI [60]. If the battery is operated at low temperatures, the diffusion rate will decrease significantly at the anode, leading to cell polarization [28], [53]. The higher the polarization, the longer the Li-ion battery takes to complete its diffusion, causing the reduction of the battery power capacity. Lower diffusion time/higher diffusion rates, lower internal resistance, and lower activation energies are required for batteries with increased power capabilities [52], [61].

C. SoC AND SoH MODELS

Battery modelling is a challenging task, as mentioned previously, but the varying temperature conditions can make it even more complicated. Li-ion batteries exhibit non-linear behaviour under different temperatures due to alternations in the electrochemical. This situation complicates the mathematical modelling of the battery and its state of charge (SoC) and state of health (SoH) estimation, which are critical for a battery [62]. SoC is defined as the ratio of the energy stored in a battery to the maximum possible chargeable energy at a given time. This ratio is expressed as a percentage. SoH takes into account energy losses in the ageing battery over time. It is the ratio of the maximum energy that can be charged in the battery to its nominal capacity. This ratio is also defined as a percentage. As the battery temperature drops, the nonlinearity of the battery behaviour tends to rise [63]. Therefore, low temperatures make battery modelling and analyzing battery behaviour more challenging and lead to complex EV management systems [28].

D. BATTERY DEGRADATION

Battery degradation describes the gradual loss of a battery's performance or capacity. Li-ion batteries experience battery life degradation due to various reasons, including charging-discharging cycles, high current rates, and operating under excessively high or low temperatures [29]. Although the acceptable temperature range of Li-ion batteries for EV applications is between -20°C and 60°C, the recommended operating temperature is from 15°C to 35°C [64]. Therefore, most of the degradation processes in Li-ion batteries are temperature dependent. Low temperatures not only lead to a reduction of diffusion rate and intercalation but also grows the lithium dendrite that might cause lithium plating [65]. A significant cause of battery degradation might be the process of lithium plating in Li-ion batteries. Battery degradation leads to capacity loss, decreasing range and internal resistance, increasing energy-power losses and overheating [66].

Understanding battery degradation behaviour under varying temperatures requires developing degradation modelling methods for batteries. There are two primary battery degradation models: theoretical (based on electrochemistry) and empirical (based on experiments). The former models focus on active materials in the Li-ion battery and the loss of lithium ions. These models explain in detail the numerous degradation mechanisms and how they are impacted by the battery's use and condition [67], [68], [69], [70]. For instance, the effect of the temperature can be modelled with Arrhenius equations [65], [71] as given below

$$r = A \cdot \exp{(-\frac{E_a}{kT})}. \quad (1)$$

In (1), r reflects the rate of reaction, E_a is the activation reaction energy, k is the Boltzmann constant, T is the ambient or operation temperature, which indicates that kT is the average kinetic energy, and finally, A is a battery specific constant determined by laboratory battery tests [72].

Arrhenius model performs well in the high-level estimation of the battery's operating mode at the planning stage. In contrast, it is not successful in providing detailed information about the battery's internal structure, and molecular-level degradation processes still need to be improved [73], [74]. As a result, it is hard to link charging and discharging patterns to the molecular-level processes inside battery cells.

Empirical models are simpler for storage planning and operations studies [75], [76], [77]. These models provide suitable accuracy when the battery operation region is not wide. However, they are limited to the empirical data on which they are based, and the model developed for the specific application cannot be used for another model. Semi-empirical battery degradation models have been implemented in some studies to overcome these challenges [78], [79]. The new method incorporates theoretical analysis with practical observations. Therefore, the model is reliable and effective in both operating ranges covered by the experimental data and other operational scenarios.

Battery degradation is a general term that encompasses all the factors that can lead to a decrease in the performance and capacity of Li-ion batteries, including driving, charging patterns, environmental factors and elapsed time. It is a complicated process triggered by various chemical and physical transformations in the battery's electrodes, electrolytes, and other parts. On the other hand, battery ageing refers to the degradation of a Li-ion battery over time due to parking, charging and driving [80], [81]. The following section will provide a detailed explanation of how battery ageing causes a gradual reduction in the capacity and charge-holding ability of the battery. Battery ageing and degradation are frequently used interchangeably because ageing is a specific type of degradation that occurs over time due to the cumulative effects of usage and the passage of time.

E. BATTERY AGEING

Protecting and improving the life of Li-ion batteries is critical since they are the most expensive part of EVs. Particularly at low temperatures, it is necessary to understand the ageing mechanisms of the battery in order to measure and estimate its useful life. Battery ageing starts at the interfaces between the electrodes and the electrolyte due to the chemical compound

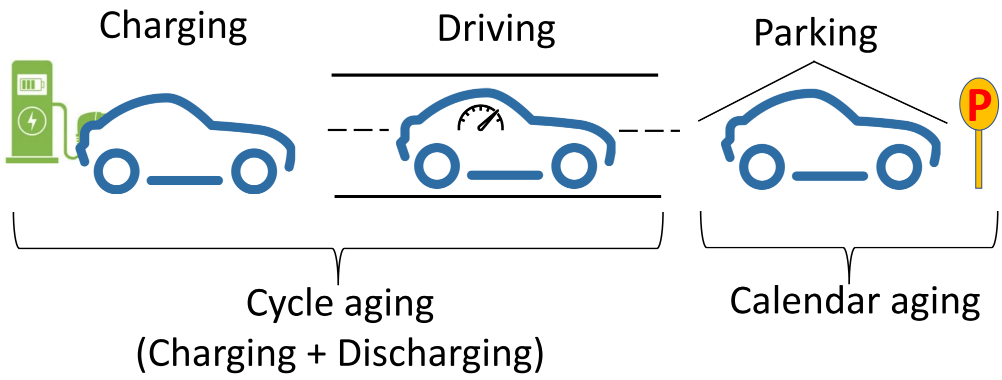

FIGURE 7. Ageing mechanisms for different EV operation modes.

of the cell electrolyte [82]. The composition of electrodes significantly influences ageing mechanisms, which can be either chemical or mechanical. Two significant consequences of battery ageing are increased resistance and capacity loss [83]. Various chemical-based mechanisms, depending on electrode materials, lead to decreased performance of batteries. Loss of capacity decreases the driving range, whereas the battery's increased resistance may directly correlate with power losses [67].

The methods used to measure the characteristics of ageing can be divided into three types: electrochemical model, equivalent-circuit-based model and performance-based model. The electrochemical model is known as the modelling of fundamental or particle-based distributions. Its goal is to fully comprehend the physical and chemical events that occur in the use of batteries [84]. Furthermore, the internal parameters of the cell can be used to estimate battery degradation. These parameters can be measured directly or using an equivalent circuit-based model with battery modelling [85]. The performance-based model is built by determining the correlation between stress (ageing factors) and battery performance (capacity degradation). This model aims to quantify the effects of stress on battery degradation and battery performance throughout its entire life cycle [86].

There are two types of ageing mechanisms, namely, calendar ageing and cycle ageing. Each ageing type refers to the modifications due to various battery usage, as shown in Figure 7. Calendar ageing is the natural degradation of a battery that occurs over time without any charge or discharge cycle. Cycle ageing, on the other hand, refers to the degradation of a battery that accumulates over time due to charging and discharging cycles.

1) CALENDAR AGEING

Calendar ageing occurs when the battery is used for storage while parking. There is no current flow through the battery. The formation and growth of the SEI layer on the anode is the primary ageing mechanism for calendar ageing. The most significant factors affecting calendar ageing are parking duration, temperature, and SoC levels. Long-term parking of the EV, high or low levels of temperature and an elevated SoC cause increased ageing due to acceleration of SEI formation [81], [87], [88], [89], [90].

In order to examine the calendar ageing of a commercial Li-ion battery, a study was conducted at the Faraday Institute for one year by considering the storage SoC and storage temperature [91]. This study considered eight different storage SoC (from 0% to 100% with equal increments) and three different storage temperatures (25°C, 40°C and 50°C). According to monthly electrochemical check-up measurements, Li-ion cells with 70–80% SoC degrade the fastest at all temperatures. Cells stored at 80% SoC had the worst capacity preservation, with relative capacities reaching around 94%, 92%, and 90% after a year for cells stored at 25°C, 40°C and 50°C, respectively. As the temperature rises from room temperature, the capacity of the cells decreases. Capacity degradation rate and temperature dependencies for cells show different results below or above 60% SoC. Cells held at 0% SoC have the best capacity retention and the most negligible temperature dependence for the one year studied, while cells maintained at 100% SoC do not indicate the fastest capacity reduction, but they produce internal short circuits when the temperature is above 40°C.

An empirical study is presented in [92] to estimate the irreversible degradation (calendar losses) when an EV is not connected to a charger for long hours. The developed model is based on a regression model that shows the loss degradation rate (% of loss per hour) as a function of temperature and is given as

$$L(T) = c_1T + c_2T^2 + c_3T^3 + c_4T^4 + c_5, \tag{2}$$

where the T denotes the temperature and polynomial constants have the following values; $c_1 = -0.0009224$, $c_2 = 3.71 \times 10^{-5}$, $c_3 = -6.6 \times 10^{-7}$, $c_4 = 6.23 \times 10^{-9}$ and $c_5 = 0.0086$. The loss degradation function given in (2) is evaluated for $T = -20, \ldots, 45$°C and results are presented in Figure 8. It can be seen that the degradation rate significantly increases in subzero temperatures.

2) CYCLE AGEING

Cycle ageing refers to the regular loss of life while an EV is either in charging or driving mode (discharging). The

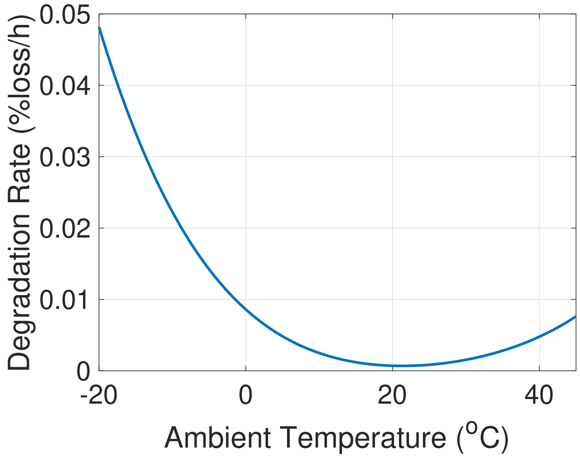

FIGURE 8. Calendar ageing mechanism for EVs parked under low temperatures.

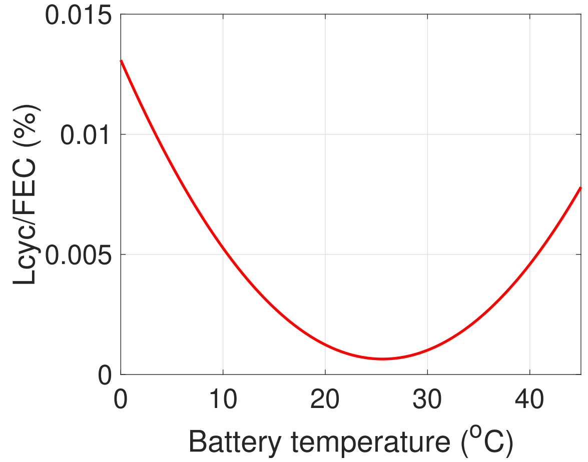

FIGURE 9. Capacity degradation per FEC at various battery temperatures.

ageing that occurs while charging an EV battery is caused by cut-off voltage, current rate, and ambient temperature. The cut-off voltage, which determines the battery's empty state, is the battery's lowest allowable voltage. The degradation of the EV battery is accelerated by slight overcharging or a decline in the cut-off voltage. The former certainly accelerates the battery's ageing while also expanding its capacity. A lesser capacity is achieved in the latter, but there is no noticeable reduction in charging time or degradation [93]. Higher charging rates (C-rates) lead to the deterioration of batteries more rapidly. This deterioration trend and the effects of charging rate vary with each battery chemistry. Both charging efficiency and energy available for charging are reduced accordingly under low temperatures. In addition, it has been found that the battery capacity lowers with the decrease in the ambient temperature during charging [94]. Besides, lithium depositing as a metal onto anode surfaces (so-called lithium plating) is a significant problem during low temperatures and at higher charging rates. Anode lithium plating is a primary ageing mechanism of cycling ageing during fast charging [95], [96]. As a result, the battery ageing during the charging process accelerates due to high cut-off voltage, high current and extreme temperatures (both low and high temperatures) [80].

An empirical study is presented in [97] to estimate capacity losses due to full equivalent cycles (FEC). The battery capacity loss per FEC depends on the battery temperature and C-rate and is given as

$$L_{\text{cycle}}(\%) = (x_1T^2+x_2T+x_3)exp((x_4T+x_5)\times C_{rate})\times x_6N_{\text{FEC}}, \quad (3)$$

where the T denotes the temperature and polynomial coefficient values and units have the following values; $x_1 = 8.851\times10^{-6}\ 1/(K^2/Ah)$, $x_2 = -5.102\times10^{-3}\ 1/(K.Ah)$, $x_3 = 0.7589\ 1/Ah$, $x_4 = -6.7\times10^{-3}\ 1/K(C-rate)$, $x_5 = 2.344\ 1/(C-rate)$ and $x_6 = 1.5\ Ah/Cycle$. For a 1.5 Ah cell, the temperature reliance of the L_{cycle} is established empirically per Ah in [98]; this is normalised by multiplying by 1.5 Ah/cycle [99]. The deterioration per FEC is more significant when C_{rate} exceeds 1. Cycle loss degradation function given in (3) is evaluated for $T = 0, \ldots, 45°C$ and results are presented in Figure 9. It can be seen that the capacity loss is minimum between 20°C and 30°C.

Discharge of the battery due to driving also has an important place in the battery's ageing. Since driving ageing is complex and challenging to control, battery degradation differs depending on the driver's behaviour and environmental conditions. The everyday usage of an EV is related to the battery's depth of discharge (DoD). The speed of travel and acceleration is associated with the battery's current discharge, while the most significant environmental factor influencing battery degradation during a trip is the ambient temperature.

Compared to driving-related ageing, ageing during the charging process is less intense but easier to control and mitigate. Various charging methods, namely fast charging, trickle charging, pulse charging, smart charging and temperature control, are used to reduce battery degradation and charging time [80], [100]. These charging methods will be discussed in more detail.

Parking, charging and driving are EVs' operation modes that cause battery degradation, as shown in Figure 7. Optimum temperatures and low SoC can reduce parking battery degradation, while suitable temperatures and optimized charging methods minimize battery ageing for charging. External protection measures such as thermal management and battery pack design are required for complex ageing while driving.

F. BATTERY SAFETY

The safety of Li-ion batteries used in EVs is one of the major concerns due to their high energy density and flammable electrolytes. EVs must comply with safety standards and regulations that vary from country to country, impacting the vehicle's design, which consists of battery cells [29]. Safety measures need to be implemented to prevent thermal

TABLE 2. The effects of low temperatures on Li-ion batteries and EVs.

Electro-chemical Impact	Implications on Battery Performance	Implications on EV performance
The electrolyte conductivity The charge transfer kinetics Solid State diffusion of lithium ions in the anode ↓	Equilibrium potential Discharge capacity Battery life span Battery capacity ↓	Charging power Driving range ↓
Anode lithium plating ↑	Internal resistance Safety risk Battery degradation Power losses ↑	Charging duration Cabin heating requirements ↑
'↓' represents the decrease and '↑' represents the increase		

runaway, which can cause the battery to overheat and increasing the internal pressure is critical for battery safety [101].

Li-ion batteries can be dangerous when exposed to high temperatures because they can experience a sudden increase in temperature caused by uncontrolled electrochemical reactions, known as thermal runaway. This may cause the battery to be destroyed and increase the likelihood of fire and explosion, resulting in potentially fatal consequences [101]. Thermal runaways can occur for various reasons, such as mechanical (car crash) or electrical factors (overcharging and thermal abuse). If aged batteries are used under extreme temperature conditions or are charged or discharged too quickly, the thermal runaway problem can worsen. This can cause the battery to overcharge or overdischarge, leading to potentially dangerous situations. Even though the risk of thermal runaway is lower at low temperatures, it is still essential to be cautious and monitor the battery for any indications of internal short circuits that could cause thermal runaway to occur [102].

Low-temperature conditions can also pose safety risks to Li-ion batteries for EVs. While the chances of thermal runaway happening under low temperatures are reduced [64], a potential problem that can arise is a decrease in power when operating an EV under low temperatures, which can lead to a reduction of driving range. In this situation, the powertrain control strategy must consider the battery's power level, which can be very unpredictable, mainly when using large amounts of current under low-temperature conditions. Another safety risk due to low temperatures might be during EV charging since the electrochemical structure of Li-ion batteries is adversely affected by low temperatures. Accelerated chemical reactions can cause a safety hazard when the EV is charged. Therefore, the charging rate must be limited and also reduced considerably to prevent overcharging and maintain battery safety, especially for DC fast chargers. As previously mentioned, BMS play an essential role in ensuring battery safety by limiting the charging rate when the battery is cold [28], [29].

IV. BATTERY THERMAL MANAGEMENT SYSTEMS AND HEATING STRATEGIES

Most operational challenges that EVs experience under low temperatures are associated with thermal impacts on the EV battery. Therefore, accurate models of the batteries' thermal properties are necessary for developing battery thermal management. In the literature, several modelling techniques have been used for low temperatures. General heat rejection equation [103], prediction of the temperature in the battery cell with one-dimensional modelling [104], using experimental data with different temperature and discharge rates [105], with the combination of heat generation equations and chemical reactions on the battery [106] are some thermal modelling methods as the preparation of battery thermal management systems.

Li-ion batteries under low temperatures have demonstrated a need for advanced model-based battery management strategies in EVs. Indeed, battery models are crucial to understanding the internal processes and effects of degradation and ensuring the best performance, operation and lifetime. Li-ion cells used in EVs in various operational conditions require an advanced strategy of battery thermal management in order to achieve the best possible performance and longevity. This can be achieved by battery thermal management systems (BTMS) [28]. The BTMS is designed to maintain battery temperatures within a completely EV operational envelope, within a temperature operating range that is closer to ideal (15° C and 35° C) [64]. Nevertheless, the current tendency in thermal management is to improve battery pack architecture to get a longer distance range or faster charging times [109].

The most common technique BTMS uses to keep the batteries within the operational ranges under low temperatures is to heat the battery using an appropriate heating strategy. The overall impacts of the low temperatures on Li-ion batteries and EVs are shown in Table 2. The significance of BTMS in EVs arises from the adverse effects of low temperatures on battery electrochemical properties and performance, which consequently affect the vehicle's overall performance, as seen in Table 2. Therefore, to ensure optimal performance and avoid negative impacts, it is crucial to have a reliable BTMS. In this paper, BTMS will be given in two main categories, as seen in Figure 10, which depend on the working medium and management type and location of heat generation.

A. BTMS BASED ON WORKING MEDIUM

Air, liquid and phase-change materials (PCMs) are common working mediums for heating and also cooling the battery. Air

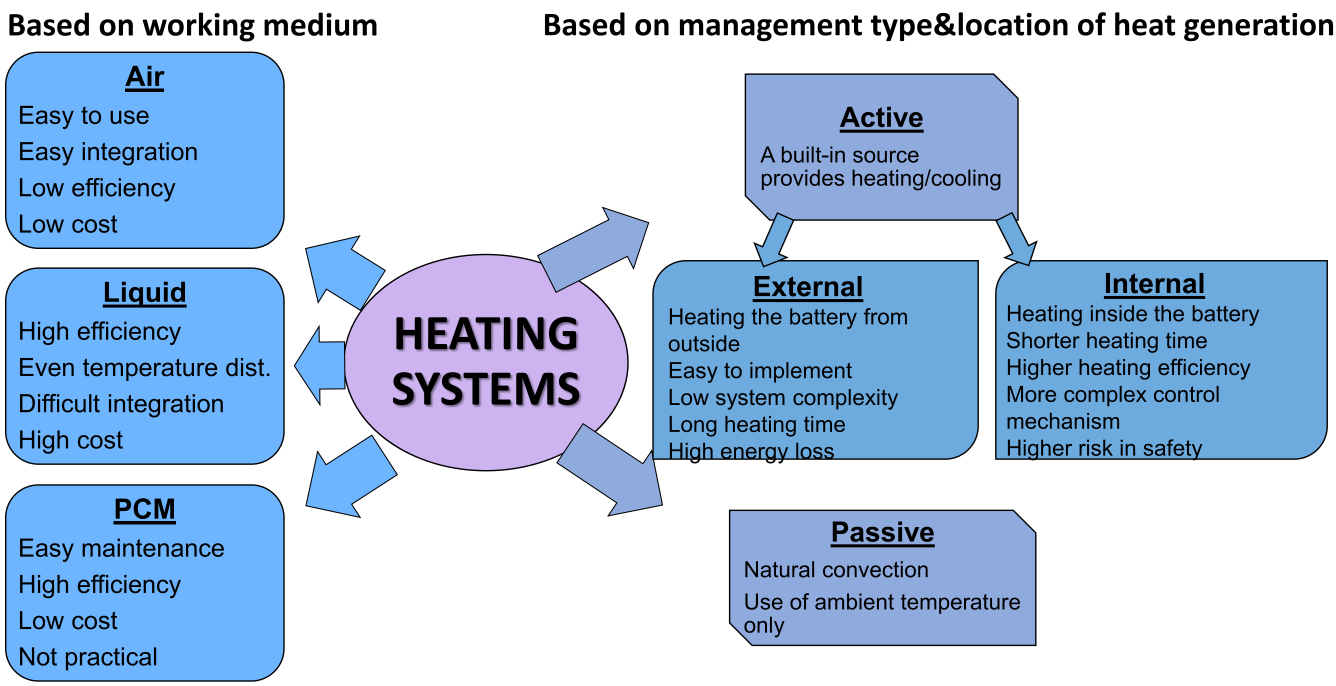

FIGURE 10. Overview of EV heating systems based on working medium and management type and location of heat generation [107], [108].

heating was the first heating management method considered under low temperatures. A battery bank is usually designed with many rows of cells placed in a row. Air heating/cooling systems are commonly used in EVs due to this battery pack configuration. The heating/cooling effect can be efficiently achieved using an airflow directed at the pack. Compared with other systems, like fluid handling, the flow control requires only basic equipment and a small amount of real estate [110].

By installing fans in different locations around the battery pack, the uniformity of temperature that can be obtained by utilising air-cooling solutions is also explored. The best cooling performance was achieved with fans located at the top of the pack, according to results presented by [111]. Heating/cooling a battery by air is challenging due to the low conductivity of air [112]. Therefore, this method is recommended at reasonable temperature conditions and discharge rates [113].

Liquid cooling and heating of a battery bank pack can be accomplished by either encasing the pack within a plate holding streams of the cooling/heating liquid or immersing the pack into the cooling/heating fluid. Water, oil, glycol or acetone could be used as a heat transport medium [114].

Liquid heating control systems are more effective than air heating control systems because liquid-based methods have higher thermal conductivity and convective heat transfer rates. However, this type of heat management is more complicated to set up compared to the air-based systems [115]. As a result, EVs often use liquid heating. For instance, 360-V electrical heaters heat the coolant water circuit that circulates the battery pack of the Chevrolet Volt [116]. The needed current to utilise the high-voltage electrical heaters is calculated by temperature sensors.

Liquid and air thermal management strategies (traditional strategies) are commonly sizable, convoluted and expensive because of having ventilation systems, fans, pipes and pumps [117]. Therefore, phase-change materials (PCMs) have emerged as innovative solutions for EV applications under low temperatures. PCM is a substance capable of storing and discharging a lot of energy (heat) using fusion and solidification. Heat is released or absorbed during the solid-liquid material transformation. When battery temperatures drop below the melting temperature of the PCM, the stored energy from the PCM is released back into the battery. While PCMs outperform conventional thermal management systems for EV applications under low temperatures, this management strategy is less mature than traditional strategies [118].

B. BTMS BASED ON THE MANAGEMENT TYPE AND LOCATION

BTMS is composed of active, that is, external and internal sources of heating/cooling, and passive systems, namely natural convection [108]. Active heating sources or EV power supplies can also be used for preheating. One of the most fundamental ways to improve the performance and life of Li-ion batteries for EVs under low-temperature conditions is to warm up the batteries [119], [120].

External heating aims to heat the battery from outside with different heat transfer approaches, such as using electrical

TABLE 3. Comparison of battery thermal management strategies for EVs.

Heating Strategy	Description	Advantages	Disadvantages
Active External BTMS	Uses an external heating source to heat up the battery pack before and during use	Fast and effective, allows for precise temperature control	Requires additional equipment, increases energy consumption
Active Internal BTMS	Uses battery-powered heating elements within the battery pack to warm up the cells	More efficient energy usage, no additional equipment required	Can be less effective in extremely low temperatures
Passive BTMS	Utilizes natural convection and ambient temperature to warm up the battery pack	No additional equipment required, no energy consumption	Slower and less effective than active heating strategies
Preheating	Warms up the battery pack while it is plugged in and charging, prior to use	Ensures the battery is at optimal temperature when needed	Requires planning ahead, may not be feasible in all situations

resistance heaters or heat exchangers. In most BTMSs, external heating and cooling methods are combined. However, specific methods, such as the use of electrothermal elements, are utilised explicitly for preheating. This heating method provides precise temperature control. It is easy to implement with low system complexity. On the other hand, it takes a long time to heat the battery, and high energy losses occur. In addition, it is difficult to evenly distribute the temperature inside the battery, which causes the electrode materials to deteriorate, thus reducing the battery's life. Air and liquid heating are more commonly used in EVs for external heating as they are more easily implemented and have less technical complexity. At the same time, PCM shows the best performance as an external heater regarding the rate at which the battery can heat up [28], [108].

As opposed to the widely used external heating, internal heating can achieve a higher rate of temperature rise in a shorter time, minimizing the effects of thermal ageing. For example, integrating multilayer nickel foil as both the heater and the temperature probe within the pouch-sized cell with 9.5 Ah allows for it to heat up in one minute from $-50°C$ to room temperature. Thus, the battery can reach 80% SoC level in 15 minutes in an environment of $-50°C$ [121]. This heating method is unaffected by the shape of the batteries [119]. The internal heating process, however, has a complex control system. Internal heating techniques might potentially compromise the battery pack's safety. This heating method, which has not become as widespread and developed as external heating, is still at the laboratory stage [108].

Preheating is a strategy to heat the Li-ion battery of an EV prior to use under low-temperature conditions. It involves using an external power source, such as a charger, to supply heat to the battery pack, increasing its temperature to a suitable level for operation. Preheating is typically performed when the battery is connected to an external power source to allow the battery to warm up before the vehicle is started. This can help to improve the battery's performance and extend its lifespan in cold weather conditions [28], [122].

Preheating batteries are quite common due to their relatively simple implementation to improve battery performance under low temperatures. However, preheating takes tens of minutes, causing EV drivers to wait to use their vehicles [122]. Therefore, a control strategy, representing a paradigm that actively controls and manipulates batteries, has emerged to avoid waiting for the car to preheat [123]. This control strategy aims to restore battery power while driving and eliminate waiting time for the battery to warm up. In EVs, the energy from regenerative braking is used to charge the battery if the battery is hot enough. Nevertheless, if the battery is cold, regenerative braking is restricted or even turned off completely to prevent lithium plating, which wastes a significant amount of energy. With the battery heating method, while driving offered by this control strategy, the braking energy is used as internal heating, restoring the battery power instead of preventing the lithium plating. When the battery is sufficiently heated, the regenerative energy is then used to charge the battery. This control method ensures all braking energy is used efficiently and restores the battery power without interrupting the vehicle's mobility. The battery temperature remains high at the end of the driving, making the vehicle ready for fast charging. However, the main disadvantage of preheating the battery for an EV during driving is that it requires additional energy from the battery to power the heating system, which can reduce the vehicle's driving range. Additionally, preheating during driving may not be as effective as other heating strategies since the battery may continue to cool down due to airflow and other factors.

Overall, Table 3 compares various battery heating strategies used to mitigate the impact of temperature on the performance of Li-ion batteries in EVs. The methods include external and internal active heating, passive heating, and preheating. Active heating uses external or internal heating sources to regulate the battery's temperature, while passive heating relies on ambient temperatures to maintain the battery temperature. Preheating involves heating the battery before it is used to reduce the impact of low temperatures on its performance [120].

Based on Table 3, it can be seen that each option has its own advantages and disadvantages depending on various factors, such as the specific battery chemistry, the ambient temperature, and the driving conditions. However, active heating strategies such as internal and external heaters are generally considered more effective in reducing the influence of temperature on battery performance than passive heating strategies. Preheating and internal heaters are often preferred as they can provide more targeted and efficient heating. Ultimately, the effectiveness of the heating strategy should be evaluated based on the specific application and its ability to mitigate battery degradation and improve performance.

On the other hand, alternative approaches aim to develop battery components such as the electrode and electrolyte to be suitable over a higher temperature range [124] because many heating/cooling techniques are only effective at low or high temperatures. The thermal management strategy can also be implemented not directly to the battery but by creating a microclimate zone in charging stations. Then, the Li-ion battery can be independent of the actual weather conditions [125].

V. IMPACTS ON ELECTRIC VEHICLE DRIVING EXPERIENCE

A. CHARGING UNDER LOW TEMPERATURES

Thermal strategies for batteries are crucial to ensure battery performance, longevity and safety, regardless of driving (discharging), charging or parking (idle) [126]. Battery discharging current is unrestricted under low temperatures while charging battery current is reduced to avoid undesirable effects if the ambient temperature drops below specific limits, showing the importance of low temperatures for charging EVs [127]. Charging Li-ion batteries is challenging under low temperatures because the electrical current must be controlled to avoid cell overvoltage and overcharging. Otherwise, the battery will get old, and there might be safety issues [29]. Therefore, It is not always suggested to charge EVs under low temperatures. For example, it is stated in the datasheet of the Panasonic 18650 $LiNiCoAlO_2$ battery that it should not be charged below +10°C [128]. However, avoiding operating and charging EVs under low temperatures is not a rational solution, as these vehicles may also need to be used under low temperatures. Such a solution is not a good option, especially for Scandinavian countries like Norway, which spend most of the year cold [129].

1) FAST CHARGING

Fast charging capability is achievable through understanding temperature effects on batteries and requires temperature-independent thermal management strategies [125]. Lithium plating hazards are the most significant issue for fast charging under low temperatures. Charging cold Li-ion batteries leads to metallizing of lithium plating on the anode, increasing the SEI and speeding degradation. According to the Arrhenius ratio, lithium plating is affected by kinetic processes, as the electrolyte ionic conductivity and reactions at graphite surfaces are significantly reduced with decreasing temperatures. As a result, unless supplementary preheating is set, the majority of today's EVs do not support fast charging at low temperatures [28], [125], [130].

TABLE 4. Fast charging statistics in Norway (Q1 2016–Q1 2018) [133].

Parameter	Average	20th Percentile	Median	80th Percentile
Energy (kWh)	9.6	4	8	13
Time (Min)	20.5	10	18	28
Power (kW)	30.2	20	31	40

The C-rates control the charge and discharge rates of a battery. This rating measures the current used to charge and discharge the battery. A battery's capacity is generally measured in 1C, meaning a fully charged 100Ah battery should supply 100A for one hour. The same battery should deliver 150A for 40 minutes when charged/discharged at 1.5C while 66A for more than 90 minutes when charged/discharged at 0.66C. The lithium deposition potential simulations showed that the Li-ion battery could be charged at 25°C with 4C without lithium plating. In contrast, the charging rate drops to 1.5C at 10°C and 0.66C at 0°C without plating [121].

Low ambient temperature is a severe obstacle to fast charging efficiency because the charging rates are kept at a minimum to ensure the safety and performance of the vehicle. With lower temperatures, the possibility of lithium plating during charging increases considerably, reducing battery capacity [121], [131]. The power conversion efficiency of a 50 kW fast charger is 93% at 25°C, compared to 39% at −25°C as a result of BMSs requesting reduced power levels at lower temperatures [132].

Norway is one of the leading countries with high EV penetration and a frigid climate. In [129], various data were collected from 50 kW CCS/Chademo fast-charging stations across that country. Table 4 shows significant differences in annual charging power, energy and time. It has been noted that the delivered charging power is reduced to 30.2 kW from 50 kW peak power fast-charging stations, and these sessions lasted on average 20.5 minutes and supplied 9.6 kWh of energy. In addition, the average charging power difference between summer and winter was also found to be 6.63 kW because the charging current is limited and depends on the battery temperature during fast charging.

A measurement conducted in Sweden [134] found that when the ambient temperature is below 10°C, the charging current is 25 A, while the ambient temperature is above 20°C, the charging current is 125 A. The BMS used in EVs aims not to damage the battery cells by limiting the current depending on the battery temperature. Since charging rates of EVs are decreased, charging speed also drops significantly, which causes a longer charging duration. For example, when Nissan Leaf is charged at a 50 kW fast-charging station, it reaches 80% SoC level in 30 minutes at room temperature. In contrast, it takes even more than 90 minutes to achieve the same level depending on the temperature [135]. Besides, the Li-ion battery of an EV can be charged via fast charging up to 80% SoC due to safety limitations. The current must be

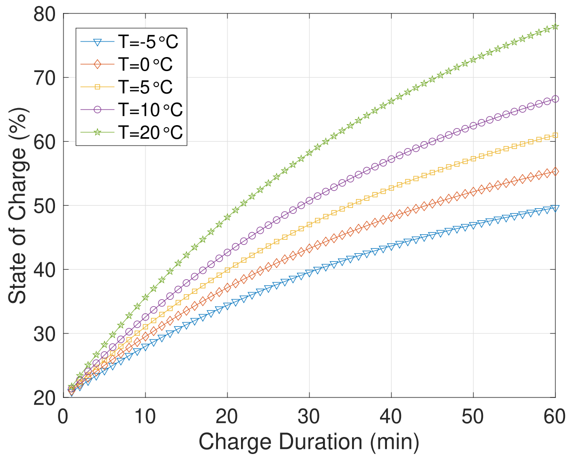

FIGURE 11. Nissan Leaf charging durations under different temperatures.

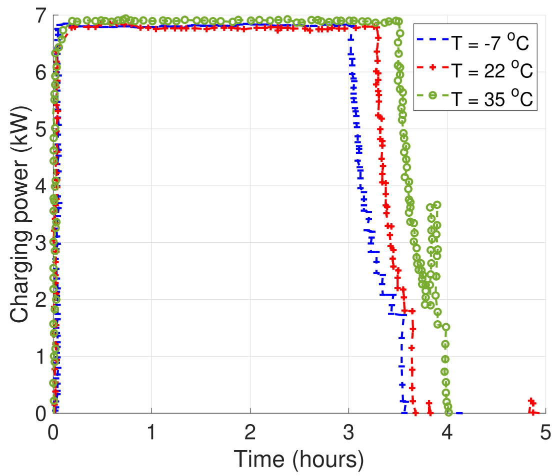

FIGURE 12. Level-2 charging under various ambient temperature for Ford Focus. [139].

reduced gradually, not to exceed the maximum cell voltage at high SoC levels. As a result, longer times are required to charge the battery fully [136].

In [30], the authors further present statistical models to estimate the charging durations for a given ambient temperature. Using regression analysis, the following function is devised to represent the final state of charge level S, for a given charging duration t (in minutes), ambient temperature T (in Celsius), and the initial state of charge level S_0:

$$S(t) = \left(S_0 + \frac{\beta_0 + \beta_1 T}{\beta_2}\right) e^{\beta_2 t} - \frac{\beta_0 + \beta_1 T}{\beta_2}, \qquad (4)$$

where β_0, β_1, and β_2 are parameters and calculated as 0.015, 0.00034, and -0.022, respectively. (4) is evaluated for five different temperatures, and associated charging durations are shown in Figure 11. It can be observed that at lower temperatures, the charging power significantly reduces when compared to mild weather (e.g. 20°C). For instance, reaching 50% SoC takes about 21 minutes at 20°C, while achieving the same SoC is nearly 60 minutes at -5°C. Recharging times are particularly important for EV fleets such as taxis, delivery vehicles or buses as they need to follow a certain schedule.

To make EVs as competitive as ICEs, fast charging rates of EVs must be independent of weather conditions for EVs. However, lithium plating makes fast charging at low temperatures impossible in today's EVs. A considerable impact of lithium plating is a significant loss of capacity in the Li-ion battery. Lithium plating-free (LPF) fast charging is based on the principle of charging a battery at a specific temperature that prevents lithium plating. A rapid internal heating step is added just before the charging step so that the battery cell can be suitable for fast charging at a specific temperature above a certain value that prevents lithium plating [121]. Eliminating lithium plating enhanced cycle life at low temperatures tremendously. Research shows that advanced battery materials that do not have temperature concerns are needed to improve the fast-charging ability of EVs further [137], [138].

2) SLOW CHARGING

The impacts of ambient temperature are less severe with slow charging. Empirical evidence is presented in [139] by examining the charging performance of a 2013 model Ford Focus with an AC Level 2 charger under different ambient temperatures. The results are illustrated in Figure 12. The charger draws an average of 6.6 kW power (typical Level 2 rating in the US) for at least the first three hours for all temperature levels. After this period, minor differences are observed, as shown in Figure 12. The charging power gradually decreases in the last part of the charging session. For an EV driver who wants to use slow charging for a few hours, it is observed that there is no significant difference in the charging pattern since the charging power is much lower than the fast charging, and most EV batteries can accept Level 2 (hence Level 1) charging rates.

Another empirical study was carried out in France [122] to understand the amount of energy needed to preheat the battery and the cabin with a slow charger. The measurements took place when the ambient temperature was -10°C, and the battery was preheated to 5°C and the EV cabin to 20°C. The grid supplies the power to the battery for warming and the HVAC subsystem during preheating through the 3.6-kW onboard charger. It can be seen from Figure 13 that almost 45 minutes is required to perform these operations. These results suggest cold regions with high EV penetrations could experience additional weekday morning peaks.

B. ADDITIONAL DEMAND FOR EV CABIN THERMAL COMFORT

Low temperatures not only impact battery performance and longevity but also affect the thermal comfort of an EV cabin. Heating, ventilation, and air-conditioning (HVAC) are critical for ensuring thermal comfort. In order to ensure thermal comfort inside an EV cabin under low temperatures, the need for cabin heating is increased, resulting in a rapid

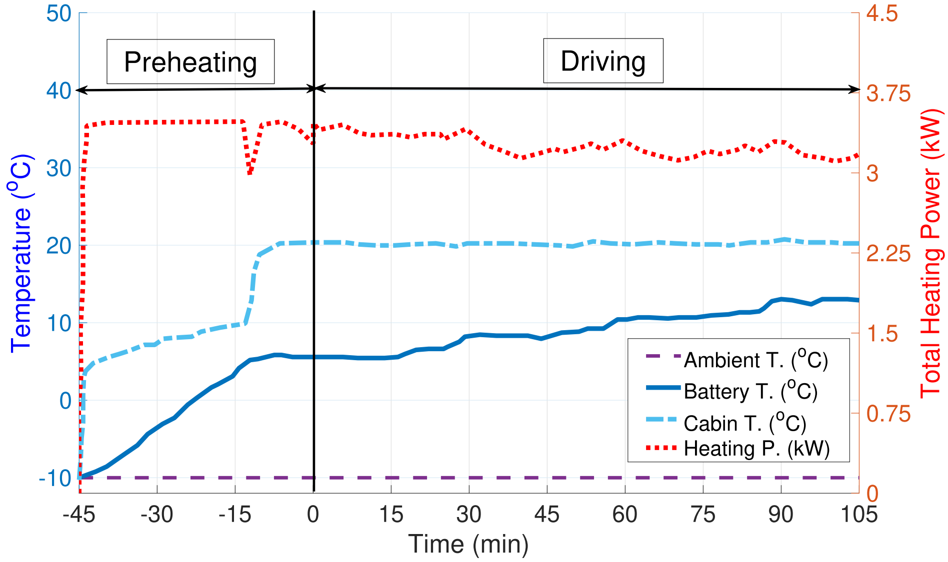

FIGURE 13. Preheating for an EV cabin and battery [122].

TABLE 5. The impact of preheating on EV in terms of energy consumption for urban and highway [122].

	Urban		Highway	
	No PH	With PH	No PH	With PH
Traction Energy (kWh)	2.05	1.99	10.37	10.35
HVAC and auxiliary energy (kWh)	3.79	5.1	3.95	5.29
Battery losses (kWh)	0.228	0.122	0.567	0.339
Battery warmers' energy (kWh)	0	0.84	0	0.84
Energy supplied by the battery (kWh)	6.07	5.44	14.9	14.2
Total Energy (kWh)	6.07	8.05	14.9	16.8

drain on the battery's energy reserves [26]. For ICE vehicles, providing thermal comfort is relatively straightforward, as waste heat produced from the motor is used. However, due to EVs' high-efficiency drivetrain, little waste is generated, necessitating the provision of heating systems for providing thermal comfort inside cabins [140]. The EVs' electrothermal component uses the power supplied by the batteries for cabin heating via resistors. Since energy stored in the battery, intended to be used primarily for driving, is used to warm the cabin. This decreases the amount of energy that can be used for driving, thereby shortening the vehicle's range of operation [25], [141].

A number of studies present the correlation between the ambient temperature and the energy demand, which is often simplified to a linear correlation [142]. According to [26], the worst-case correlation scenario between ambient temperature and energy demand assumes that both HVAC and AC are actively engaged. In addition, this test was conducted outside in winter weather conditions. Based on the test conditions stated above, the worst-case correlation is given as follows:

$$y = -4.78 \times T + 82.3, \tag{5}$$

where y represents the percentage of increase in energy demand, and T represents the ambient temperature as a Celsius. On the other hand, the best-case scenario is presented in [143], in which HVAC is used in recirculation mode, and the tests were performed inside a closed garage. Thus, the vehicle was not affected by environmental conditions such as snow and rain that would increase the battery resistance. The best-case correlation between EV demand and temperature is found as follows:

$$y = -2.76 \times T + 47.5. \tag{6}$$

The increase of energy demand correlation scenarios is given in Figure 14.

In [122], an empirical study is presented to quantify the impacts of low temperatures EV driving on additional energy use and preheating, and cabin heating demand is measured. More particularly, the effects of battery preheating on short-distance trips under -10°C are investigated. The battery preheating continued until the battery reached 20°C using a domestic 3.6 kW charger. The impact of preheating on the energy consumption of each subsystem for Renault Zoe is examined for urban (18 km in 1 hour) and highway (77 km in 1 hour) driving cycles and presented in Table 5. The energy consumed in the traction subsystem depends on the type and duration of the drive. Since battery preheating contributes to regenerative braking, traction consumption decreases slightly

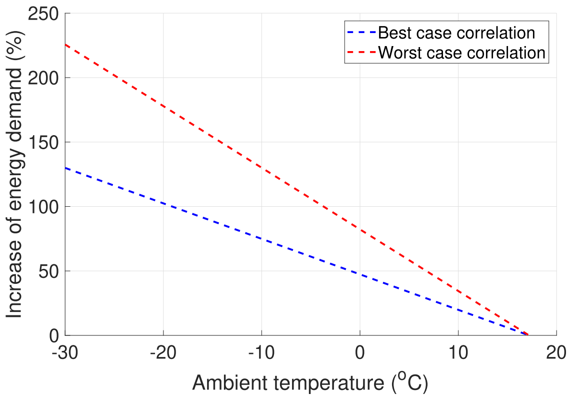

FIGURE 14. Energy demand changes for best-case and worst-case scenario under low temperatures.

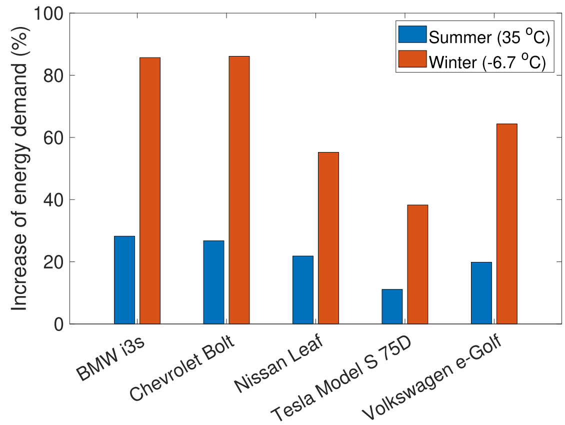

FIGURE 15. Energy demand changes for various EVs for summer and winter [143].

with preheating. The driving time determines the energy consumption of the HVAC. Therefore, considering the same travel time, the results are similar with preheating and without preheating conditions. However, it is shown in Table 5 that preheating seriously increases HVAC consumption (37% increase for urban). Since battery losses depend on temperature and driving type, battery losses are significantly reduced by preheating. Finally, energy supplied from the battery with preheating decreased by 10.4% for urban and 4.7% for highways; the total energy consumption increased by 33% and 13%, respectively.

C. REDUCED DRIVING RANGE

All electric driving range is the distance an EV can travel on a single charge, which is crucial to their widespread adoption. All electric driving range is affected by several factors, including battery capacity, driving style, temperature, and heating or cooling systems. Low temperatures can significantly decrease the driving range of EVs due to the reduced capacity of the Li-ion battery and increased consumption HVAC system. The capacity of an EV's battery decreases under low-temperature conditions because the chemical reactions that power the battery slow down. As a result, the amount of energy the battery can hold and provide to the car is reduced. Additionally, the increased power consumption of the HVAC system to maintain cabin temperature can further reduce the driving range of EVs [25], [26]. Therefore, developing BTMS can play an essential role in mitigating the impacts of low temperatures on the EV range and improving the overall driving experience, as mentioned previous section.

The limited driving range is another significant factor that impacts EV driver experience under low temperatures [144]. The driving range is reduced for EVs due to low-temperature conditions, further boosting anxiety about driving range. For example, the available energy of a Li-ion battery at −20°C is 70% of its value for the same current at room temperature [145]. According to studies conducted in Canada [26], [146], the range of the EV decreases by 1.1 km with each 1-degree reduction in temperature (in Celsius). These studies also observed that the vehicle range decreases by 20% for −7°C compared to 20°C.

High or low ambient temperatures cause a noticeable decrease in the distance a vehicle can travel before recharging due to using HVAC. This usage increases the demand for energy stored in the vehicle battery, causing the reduction of driving range, particularly under low temperatures. The increasing energy demand in summer and winter in various EVs can be seen in Figure 15. In parallel to these findings, it is further reported that the Nissan Leaf, which has a range of 161 km at 25°C, delivers a range of 49 km at -25°C. Similarly, Mitsubishi i-MiEV's driving range reduces to 42 km at −25°C from 128 km at 21°C [26]. According to [147], the distance ranges associated with the ambient temperatures of a few 2019 model-year EVs are shown in Figure 16. It can be observed that EVs have the maximum range when the ambient temperature is 21°C. When the temperature drops or exceeds 21°C, the driving range decreases.

The study presented in [122] further quantifies the impacts of preheating on the driving range. A pure EV's driving range under −10°C is examined under various heating scenarios and presented in Table 6. The results show that preheating leads to a slight increase (only an 8.5 km increase in the best scenario) in the EV driving range. However, as discussed in the previous section, the main benefit of battery preheating is on protecting battery health.

TABLE 6. Impacts of preheating (PH) on driving range improvement. (The driving range under 21°C is 300 km.) [122].

	No PH	Battery PH	Cabin PH	Battery and Cabin PH
Range (km)	179	181.3	185.7	187.5

We have reviewed the consequences of low temperatures on both EVs and their Li-ion batteries so far. In the next section, we present an in-depth examination of the impact that EV charging has on power networks in the context of low-temperature conditions, with a particular emphasis on the

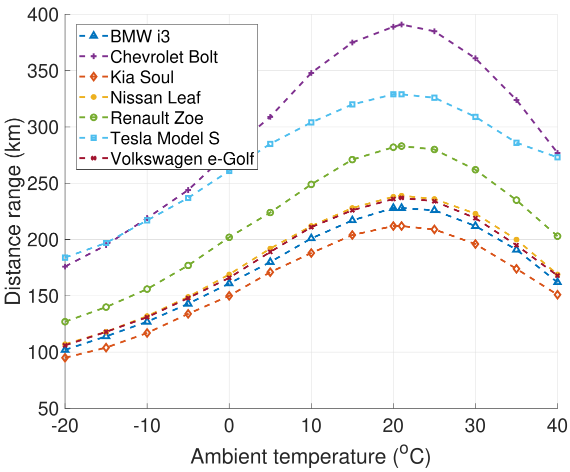

FIGURE 16. Distance range in some EVs depending on ambient temperature [147].

potential power quality issues, specifically harmonic distortion due to EV charging.

VI. IMPACTS OF EV CHARGING ON POWER NETWORKS

A. OVERVIEW

There is a growing body of literature on the impacts of EV charging on electrical power grids. Existing studies can be grouped into two groups. The first group of studies examine the impacts of EV charging at the distribution level and primarily evaluates the impacts on power quality, namely harmonics, substation overloading, voltage drops, and phase unbalances [16], [148], [149], [150]. Power quality issues are the critical elements in electric networks with the increasing penetration of EVs and their charging stations due to high power demand and the non-linear behaviour [16]. The impact of these issues is mainly reflected in the load profile of consumers and equipment (overheating of transformers, cables, and motors, malfunction of smart metering devices and the sensitive control equipment, mechanical damage to electrical motors nearby, and impacting the performance of other sensitive control and monitoring instruments) in the grid. Therefore, it is essential to understand how Electrical Vehicle Supply Equipment (EVSE) influence the power quality of power distribution networks, especially low voltage (LV) ones [151].

The second set of studies focuses on regional/national impacts on power grid reliability/stability and peak generation increase [152], [153]. The former is related to the instantaneous connection or disconnection of large collections of EVSEs and their impacts on grid frequency. The latter, in contrast, investigates different EVSE penetration scenarios and estimates additional electrical demand needed to charge EVs in a region. This section presents an overview of EVSE impacts analysis, linked with the following section, which provides further impacts from charging under low temperatures.

B. POWER QUALITY ISSUES

Power quality refers to the ability to provide power that has current and voltage waveforms with a nearly perfect sinusoidal shape at the rated magnitude and frequency [154]. Power quality is related to the interaction between the electricity network and its users or between the network and the equipment and facilities connected to it. Providing appropriate power quality is the responsibility of the distribution network operator and is usually shaped by industry standards (IEC, IEEE, etc.). Power quality disturbance occurs when the current or voltage deviates from its ideal sinusoidal shape, magnitude, and frequency. Power quality is a combination of current and voltage quality, and both current and voltage disturbances adversely affect the grid and its components [155].

Power quality in the presence of EVs depends on the type of EV charger, its rated capacity and the capacity percentage operating in the power network. Since EVSEs draw power from the grid via power electronics-based devices, utility companies are concerned with violating the hosting capacity of LV networks. The hosting capacity of a given network determines the number of EVs that can be charged while keeping the power quality within acceptable limits [151], [156], [157]. For example, transformers might be overloaded with increasing demand for additional EV power in urban areas with high load density. In rural areas, this additional demand causes undervoltage problems due to the feeders' length and the cables' small cross-section. The unbalance in distribution phases leads to energy losses and increases the heating of network equipment. A significant power quality issue in voltage and current harmonics is observed due to AC/DC conversion in EV chargers. Many power electronic devices connected to the grid increase the harmonic emissions in the system. Thus, the erratic charging behaviour of EV users will cause power quality issues in power systems in terms of harmonics, voltage levels, and phase unbalances [148], [151], [158]. Note that special attention is given to the harmonics issue, as the analysis presented in the next section reveals that harmonics are the primary concern for EV charging, especially under low temperatures.

C. HARMONICS

In modern power systems, there is a problem of non-linearity in terms of generation and demand [159], [160]. Non-linear loads, such as EV chargers, computers, adjustable speed drives and air conditioners, produce harmonics. Power electronics devices used in charging EVs inject current and voltage harmonics into the power system by making non-linear switching [161] when converting power from AC to DC form. A Block diagram of EV charging is given in Figure 17. AC/DC conversion can take place in EVSE or the vehicle's internal charger.

Harmonic distortion plays a crucial role in terms of power quality due to the growth of the number of EVSEs. A current or voltage waveform deviation from an ideal sinusoidal shape is known as harmonic distortion [162]. This distortion

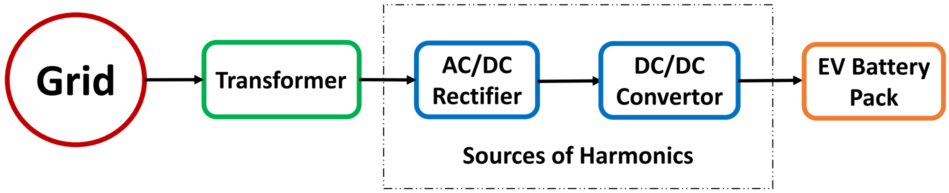

FIGURE 17. Block Diagram of EV charging.

occurs in the main frequency waveform by the components, which are integer multiples of the fundamental frequency. Harmonics are divided into odd or even harmonics. A current or voltage waveform with harmonic distortion has periodic elements and a non-sinusoidal waveform [155]. Harmonic distortion is a type of electric network pollution that can become problematic if the total harmonic currents exceed certain thresholds decided by industry standards [163].

A growing body of literature has investigated the impacts of EV charging on power system harmonics. The pioneering study of the harmonic currents produced by EV chargers was initiated by Arr et al. [164] in 1982. In this study, EV chargers were assumed to be connected to a single distribution bus, and the harmonics impacts were quantified. According to a study which investigates the impact of multiple EV fast charging on the power grid [162], it was found that harmonics limitation is the first binding condition, even before power limitation. Therefore, the initial limit of the number of chargers was determined by the limitations on harmonic distortion rather than the power capacity of the upstream power transformers. In [149], a Monte Carlo-based simulation method is presented to investigate the power quality impacts of domestic chargers (Level 1) on the distribution network. According to this study, domestic charging has a negligible harmonic impact on a power grid in the foreseeable future (up to 2022). However, vehicles charged at home can increase the neutral-ground voltage, leading to stray voltage problems.

On the other hand, transformers heat up due to additional losses caused by harmonic currents [165]. In addition, audible noise occurs in the presence of high harmonic emissions [155]. According to [166], wind generators and EVs produce common harmonic current sources even at low EV penetration, significantly affecting the electricity grid. Voltage distortion occurs throughout the network due to the flow of distorted currents. In the resonance case, the distortion rises, leading to higher node distortion levels moving away from the harmonic source. Resonance occurs when the inductive reactance matches the capacitive reactance of the circuit. Harmonics are often not a concern for customers due to regulation and standardisation. However, occasional problems might arise due to resonances since they amplify the harmonics [155]. In order to quantify the power quality issues' impact on the power system, some power quality indexes are needed. With these indexes, it can be measured how seriously harmonics affect the power networks.

D. POWER QUALITY INDEXES FOR HARMONICS

1) TOTAL HARMONIC DISTORTION (THD)

Total harmonic distortion (THD) is used to measure the degree of distortion of current or voltage compared to the ideal. In other words, it is expressed as the relative signal energy at frequencies other than the fundamental frequency. THD for current harmonics is given as

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1}, \tag{7}$$

where $I_{n\in\{2,3,4\ldots\}}$ is the rms value of the nth harmonic component, and I_1 represent the nominal fundamental frequency component for current. Maximum allowable current harmonic distortions in IEEE 519-2014 for different levels of ratio of short circuit current to load current and IEC 61000-3-12 for different short-circuit ratios are shown in Table 7 and Table 8, respectively.

Similarly, THD for voltage harmonics is given as

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1}, \tag{8}$$

where, similar to above, $V_{n\in\{2,3,4\ldots\}}$ is the rms value of the nth harmonic component, and V_1 represent the nominal fundamental frequency component for voltage. Voltage distortion limits in IEEE 519-2014 for different bus voltage levels and IEC 61000-2-4 for various harmonic orders are shown in Table 9 and Table 10, respectively.

2) TOTAL DEMAND DISTORTION (TDD)

On the other hand, Total Demand Distortion (TDD) relates the harmonic current distortion against the maximum or full load that is given by

$$TDD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_L}, \tag{9}$$

where I_L is the maximum demand load current. This power quality index is more realistic because the magnitude of the load current is considered rather than the fundamental current. For a given consumer, it is recommended to take into account the maximum average current for at least a 15–30 minute time frame over the last six months.

THD is usually calculated first and compared to the limits in real-world engineering applications. If a problem arises,

TABLE 7. Harmonic current distortion limits between 120 V and 69 kV in IEEE 519-2014.

Maximum harmonic current distortion in percent of I_L						
	Individual harmonic order (odd harmonics)					
I_{SC} / I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
[0, 20)	4.0	2.0	1.5	0.6	0.3	5.0
[20, 50)	7.0	3.5	2.5	1.0	0.5	8.0
[50, 100)	10.0	4.5	4.0	1.5	0.7	12.0
[100, 1000)	12.0	5.5	5.0	2.0	1.0	15.0
[1000, −)	15.0	7.0	6.0	2.5	1.4	20.0

TABLE 8. Maximum Harmonic Current Distortion in Percent of I_L set in IEC 61000-3-12.

Minimum RCSE	Admissible individual harmonic current I_h/I_{ref} (%)				Admissible harmonic parameters (%)	
	I_5	I_7	I_{11}	I_{13}	THC/I_{ref}	$PWHC/I_{ref}$
33	10.7	7.2	3.1	2	13	22
66	14	9	5	3	16	25
120	19	12	7	4	22	28
250	31	20	12	7	37	38
350+	40	25	15	10	48	46

RSCE - Short-circuit ratio; I_h-Harmonic current component;
I_{ref} -Reference current;
THC-Total Harmonic Current; PWHC-Partial Weighted Harmonic Current

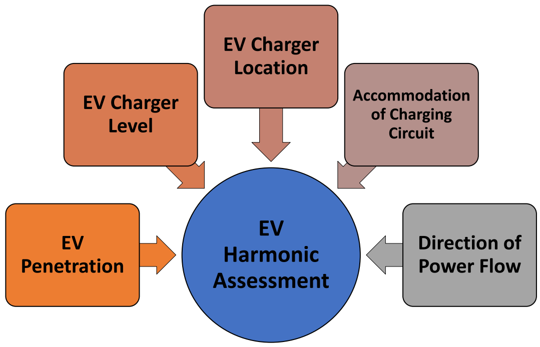

FIGURE 18. Main factors affecting EV harmonic assessment.

TABLE 9. Harmonic voltage distortion limits in IEEE 519-2014.

Bus Voltage V at PCC	Individual Harmonic Voltage Distortion (%)	Total Harmonic Voltage Distortion (THD_V) (%)
$V \leq 1$ kV	5.0	8.0
1 kV $< V \leq 69$ kV	3.0	5.0
69 kV $< V \leq 161$ kV	1.5	2.5
$V > 161$ kV	1.0	1.5

TDD is calculated [162]. Since TDD and I_L are rarely needed, the concept of THD is widely used. However, since there is a variation in current during the cycle and to improve future editions of the European standard, TDD should be used instead of THD for standard limit analysis [167]. The study carried out in [162] by measurement shows that TDD is more appropriate to evaluate EV charging current distortion instead of THD due to variations in the fundamental current during the charging cycle of EVs.

E. FACTORS AFFECTING HARMONIC PROFILES OF EV CHARGERS

In addition to individual harmonic profiles of EVSEs, other factors such as the number of EVs concurrently charging (penetration level), charging power level, charger location, accommodation of charging circuit and direction of power flow affect the profile of harmonics arising from EVSEs as depicted in Figure 18. The role of each factor is described below:

- *Based on EV penetration*: The aggregate harmonics profile is ultimately linked to the number of concurrent utilising EVSEs. With various EV chargers from different manufacturers, there will likely be a variety of harmonic patterns. There may be noticeable harmonic cancellation as a result of this diversity. If harmonics with varying angles of phase produce an effect of a smaller magnitude than the sum of their individual magnitudes, the effect is called a doubling effect. Analysing this effect is still rather challenging. As the number of consumers increases, cancellations become more likely. There has also been evidence to suggest that harmonic cancellation occurs more frequently at higher harmonic orders, which can explain the relatively minor THD_I decrease observed in different studies [168]. However, significant voltage and current harmonic distortion may occur due to the increased penetration of EVs and fast charging rates [162], [169], [170].
- *Based on voltage and current (power level)*: The charger's power is significant in examining the impact of EV charging on harmonic levels of the distribution network. Level 1 chargers are primarily supplied from domestic outlets. Level 2 chargers deliver more power and are typically located in public facilities. Level 3 chargers, the fastest charging method, are located on commercial charging applications with a dedicated transformer [171].

  In [149], EVs are classified as one of the large devices in the home. It was observed that EVs charged at home with Level 1 chargers did not significantly affect harmonics. A single EV equals approximately 1.5 computers and 10 compact fluorescent lamps in terms of their impact on harmonics. In another study on Level 1 charging [163], it has been observed that the 3rd harmonic had the

TABLE 10. Voltage Distortion Limits set in IEC 61000-2-4.

Harmonic order n (Non multiples of 3)	Class 1 Harmonic Voltage (%)	Class 2 Harmonic Voltage (%)	Class 3 Harmonic Voltage (%)
5	3	6	8
7	3	5	7
11	3	3.5	5
13	3	3	4.5
17	2	2	4
THD_V	5	8	10

Class 1: Compatibility level lower than public (protected supplies).
Class 2: Compatibility level equals the public (industrial networks).
Class 3: Compatibility level higher than public (dedicated or heavy industry networks)

highest harmonic magnitude. This harmonic poses a significant problem for grounded-wye systems where the current flows on the neutral.

In [172], with the probabilistic modelling method, the real harmonic spectrum data from the Level 2 charger proposed an appropriate EV electrical model for power quality issues in LV networks. The current harmonic distortion, which included a severe third harmonic component, exceeded the standard limitations. More research is needed to investigate harmonic distortion and its relationship with battery capacity in various onboard chargers.

When a considerable number of EVs are simultaneously charged via Level 3 charging, the line voltage and frequency deviate, the harmonics injected into the line current increase, and the peak load on the grid rises [173], [174]. Lucas et al. [162] found that harmonic limitation is a much more significant issue than power limitation. The first limit of the number of chargers placed in the fast charging station is the harmonics injected into the network instead of the power capacity of the generating station. The same study investigated the impact of two EVs charged simultaneously on harmonics. According to the simulation results with one and two EVs, both TDD values were close by approximately 12%. The harmonics decreased slightly because the amplitudes were not perfectly summed up in the two EVs. Since the standard deviation was found to fall with two EVs, it is predicted that TDD tends to be the same or slightly decrease if the number of EVs increases. When the maximum load current (I_L) also increases linearly with the number of EVs, the distortion remains the same. However, if the short circuit current (I_{SC}) does not increase and remains constant, the same case will cause a violation of the harmonic limits. Therefore, the amount of current drawn by the EV fleets and the network's short circuit current determine the systems' robustness. When EVs are linked to the same feeder, the average difference between the identical harmonic order phase angles is less than 90°, implying that the amplitudes will add. There was no synchronisation or random behaviour in the harmonic phase angles of the two EVs for fast charging.

- *Based on charger location*: Many nonlinear loads, including the EV chargers, are connected to a typical distribution network. The harmonics produced by EV chargers may be added to or cancelled by harmonics produced by household and commercial loads [149]. It is even claimed that adding chargers from different manufacturers to the same distribution network will result in diverse harmonic patterns, and the variability of the patterns may result in significant harmonic cancellation [174]. This phenomenon happens when harmonics with varying phase angles add up to a smaller sum in magnitude than the individual harmonics' magnitudes. However, assessing this effect is rather complex. Considering the charging stations and wind generators connected to the same distribution network, wind generators and EVs can provide common harmonics to the grid even at low EV penetration. In contrast, wind generators and charging stations selected in the appropriate size and location can reduce harmonics by cancelling their harmonics [166]. According to authors examining low voltage nonlinear loads in [175], cancellation becomes more likely as the number of users and appliances rises. Harmonic cancellation is more likely at higher harmonic orders, resulting in the THD_I reduction. Therefore, it is necessary to comprehend the phase angles when considering the amplitude of the harmonics measures as a part of a cluster connected to the same feeder.
- *Based on accommodation of charging circuit (EVSE technology)*: On-board chargers are built into the EV with the storage batteries. However, the power level of these chargers is limited due to weight and space limits [176]. Since off-board EVSEs are installed independently, no size and weight limitations exist. These chargers can be placed in public parking areas such as shopping malls, workplaces, and universities [72]. On-board charging systems are often utilised for slow charging, such as Level 1 and Level 2 on a single-phase grid supply, whereas off-board EV charging facilities are designed for rapid charging, such as Level 3 on a three-phase grid supply. The harmonic distortions due to different EVSE technology and the rated capacity may also differ. The harmonics injected into the grid vary depending on the load, and [163] has found that if the

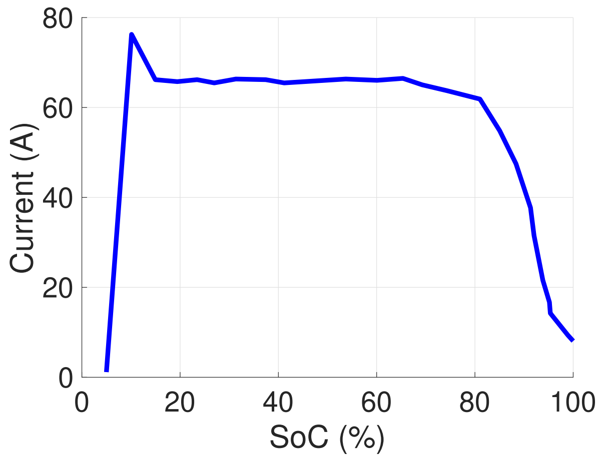

FIGURE 19. Current behaviour during CC and CV charging phase [162].

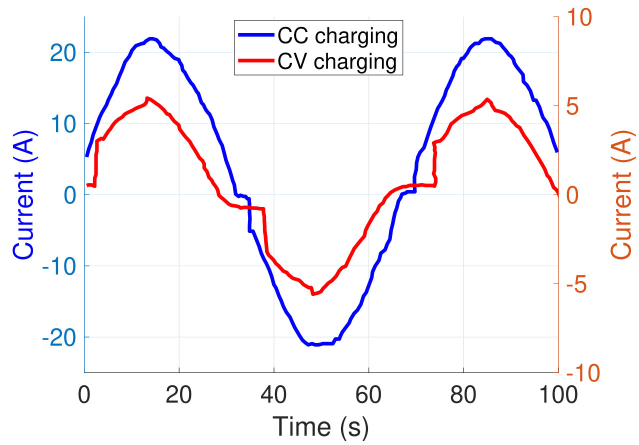

FIGURE 20. Current waveform during CC and CV charging phase [177].

load is dominantly capacitive, the harmonic distortion may also increase.
- *Based on the direction of power flow*: Unidirectional charging allows power to flow from the grid to the vehicle, whereas bidirectional charging allows power to flow both from the grid to the vehicle and from the vehicle to grid (V2G) [178]. It was observed that at 70% EV penetration in winter, harmonic emissions produced by EV charging (THD_V=0.36%) and V2G (THD_V=0.37%) are almost at the same rate [179]. Although THD_V does not exceed IEEE standards at low voltage levels (THD_V<5%), V2G appears as critical in harmonic distortion as charging.

In addition to the factors discussed above, constant current (CC) and constant voltage (CV) charging, the standard used during fast charging, affects the harmonics level. In CCCV charging, based on the battery SoC, two stages allow a battery to complete its charge cycle. CC charging involves charging a battery with a fixed current, regardless of its voltage, until it reaches a predetermined SoC. CC phase is the main charging period of the battery and is generally used from 0 to 80% SoC. On the other hand, CV charging involves charging a battery with a fixed voltage until it reaches a certain voltage level corresponding to a specific SoC. Beyond the level of SoC charged with the CC phase, CV is used until the battery is fully charged [180]. Figure 19 shows the current-SoC graph during the CC and CV period.

CC charging methods include fast charging, trickle charging, and pulse charging. Fast charging is a type of CC charging that uses high current to charge a battery quickly, while trickle charging uses low current to maintain a fully charged battery over time. Pulse charging uses intermittent bursts of high current to charge the battery and then allows it to rest before repeating the process. CV charging techniques include float and taper charging [181]. Float charging is a type of CV charging that maintains a battery at its fully charged state, while taper charging reduces the charging current as the battery approaches its full charge to prevent overcharging and damage to the battery.

Since each battery has its own set of characteristics, it necessitates slightly different charging methods/techniques. CC and trickle charging are used by nickel-metal hydride batteries, whereas CC, CV and trickle charging are used by Li-ion batteries. These batteries cannot be charged effectively under low or high temperatures. Therefore, in cold climates, the battery is first heated by trickle charging, and the battery cells are brought to 20-25°C to make them ready to charge efficiently. The charging of the Li-ion battery is stopped when it is nearly fully charged, preventing the battery from becoming overcharged [182].

From the harmonics perspective, EV chargers act differently at each charging stage. The current waveform is less distorted during the CC phase but more distorted during the CV phase. Figure 20 demonstrates the current waveform during the CC and CV charging phase. When the behaviour of THD and TDD in the CC and CV stages is examined, the differences can be observed as shown in Figure 21. Both Figure 19 and Figure 21 correspond to around 40 minutes of fast charging, and these graphs show three different stages. At the beginning of the charging process, THD peaks and then gradually falls as the current gradually increases, while TDD rises at a minimum. This occurs during the first few minutes of charging. THD and TDD values are very close, around 12% in the second stage, where there is constant current behaviour. There is a gradual decrease in current during the final stage of charging, which occurs over 15 minutes as the battery reaches 77% to 100% of its SoC. THD increases gradually and peaks during this time, while TDD decreases gradually and reaches its lowest level.

F. INDUSTRY STANDARDS ON HARMONICS (IEC 61000, EN 50160 AND IEEE 519)

Power quality has several standards in comparison to other areas of the power systems industry. Power quality standards can be categorized into two categories. The International Electrotechnical Commission (IEC) power quality

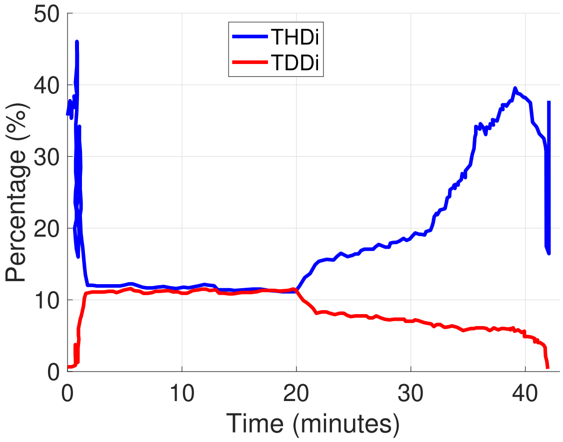

FIGURE 21. Comparison of THD_I and TDD_I during CC and CV charging phase [162].

measurement standard (IEC 61000) identifies certain types of disturbances and their characteristics and measurement methodologies. EV chargers must meet the electromagnetic compatibility IEC 61000 series standards for loads connected to a power grid. These standards determine the harmonic emission levels, such as the harmonic current-voltage or power factor that an EV charger is permitted to have. IEC 61000-3-2 [183] and IEC 61000-3-4 [184] are the standards that apply to EV chargers and set limitations on harmonic emissions that EV chargers inject into the grid. The IEC 61000-4-7 [185] and IEC 61000-4-30 [186] standards handle these harmonic measurements and instrumentation. According to the IEC international standard, since the ratio denominator in equations (7) and (8) are the total rms value, the THD value never surpasses 100%. European Committee for Electrotechnical Standardization (CENELEC) sets permissible limitations as a second category. The European Norm (EN) 50160 [187] standard is a leading standard document that sets the limits for network operators. EN 50160 presents the voltage distortion limits the network operator must comply with in LV and MV electrical distribution networks, the main voltage parameters in the customer's PCC, and their allowable deviation range. In addition to these standards, IEEE 519-2014 [188] provide recommendations for voltage and current distortion limits for network operators and users, respectively. IEEE 519 standards distinguish THD and TDD notions. Figure 22 illustrates a summary of power quality standards related to harmonics. These standards, which explain the problems that harmonic distortions cause in power systems and the degree of tolerability of harmonics, have been widely adopted by industry and research groups.

G. OVERLOADING

EVs charged during peak periods are among the most critical factors affecting the sub-transmission grid. The resulting overload is a severe issue encountered when the network hosting capacity is insufficient. Overloading issues caused by the high penetration of EVs are generally addressed at

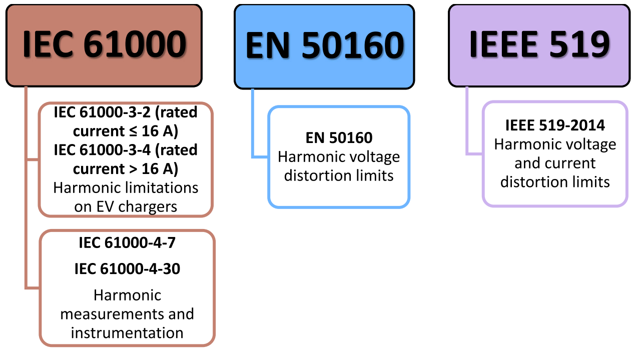

FIGURE 22. Various harmonic power quality standards.

the low voltage level [189], [190]. On the other hand, this increased penetration of EVs also has the potential to compensate for the load and grid problems caused by increased wind and solar energy production. There are also several hours when the current production capacity is much higher than the EV loads, except for the overload hours. EV loads will result in higher peaks in the network without electricity tariff incentives and control mechanisms, affecting both sub-transmission lines and distribution. Different demand response techniques, such as coordinated load shifting, peak shaving, and valley filling, can overcome overloading problems due to EV charging [191], [192].

H. VOLTAGE DROPS

The presence of EVs and other traditional loads in electricity distribution networks creates an increased demand, which also causes voltage drops in the power grid [193]. According to the EN 50160 standard [187], the 10-minute rms values of voltage levels should be between 90 and 110% of the rated value (e.g. 230V, 110V, etc.). Overvoltage is defined as a voltage magnitude higher than 110%, while undervoltage is defined as a voltage magnitude less than 90%. Similar to overloading, the electricity demand that is very high at certain hours can also be the main reason for undervoltage in distribution networks. Undervoltage is a term for a voltage drop that lasts for more than one minute, and voltage dip occurs when the voltage falls below 90% of the nominal value for up to one minute [155].

There is a rich body of literature on the impacts of EV charging on voltage drops. A study in [194] demonstrates that when EV load penetration ranges from 20% to 80%, there is a voltage drop of 13% to 43% from the rated voltage. According to [195], even a 1% to 2% increase in EV integration in the utility grid affects the system voltage. LV distribution network with 50% EV load penetration in [158] and [196] was studied in the UK and Portugal, respectively. They indicate that the limits are surpassed even during slow charging. Utility supply may be insufficient to supply the number of EV loads that increase significantly. Therefore, it is deduced that a specific EV penetration level should not be exceeded to prevent deviation in the supply voltage.

Estimating the load profile and charging behaviour is critical to overcoming these voltage issues [197]. Reducing the feeder length by adding more transformers to the power network is one of the classical mitigation methods [198]. Although reactive power control is often mentioned as mitigation, it is more likely to worsen in low-voltage networks. Reactive power control can be a possible solution for large installations connected to medium voltage networks or facilities directly connected to the distribution transformer. In order to mitigate an overvoltage with one customer, for example, an undervoltage is established for other consumers, or vice versa [155].

There are additional voltage-related issues with EVs connected to the power networks. The charging of EVs can influence network voltage issues such as voltage fluctuations. The voltage fluctuation is caused by a change in load current, which causes a change in voltage drop across the grid's source impedance [150], [151]. Light flicker is a common side effect of fast voltage fluctuations. The reactive components of devices where the load current changes rapidly and continuously cause voltage fluctuations and light flickers at high voltage levels. In contrast, the active components of the same devices cause these problems at low voltage levels. Flicker is considered the effect of voltage fluctuations on light intensity due to varying load current [151], [199].

I. PHASE BALANCE (UNBALANCED VOLTAGE)

The growth of EVs and slow chargers might cause unbalanced problems if loads in a single phase are higher than in other phases for a three-phase distribution system. The increased neutral current causes voltage unbalance, which increases power losses and violates voltage limits in the system [200]. The term voltage unbalance represents that the three voltages have different rms values in a three-phase system [155]. According to EN 50160 and IEC 61000-2-5, the maximum acceptable voltage unbalance level is usually 2% in electrical networks. It can be up to 3% in some particular circumstances [187], [201].

In [202], the impact of uncontrolled charging and tariff-based charging on voltage unbalance in the urban distribution network was investigated. In the first method, EV charging is done whenever it is needed, while in the second method, it is assumed that EVs are charged during off-peak hours. Utilising tariff-based charging keeps the voltage unbalance factor within acceptable ranges. It has been determined that voltage unbalance limits are exceeded after 50% EV penetration with the uncontrolled charging method. A test network was conducted at an LV residential distribution feeder in a suburban area with 134 residents in Dublin, Ireland [203]. According to this study, most EVs are charged with standard single-phase AC sockets in the customers' houses, and it is assumed that the EVs are connected to the distribution grid through the same point as the residence. The impact of EV integration on the voltage of each phase is shown in Figure 23. It can be seen from Figure 23 that the voltage of each phase decreases as the EV integration increases. Moreover, the voltage levels differ significantly for each phase. For instance, the voltage drop in phase-c reaches the lower limit of 0.9 per unit (pu) after penetration of 20%, while phase-a and phase-b reach the same limitation when integration is 27% and 44%, respectively.

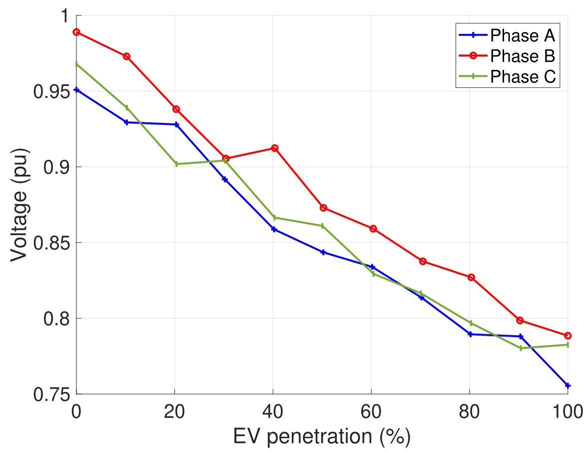

FIGURE 23. Unbalanced single phase voltages due to EV penetration [203].

In addition to single-phase EV charging, single-phase solar PV also causes unbalanced problems. Therefore, the coordination of single-phase EV and PV systems becomes increasingly crucial to address the issue of energy unbalance [204]. Utilising energy storage devices, voltage regulators, and feeder capacitors can also help to improve power quality in terms of voltage unbalance [200], [205].

J. PEAK DEMAND

Mainstream use of EVs will increase the peak loading of the power systems. Quantification of this additional load is usually conducted via scenario-based probabilistic approaches. The National Grid's future energy scenario [206], outlined in 2021, shows a significant increase in EV sales compared to previous years despite the pandemic. This increase needs to be accelerated to reach the net-zero carbon emissions target in 2050. 4.7 million EVs are predicted in 2030 in the slowest decarbonization scenario (''Steady Progression''), while this number reaches 11 million in the fastest scenario (''Leading the Way''). The former and the latter predict 23 and 31 million EVs on the road by the year 2040. Total annual energy demand from road transport due to transportation electrification is expected to be around 100 TWh for both scenarios. Peak demand for electricity is expected to increase, particularly with the electrification of heat and transport. For example, a typical daytime demand could be increased by 19 GW of EV charging in the fastest scenario in 2050.

With increasing EV integration, smart charging and V2G will be essential in reducing peak demand. The flexibility provided by these two methods can lead to shaving peak demand in the mid-scenario ''Consumer Transformation'') up to 32 GW. Reference [207] estimates that the UK will have more than 7 million ultra-low emission vehicles by 2030.

TABLE 11. Power system stability issues due to EV charging.

Issue	Reason
Step (demand jump)	When there are too many chargers that are switching on or off simultaneously.
Ramp (demand increase)	When there are too many chargers that are switching on and off in minutes.
Oscillations	When there are a bunch of chargers that keep switching on and off repeatedly.
Restoration	The restoration procedure will be hampered by erratic behaviour after restart.

According to Deloitte's assumption [208], 31.1 million EVs will be on the roads worldwide in the same year. With the increase in EV demand, there will also be a significant proliferation in the number of charging stations. The increased number of fast-charging stations can further increase peak EV demand due to EV fleets simultaneously charged at high power ratings [209]. Further, batteries with higher energy capacity are expected to increase peak demand with the developing battery technologies [3].

K. GRID SECURITY AND RELIABILITY

Electric network generation and demand must be balanced in real-time; otherwise, the grid frequency deviates from its nominal value. The ideal frequency for a power system is 50 or 60 Hz, called nominal frequency. However, the frequency is not constant, and slight variations occur due to unbalanced electrical energy generation and demand. The ideal frequency range is between 49.5 and 50.5 Hz for a 50 Hz system [155]. If the demand for charging EVs is high, the required electrical energy generation needs to increase to keep the grid frequency between this frequency range [210].

Uncertainties related to the starting time of charging and charging duration of EVs cause increasing uncertainty on the demand side of the power systems [211]. Power system stability issues due to EV charging are shown in Table 11. The first two issues (step and ramp) are related to switching on and off large collections of EV chargers simultaneously or in short periods. In this case, the power system cannot handle varying demands, and frequency deviations could lead to system stability issues. Other significant problems are related to the uncontrolled switching of chargers after a major blackout or restoration. On the other hand, EVs interconnected to the power networks can also be utilised to help frequency stability with smart charging methods and V2G capability [212]. Load shaping and Demand-Side Management (DSM) techniques can be used to maintain the frequency stability in the power grid [213].

VII. IMPACTS OF LOW TEMPERATURES EV CHARGING ON POWER NETWORKS

The critical review of the literature presented in the previous sections shows that low temperatures in EV charging could negatively impact the power grids. More particularly, this section aims to investigate the implications of (i) reduced charging rates, (ii) increased energy use for driving, (iii) preheating of cabin and battery, and (iii) charging durations on power networks. The impacts of EV charging on power networks under "perfect" (e.g. 21°C) weather conditions have been well-documented in the literature [214]. At the distribution level, uncontrolled EV demand could increase the peak loading of transformers and lead to power quality issues (mainly voltage drops and phase unbalances). Similarly, large collections of EV charging could increase nationwide peak demand. For instance, National Grid in the UK estimates that EVs will create an additional 18 GW of demand by 2025, which represents an extra 30% of today's peak demand [206].

On the other hand, as documented so far in this paper, actual EV demand impacts could intensify under low temperatures. The regional difference in energy demand for large EV collections potentially poses a risk to the operators if the charging infrastructure is not adequately planned. In Europe, the US, and China, ambient temperatures vary between −30°C to +40°C, and their impacts on EV batteries cannot be neglected. Consequently, the EV hosting capacity of distribution networks is expected to be lower in winter due to potential challenges and impacts presented next.

A. INCREASED HARMONICS DISTORTION

As given in the previous sections, the impacts of EV charging on the power distribution network have been investigated from various aspects of the literature. In those studies, the temperature was not generally considered, and the optimum temperature was assumed as the ambient temperature. Therefore, the impacts of the low temperatures expressed in the article on EVs and power quality issues while charging have not been addressed sufficiently in the literature. For instance, harmonic distortion constitutes an intensified problem under low temperatures.

According to an experimental measurement in [215], low temperatures significantly impact fast chargers' charging rates. As a testing study, the harmonics impacts of an ABB Terra 53 CJ 50 kW DC fast charger were used to charge a Nissan Leaf (2015 model) to examine the harmonics profile. Figure 24 shows an inverse relationship between the charging output power and the harmonics injected into the power network. As the ambient temperature approaches the optimum temperature, the charging power increases, thus reducing the additional harmonics. In contrast, with the decrease in temperature, the charging power decreases, and the harmonics increase. At subzero temperatures, THD exceeds the limits set by the standards.

In [216], the Nissan Leaf with a 24 kWh battery was fully charged at four different temperatures (−25°C, −15°C, 20°C and 40°C) using six commercial fast chargers. Table 12 shows

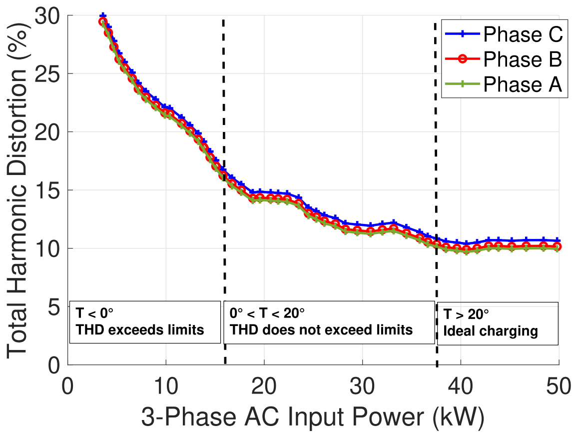

FIGURE 24. Current harmonic distortion variation of DC fast charger (ABB Terra 53 CJ) [215].

TABLE 12. Current total harmonic distortion and corresponding currents for different temperatures [216].

Charger	Units	Temperature Levels			
		-25 °C	-15 °C	20 °C	40 °C
A 120 kW DC	THD_I (%) I_L (A)	15.06 17.6	13.37 28.53	6.43 82	8.23 81
B up to 50 kW DC	THD_I (%) I_L (A)	37.63 9.13	24.67 24.47	10.63 79.2	11.03 77.03
C from 20 to 44 kW DC	THD_I (%) I_L (A)	Failed to charge	8.33 37.1	8.6 68.3	6.37 67.13
D Max power 50 kW DC	THD_I (%) I_L (A)	Failed to charge	11.07 31.73	7.97 61.8	8.33 80.83
E Max power 50 kW DC	THD_I (%) I_L (A)	Failed to charge	8 29.07	4.4 75.67	4.1 75.5
F Max power 60 kW DC	THD_I (%) I_L (A)	23.9 15.87	15.67 43.3	11.77 80.33	8.53 83.03

the total harmonic distortion and corresponding currents for different temperatures. The table has been prepared by averaging the THD_I and I_L values calculated separately for the three phases. According to the findings, THD_I levels tended to rise at lower temperatures. In addition, some chargers have failed to charge the EV under low temperatures. Similar to results presented earlier for Norway (see Table 4), the charging power significantly reduces under low temperatures.

In [134], the impacts of ambient and battery temperature and SoC on ABB fast charger were investigated, and results are presented in Table 13. A warm and cold battery with the same SoC (10%) is charged up to 80%, and this process takes 25 and 62 minutes, respectively. When the battery temperature reduced, the charging current also fell, shown in Table 14. The same study also found that TDD increased initially when the charging power decreased, and TDD declined at the end of the charging cycle. TDD was measured above 2% with 120 A (rated current), while TDD is around 1% regarded as good power quality for 400 V (rated voltage).

B. VOLTAGE ISSUES

The surveyed literature further reflects that distribution networks could experience additional voltage issues, such as voltage dips and phase unbalances when charging EVs under low temperatures. Even though the literature lacks such studies, potential problems could be enumerated as follows. First, preheating of EVs, especially in cold mornings, will be required for EV owners who commute to work and school. Considering the fact that the morning commute time of most drivers could be within a short time frame, the preheating of EVs (as depicted in Figure 13) could create additional morning peaks and increase the existing ones.

The preheating times also depend on the battery temperature. For EVs located in closed and insulated parking garages, the preheating periods could be relatively shorter than the ones that are parked outside. Hence, there could be uneven demand across each phase, which further intensifies phase unbalances. The varying demand under low temperatures ultimately impacts the hosting capacity of distribution networks. In [217], it is shown that the hosting capacity in Sweden drops by 30% in winter when compared to summer when a 30 MVA transformer feeding an IEEE 33-node distribution network is examined.

C. INCREASED PEAK DEMAND

As presented earlier, low temperatures drastically reduce the driving range of EVs. To that end, depending on driving patterns, a fraction of the EVs may need an additional recharge during the day to complete the trip. For instance, according to Swiss national travel data [218], nearly 6% of daily trips are longer than 200 km, and 2% are more than 400 km. If these trips are made with small or medium-sized EVs, multiple EV chargings are needed during the day. Considering the case when EV penetration reaches a couple of million, it is critical to quantify such extra load to plan for the power generation needs. For example, this extra EV demand can force system operators to use carbon-intensive generators (e.g. natural gas), which contradicts net-zero targets.

A probabilistic simulation study is presented in [219] to quantify the impacts of low-temperature charging in the UK. Different simulation scenarios are created based on different EV penetration levels, ambient temperature, and battery charge-discharge cycles using travel surveys in the UK. The results show that an additional 630 MW extra generation is needed to charge 11 million EVs in winter when compared to optimal temperatures. The case studies further show that the associated carbon intensity could increase by 25% for the days with low wind generation.

VIII. RESEARCH GAPS AND MITIGATION STRATEGIES

In this section, we provide an overview of research gaps and associated mitigation strategies for key surveyed topics.

EV Battery: Batteries represent the highest cost for an EV purchase [220]. The difficulty in understanding and predicting the non-linear behaviour of batteries in different driving

TABLE 13. Impacts of ambient-battery temperature and SoC on ABB fast charger [134].

Measurement	Initial SoC (%)	Initial ambient temperature (°C)	Initial min/max battery temp. (°C)	Charging time to 80% SoC (min)
1. Warm battery	17.5	19	27/30	23
2. Warm battery	10.0	18	22/27	25
3. Cold battery	10.0	-4	07/14	62
4. Cold battery	9.5	-1	10/15	55
5. Half-discharged warm battery	43.5	23	24/26	21
6. Half discharged warm battery	50.0	26	31/32	17

TABLE 14. Impacts of temperature on fast charging current. (T represents the battery temperature) [134].

	$T < 10°C$	$10°C \leq T \leq 20°C$	$T > 20°C$
Charging current (A)	25	50	125 (rated)

and temperature conditions leads to the overdesign of batteries and incremental cost [221], [222]. The technical solutions applied to overcome the problems experienced by the Li-ion battery under low temperatures may increase up to a certain point, increasing the vehicle costs and making the vehicle unaffordable for purchase [223]. There are efforts to mitigate the negative impacts of low temperatures on EV batteries. The hybridization of supercapacitors with batteries [224] could provide a high power density and cushion temperature impact. Also, the use of lithium titanate [225] could increase resistance to lithium plating, making the battery more robust to temperature fluctuations. While improving battery operation for low temperatures may contribute to EV adoption, the aforementioned efforts further increase the cost of EVs.

Fleet Charging: Large vehicle fleets are charged overnight with the traditional charging method. However, if large vehicle fleets are charged with fast charging during the day, EV load demand increases significantly. Moreover, due to the location of the fast-charging stations, it is not possible to charge overnight like slow chargers. Therefore, it is essential to ensure coordination by altering the charging power and price according to the power grid conditions and the demand from the EV fleet. However, public transport vehicles such as taxis, buses and delivery vehicles must comply with a specific schedule. The increase in peak demand, which increases significantly during winter evenings, may also increase more by charging vehicle fleets simultaneously. Further, the charging behaviour of EV drivers alters the impacts of fast-charging stations on the power network. For example, charging vehicles too often despite having sufficient SoC also increases demand from EV fleets.

Preheating: Preheating has a vital role in preparing EVs to drive under low temperatures. Both the battery and the EV cabin are heated via an EV charger. The power of the charger determines the preheating time. This time will be longer with a lower charging power [119]. Therefore, drivers have to wait for a long time for their vehicles to be ready during preheating with slow chargers. The waiting time can be shortened with fast chargers. On the other hand, drivers using fast chargers for preheating at peak times in winter may cause the peak load to increase. For this reason, a suitable charging power should be set by considering the demand of the load from the grid and the energy provided to heat the battery and the EV cabin from a fast charger. Preheating while driving is also an effective method to eliminate waiting time completely [123]. The heating energy obtained by this method is supplied from the energy stored in the EV battery and the EV braking energy. However, vehicle distance becomes shorter as more energy is supplied from the battery for heating while driving.

Harmonics: Mitigating harmonic distortion requires understanding, modifying, and restricting systems emitting harmonic components. Harmonics can be reduced by limiting equipment emissions, strengthening the power network, and using filters (passive and active). The most apparent mitigation path consists of minimal use of nonlinear loads or the usage of fewer pollutants. Thus, manufacturing equipment that produces fewer emissions has gained more importance. The next stage is to reduce the network's impedance by modifying the installation or specific equipment. Passive filters are composed of resistances, capacitances, and inductances designed precisely to suppress specific harmonics such as 3rd, 5th, and 7th harmonics. Active filters are devices based on power electronics that use reliable control algorithms to eliminate harmonic distortion. This elimination can be accomplished with impedance shaping or compensating harmonic currents. Filtering is chosen according to the most harmful harmonic current/voltage components [155], [163]. Traditional techniques to limit or eliminate harmonics injected by EV chargers include correcting power factors and installing an active shunt filter for charging stations [226], [227].

EVs also have a harmonic compensator role by injecting or absorbing harmonics from/to the power grid [228]. Integration of EVs with renewable energy resources can enable the mitigation of harmonics. In [166], it was found that wind generators can reduce harmonics caused by high EV penetration if they are installed in the appropriate size and location, while the utilisation of PVs and EVs in [170] can benefit both charging EVs with PV sources and filtering the harmonics. When many EVs are charged via fast chargers, THD_I is calculated as 11.4%. On the other hand, using PVs to charge EVs can halve the THD_I. As a result, the coordination of EVs and other non-linear loads is vital for harmonic mitigation.

Integration of energy storage systems: Energy storage systems (ESSs) can be utilised in power systems for both power quality such as frequency regulation, voltage support, unbalanced load compensation and spinning reserve and energy management such as peak shaving, an increase of renewable energy penetration and meeting excess EV demand [229]. Integrating ESSs into fast-charging stations enables reducing the impact of the large-pulsating load due to the charging [230]. Moreover, ESSs can contribute to the cost reduction of charging [231]. In fast-charging stations where high-current charging is utilised, ESS with high power density, such as a flywheel, can compensate for the high pulse load demand [232]. By hybridising two energy storage devices with high energy and high power density, faster response and higher energy capacity demand can be met [233]. While the energy stored in ESSs may not be sufficient to charge the vehicles for a long time, this stored energy can be used for preheating vehicles. As EV fleets become more common in the future, charging stations may have difficulty meeting EV demand. Therefore, preheating can be done from the ESSs rather than the charger, and long queues of EVs waiting to be charged can be prevented.

Battery swapping stations: Battery swapping stations allow EV drivers to replace their depleted batteries with fully charged ones to continue their journey without waiting. Compared to battery charging, battery swapping has significant advantages such as time, cost-effectiveness and space. However, each replaceable battery must be ready to be used actively [234], [235]. The two most important problems experienced by EV batteries under low temperatures are the decrease in their energy capacity and the increase in the tendency of degradation. Moreover, charging under low temperatures extends the charging time as the charging power and efficiency decrease. One possible solution to address the issues faced by batteries under low temperatures while on standby or charging could be to keep them in a warm environment, like battery swapping stations. However, these stations are not very common nowadays. EV owners may find it challenging to locate a suitable battery for their vehicle as a broad range of battery types and capacities are available, which may differ even within the same EV model in different years.

The impacts of EV charging under low temperatures have not been a major issue so far, as the utilisation of public chargers (both AC and DC) is very low. For instance, in Canada, the median number of charging events in fast DC chargers is only 1 [236]. In the US, the utilisation rates for fast chargers hover around 10 - 15 kWh per port per day. These results reflect that the concurrent fast EV charging is unlikely to happen except for certain charge locations such Tesla Superchargers which have been serving single vehicle type. To tackle discomfort and reduced charging rates introduced by low temperatures, a handful of car manufacturers (e.g. Tesla, Nissan, BMW) have introduced applications to precondition EVs [237]. However, as mentioned earlier, there is a trade-off between preheating and driving range and electrified trips need to be carefully planned.

IX. CONCLUSION

This paper has reviewed the impacts of low temperatures on EVs in terms of battery performance, charging issues and power grid operations. Since countries with serious net-zero targets experience long and cold winter months (average temperature around or below 0° C), the associated impacts of EV charging require special attention to cushion negative impacts.

We showed that EV operations under low temperatures significantly impact the performance and lifecycle of Li-ion batteries for EV applications. It was discussed that with the falling temperature, the electrolyte conductivity and the charge transfer kinetics of the battery decrease, resulting in rising internal resistance and battery capacity loss. Thus, the driving range of an EV is seriously reduced. Additionally, it was found that the range decreased even more due to the rising energy needs for EV cabin thermal comfort. Empirical studies and modelling work on battery degradation, cycle and calendar ageing were provided and discussed in detail to present a compact view of the existing works. All these problems highlighted the importance of BTMS, which ensures optimal performance, longevity and safety of EVs under low-temperature conditions.

This paper further discussed the implications of low temperatures on EV charging. Charging a Li-ion battery is challenging at low temperatures since electrical current must be controlled to prevent cell and battery overvoltages. While this process did not pose a big concern for Level 1 and Level 2 charging (charging power decreased after a few hours), it caused severe problems for fast charging. The charging power dropped drastically from the beginning, prolonging the charging time. In addition, lithium plating was also becoming an important problem due to fast charging under low temperatures, which can cause permanent damage to the battery's electrodes and lead to reduced capacity, shortened lifespan, and even safety concerns.

In the next part, the paper analyses the implications of power networks. The impacts of EV charging at the distribution level brought power quality issues such as harmonics, voltage drops, phase unbalances, and other problems, including overloading and peak demand increase. Among these concerns, it has been seen that harmonics were the primary binding conditions affecting EV integration and charging. Harmonics increase with fast charging even more under low temperatures. This is the main factor limiting the number of

EVs charged simultaneously. Designing an appropriate EV model for power quality assessments of EV charger harmonic data is a nearly unexplored area. A study [172] conducted in 2022 found that no research has been discovered to be able to accurately model circuit data using mathematical techniques and consider probabilistic perspectives.

In addition, depending on the daily trip statistics, high-mileage EVs may require additional recharge during the day, which may contribute to an increase in peak demand. Many studies in the literature have assumed that EVs operate at an optimum temperature (21°C). However, in reality, EVs are exposed to various temperature ranges while parking, charging and driving. Temperature is a crucial factor affecting EVs' performance and their impact on the grid. The existence of countries with cold climates where EV penetration is developing further increases the importance of studies in this area. In the last part of the study, we presented research gaps and potential methods for mitigation strategies to reduce the impacts of EV charging under low temperatures.

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