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TOPICAL REVIEW

Electric Buses in Hot Climates: Challenges, Technologies, and the Road Ahead

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ABSTRACT This article examines the adoption of Battery Electric Buses (BEBs) in hot climates, highlighting the pursuit of sustainable transportation. It contrasts bus technologies and their adaptability to heat, with a focus on the operational strategies and performance metrics suited to these environments. The role of charging infrastructure is assessed, alongside the thermal tolerance of lithium-ion batteries, to establish their compatibility with BEBs in warm regions. Energy consumption patterns of BEBs are analyzed, considering the extra load from cooling systems. Additionally, the review touches on the economic implications and market acceptance, providing a succinct overview of financial impacts and consumer behavior. The paper identifies gaps in current research, particularly in relation to hot weather conditions, and validates findings to aid stakeholders in making informed decisions and spurring innovation in the field. With concise problem statements and state-of-the-art evaluations, this contribution offers a pathway for future research and a deeper understanding of electric bus operations under thermal stress.

INDEX TERMS Battery electric buses, public transportation, energy consumption, hot climate.

I. INTRODUCTION

The rise in global CO_2 emissions since 1990, as indicated by [1], presents a formidable challenge, even in the face of concerted international initiatives like the Paris Climate Accord (COP 21). This accord set forth the ambitious goal of limiting global warming's impact to a rise of 1.5 °C compared to pre-industrial levels [2]. However, realizing this target is intricate due to the significant contributions of certain sectors to the overall emissions profile. In a contemporary context, the transport sector is pivotal, functioning as both a cornerstone of economic vitality and as a major contributor to greenhouse gas emissions. The sector's role has become increasingly pronounced post-COVID-19 as economies endeavor to recover. Following the coronavirus (Covid-19) pandemic, there was a noticeable rebound in transport demand across the globe [3], [4]. This resurgence, driven by a reinvigoration of industrial activities and a restoration of global supply chains, manifested in a marked increase in both passenger travel and freight transport [4]. Notably, the easing of pandemic restrictions saw a release of pent-up demand for mobility, leading to a 3% surge in transport CO2 emissions in comparison to the preceding year, as individuals and businesses rapidly returned to pre-pandemic transport usage patterns [4]. Furthermore, from 1990 to 2022, transport emissions have expanded at an annual average rate of 1.7%, outpacing almost all other end-use sectors, save for industry which witnessed a parallel growth rate [5]. To align with the Net Zero Emissions by 2050 Scenario, there is an imperative need for CO_2 emissions from the transport sector to decline by over 3% annually up to 2030 [6]. To attain such substantial emission reductions, it will be essential to enforce robust regulations and fiscal incentives. Furthermore, significant investment in infrastructure is vital to facilitate operations of low- and zero-emission vehicles.

Initiatives aimed at curbing transit emissions are taking center stage, especially in light of commitments under the Kyoto protocol and the turbulent nature of oil prices. These dynamics are pushing policymakers towards considering

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alternative technologies to oil-dependent mobility. Despite robust efforts to standardize and reduce emissions from the conventional internal combustion engine, forecasts suggest we might fall short of the Kyoto protocol's emission targets [7], [8], [9], [10]. An extensive review of the literature highlights the irreplaceable role of alternative technologies to curtail the emissions stemming from road transport. Although multiple technological innovations have surfaced over the years, oil continues to dominate the transport market, with alternative technologies only making a minor share of the global transport market [7].

Choosing the most appropriate alternatives for road transport is contingent on numerous factors that traditional petrol/diesel engines adequately address [11]. These range from energy logistics, cost-benefit evaluations, infrastructure development, public acceptance, and others. Intriguingly, public transit, especially city buses, emerges as a promising area to expedite the adoption of alternative technologies [10]. The structured nature of bus transit, characterized by fixed routes, centralized depots, and shared infrastructure, makes it an ideal candidate for ushering in these novel technologies. It provides a controlled environment where new technologies can be rolled out, tested, and refined while simultaneously curbing emissions [11]. At present, a variety of powertrains designed for urban buses are available, each boasting its unique benefits tailored for emission reductions. Nevertheless, choosing the right power train hinges on a myriad of factors, from costs, network design, energy source to driving conditions. Thus, a delicate balancing act between these variables is crucial for the optimal deployment of each technology.

Considering the challenges in conventional road transport, electric vehicles (EVs) offer a promising solution. However, EVs face significant obstacles, such as limited range, charging infrastructure concerns, prolonged charging times, battery degradation, high upfront costs, recycling difficulties, market acceptance issues, and regulatory inconsistencies in major markets. To overcome these challenges, advancements in technology, expanded charging networks, consumer education, and uniform supportive policies have been pursued globally. Researchers have extensively summarized various works, offering comparative literature on these advancements. Reference [4] introduced smart microgrid integration with EVs, emphasizing seamless charging infrastructure within microgrid environments. The potential of EV to Grid (V2G) technology for enhancing grid stability and promoting renewable energy integration has been explored [5]. Sustainability aspects were highlighted in solar-powered EV charging systems, integrating renewable energy sources into the infrastructure [6]. Fast charging technologies, outlined in [7], provide insights into challenges and opportunities, while extreme fast charging technologies showcased by [8] significantly reduce charging times. Wireless charging techniques have gained prominence, with [9] offering a comprehensive overview of applications in EVs. Advancements in energy storage systems were discussed by [10], emphasizing their role in supporting charging infrastructure. Battery charging efficiency, a critical aspect of EV performance, was explored in various charger topologies [11], [12], while [13] explains the possibility and challenge of battery swapping stations as an alternative to charring time. In summary, these reviews underscore the rapid evolution of EV charging technologies, including infrastructure, energy management, fast charging, and innovative techniques, although detailed exploration of hot climate impacts on EV performance is lacking. Moreover, the influence of temperature extremes, particularly hot climates, on the charging infrastructure and battery performance of BEBs warrants a dedicated discussion. High ambient temperatures can significantly impact the efficiency of charging processes and the operational health of batteries. The thermal management of both batteries and charging stations becomes critically important in such conditions, as overheating can lead to reduced charging speed, potential damage to battery cells, and decreased overall system reliability. Studies specifically investigating the temperature impacts on overnight and opportunity charging for BEBs reveal that adaptive strategies and technologies are required to maintain efficient charging and battery longevity in hot climates [12].

Thus, in comparison to the existing literature, this article has following contribution:

1. This manuscript offers a detailed examination of the challenges and opportunities associated with BEBs in hot weather conditions, providing a comprehensive understanding of the environmental factors affecting their performance.
2. Through meticulous benchmarking and situation analysis, it presents the current state of BEBs adoption in hot regions. We highlight key strategies and performance metrics, providing valuable insights for stakeholders and policymakers aiming to enhance BEB implementations in hot climates.
3. This manuscript dissects various bus technologies and battery systems, emphasizing the suitability of lithium-ion batteries in hot environments. It delves into the adaptation of these technologies and discuss their behavior under heat stress, providing essential knowledge for manufacturers and engineers.
4. By pinpointing specific research gaps related to BEBs in hot climates, we guide future research endeavors. These identified gaps serve as a roadmap, directing researchers and policymakers towards areas needing further exploration and innovation in the context of sustainable public transportation.

II. BEBS VS. ICE BUSES: A TECHNOLOGICAL COMPARISON IN HOT CLIMATES

Following the discourse on the criticality of the transport sector in global emissions and the urgency to identify and adopt sustainable alternatives, a clear direction emerges. It becomes paramount to dissect and understand the core technologies underpinning these transit systems. Both traditional Internal Combustion Engines (ICE) and the increasingly prominent Electric Motors (EM) stand as principal contenders in the quest to redefine urban mobility. By delving into the available literature, [13] decoded the nuanced characteristics of these technologies, their respective pros and cons, and their potential role in sculpting the future of environmentally conscious transit solutions. (ICE) and EM exhibit distinctively different performance curves, leading to varying applications and efficiencies. Traditional ICEs do not provide constant power output across all speeds. In fact, their power tends to peak at relatively high speeds and isn't consistent across the rev range. This is in stark contrast to EM, which offers the luxury of producing maximum torque almost from standstill. This characteristic constant power feature starts from a base speed and extends up to the motor's maximum speed. The ability to generate high torque at very low speeds is especially advantageous for transit vehicles that often operate in ''stop and go'' conditions, typical of urban landscapes [13]. The high torque capability of Ems reduces the need for complex transmission systems, which is a requirement for most vehicles equipped with an ICE. Another challenge with ICEs is their efficiency, or rather, the lack thereof, when operated under variable conditions. These engines are crafted to cater to peak power requirements, which might be needed for rapid acceleration or hill-climbing. However, during most real-world scenarios, ICEs only utilize a fraction of their maximum power, making them inefficient [14]. On the other hand, EM boasts a higher efficiency range and is optimized for a variety of operations. The versatility of electric drivetrains has paved the way for multiple technological alternatives beyond the conventional (BEB) framework. Reference [15] elaborated that one of the foremost is the trolleybus system. Introduced in the early 20th century in regions like North America and Europe, trolleybuses draw electricity from overhead wires Initially, these systems were brought to life as a measure to convert existing tram routes, the primary motivation being the reduction of operational and maintenance costs. However, with shifts in the automotive industry, coupled with fluctuating oil prices, many cities transitioned away from trolleybuses in favor of cheaper diesel buses. It wasn't until the oil crisis of the '70s, combined with mounting environmental concerns, that trolleybuses saw a resurgence. Despite their environmental and operational benefits, the considerable fixed costs associated with their infrastructure—most notably the overhead wire systems—limit their widespread adoption. Another alternative to BEBs lies in the fuel cell domain. Reference [16] defined the Fuel cells operate as electrochemical devices, converting energy from reactive fuels, primarily hydrogen, into electricity. While they continuously produce electricity if fuel is supplied, they suffer from efficiency drawbacks concerning the production of reactive fuel. Reference [17] elaborated on the benefits of BEBs, where the authors mentioned that as advancements in battery technology continue, the prospects for BEBs have never looked brighter. These buses are shaping the future of urban transit, both environmentally and economically. The predictability in the daily mileage of transit buses and their relatively longer lifespan (around 10-12 years) compared to personal vehicles makes them an ideal candidate for electrification. Moreover, the consistency in the annual usage data (approximately 50,000 km) solidifies this stance. BEBs promise a slew of benefits over their ICE counterparts. For starters, they contribute significantly to energy efficiency. Noise pollution, a growing urban concern, sees drastic reductions with the deployment of BEBs. Furthermore, the absence of engine vibrations enhances passenger comfort, adding to the overall transit experience. From an economic standpoint, while initial investments might be higher, e-buses offer the promise of reduced operating costs in the long run, making them an enticing option for city planners and transit authorities alike [18]. Figure 1 illustrates a performance comparison between both EM and IEC, which proves that EM is more operationally efficient as a result of most of the literature.

There has been an increasing need, and hence a research interest for assessing the energy needs of BEBs worldwide. However, none of the studies assess the real-world energy performance of BEB to reflect on their precise energy needs in operation through a thorough bus testing campaign. In addition, very few studies analyzed the energy performance of all major energy systems on-board BEB, such as the powertrain, HVAC unit, and other auxiliaries. Finally, no study tackles the deployment of BEB in the Gulf Cooperation Council (GCC) region, where the extremely hot weather conditions would significantly impact the BEB energy needs. In addition, based on the presented literature review regarding the charging needs and infrastructure of BEB fleets, most of the studies focus on the infrastructure costs and planning, while no studies tackled the scheduling problem of BEB fleets, including their charging needs in the GCC or MENA region. The list of limitations is elaborated below:

- The energy efficiency of BEBs can vary considerably depending on geographical and climatic conditions. Extreme temperatures, either hot or cold, might adversely impact battery performance and efficiency.
- A significant dependency exists on robust charging infrastructure. In areas where this infrastructure is underdeveloped or nonexistent, the full advantages of BEBs may not be realized.
- Economically, the upfront investment for BEBs and their associated charging infrastructure can be considerably higher than traditional transit systems, potentially posing a barrier for economies or cities with budgetary constraints.
- While BEBs substantially reduce carbon emissions when in operation, concerns arise from the environmental footprint associated with electricity generation to charge BEBs, battery production, and end-of-life disposal. This includes issues related to the mining of

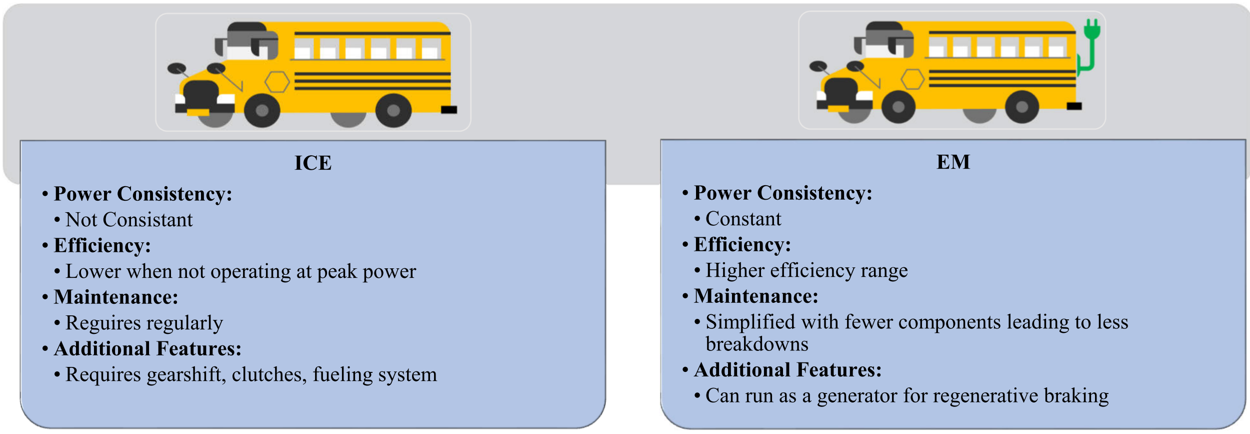

FIGURE 1. ICE Vs. EM performance comparison.

rare metals and the challenges of battery recycling or disposal.

- BEBs, being part of a continuously evolving technological landscape, might undergo rapid iterations and improvements. Early adopters might find themselves with systems that quickly become outdated as newer, more efficient technologies emerge.
- A psychological barrier known as "range anxiety" persists, wherein potential users fear the battery might deplete before reaching a destination or suitable charging point. This anxiety might deter some from considering or using BEBs for transit.

III. BUS ALTERNATIVE TECHNOLOGIES

In the concerted effort to transition from diesel bus fleets, a plethora of alternative bus technologies have come to the forefront. These technologies broadly involve electrified buses, fossil fuel combustion buses, and biofuel combustion buses. Among these, electrified buses, or BEBs, demonstrate pronounced potential to mitigate CO_2 emissions and other pollutants significantly, contingent on their degree of electrification.

The following segment delves into the nuances of electrified bus technologies based on the comprehensive analysis presented by [19] and subsequent literature.

A. HYBRID BUSES

Hybrid Buses are a pivotal transitional technology, blending the functionality of an ICE with EM fed by on-board batteries, thereby offering a diverse and efficient operational spectrum in public transportation. The intrinsic value of hybrid technology is evident in its multifaceted configurations and the interconnected play between ICE and EM, each tailored to specific operational needs and energy consumption patterns. This combination of technologies leads to the development of complex systems that optimize energy utilization, thereby creating sustainable urban transit solutions [14].

Series Hybrid Buses: Within the realm of hybrid buses, Series Hybrid Buses implement a unique configuration where the internal combustion engine predominantly acts as a generator. This design paradigm diverges from traditional propulsion mechanisms, focusing instead on generating electricity to either recharge the on-board battery or to directly power the electric motor.

The engine's role is not to propel the vehicle directly but to maintain electricity flow to the powertrain, ensuring that optimum efficiency is maintained regardless of variable driving speeds and conditions [17], [25]. Furthermore, this configuration is often foundational for the development of Plug-in Hybrid Technology, allowing the on-board battery to be recharged externally, offering an extended range for electric-only driving [17]

Parallel Hybrid Buses: Contrastingly, Parallel Hybrid Buses are characterized by the ability of both the combustion engine and electric motor to directly drive the wheels, either separately or in conjunction. This configuration facilitates dynamic power sourcing, which can smoothly transition or combine, as per the driving requirements [17]. The parallel configuration is notable for its responsiveness and adaptability during power-intensive activities such as acceleration, providing a seamless integration of power sources and ensuring optimum performance and energy utilization. Parallel hybrids leverage the synergistic effects of dual power sources, combining the high energy density of fuel with the high efficiency of electric drive.

B. FUEL-CELL ELECTRIC BUSES

Fuel Cell Electric Buses (FCEBs) stand out as another advanced electrification pathway, where propulsion is derived from electric motors that are powered by fuel cells. The technological essence of FCEBs is centered around on-board electricity generation through electrochemical processes, involving the conversion of hydrogen fuel into electricity, thus offering a more sustainable and efficient transit solution [4], [26]. The operational dynamics of this technology offer promising prospects in the context of modern public transit systems, showcasing substantial operational efficiency and environmental benefits. Fuel cell technology, by generating electricity from fuel through a process that is substantially cleaner compared to combustion, poses as a transformative solution in the field of sustainable transportation. The inherent energy efficiency and lower emissions profile of FCEBs make them a viable option in the pursuit of green and sustainable urban transit solutions, aligning with contemporary environmental and energy policies [16].

C. BATTERY-ELECTRIC BUSES

Battery-Electric Buses (BEBs) represent a defining step in the journey towards comprehensive electrification, showcasing the possibilities of green transit solutions through their use of exclusively electric powertrains. These powertrains are fundamentally made up of an EM that derives energy from an integrated battery system. The flow of power to and, interestingly, from the engine (especially during regenerative braking scenarios) is meticulously managed by a power electronic converter (PEC) [13]. The delivery of the EM's power is channeled to the wheels either through a transmission system, such as a differential or a drive-axle, or even directly to wheel hub motors. The majority of BEB powertrains harness a direct drive system, avoiding the conventional gearbox. Notable exceptions to this model exist, like the North American Proterra BEB, which employs a 2-speed auto shift mechanism [13]. Electric motors, with their inherent reversibility, can alternate roles, acting as motors or generators. One of the salient features of BEBs is the regenerative braking mode. Here, the kinetic energy generated during braking is recaptured and funneled back into charging the battery. Besides, the primary charging methodology for these batteries incorporates interfaces with the electricity grid through varied means—plugins, pantographs, or even inductive methods. Another critical aspect of BEBs is how battery power is allocated not just for propulsion but also to cater to various auxiliary device requirements, prominently for cabin cooling and heating. Diving deeper into the engineering behind BEBs, they predominantly use AC motors, chiefly the induction (or asynchronous) motors (IM) and the permanent magnet synchronous motors (PMSM). The preference for IMs arises from their established reliability, robust build, mature technological foundation, and economic viability. In contrast, PMSMs, with their compact structure, higher power density, and efficiency, offer a competitive alternative [17].

The essential PEC unit is vital for translating the battery's direct current (DC) power output to alternating current (AC) input suitable for the EM. This conversion predominantly spans two stages: i) a DC-DC conversion connecting the battery system to a high-voltage DC link, which also powers all auxiliary devices; and ii) a DC-AC conversion (commonly referred to as an inverter) that interfaces the DC link with the EM. The speed control for the AC EM is fine-tuned by modulating the AC voltage and frequency [13].

TABLE 1. Recent studies of buses alternative technologies.

Source	Year	Technologies Studied	Geographic Context	Technologies Recommended
[25]	2010	BEB, Diesel Buses, Compressed Natural Gas, Coal-derived Bus	Germany	BEBs
[26]	2023	BEBs, Hybrid, Compressed Natural Gas, Diesel Buses	USA	BEBs
[27]	2022	BEBs, Hydrogen	Australia	BEBs
[28]	2019	Diesel, Hybrid, Hydrogen, fuel cells and BEBs	Brazil, Argentina & Chile	BEBs and fuel cells
[29]	2013	Diesel, Compressed Natural Gas, Hybrid, BEBs and fuel cells	Spain	BEBs
[30]	2014	CNG, Hydrogen, Diesel, Hybrid, and Fuel Cells	USA	CNG and hybrid
[31]	2015	Diesel, Hybrid, CNG and BEB	USA	BEB for local routes, CNG for long express operations.

It's worth noting, as reported by [20] that the energy requisites for auxiliary components can vary considerably, ranging from 5 to 20 KW. This variance depends on several factors, including whether the BEB employs electrical heating or merely uses an air-conditioned driver's cabin. Auxiliary devices, including HVAC systems, thermal management systems for the battery, EM, and PEC, and other electric auxiliaries (like door operation, lights, wipers, etc.), derive their power from the primary battery system. Figure 2 represents the configuration (a) series hybrid buses, (b) parallel hybrid buses (c) fuel cell buses, and (d) fully electric buses.

Several studies have investigated the technical, environmental, and economic potential of these alternative bus technologies [11], [17], [21], [22], [23], [24]. There is a great consensus that electric bus technology is the most viable option to decarbonize the public transport sector [20]. This argument is mainly based on two key pillars:

(1) BEBs are the most energy-efficient technology, thanks to the higher conversion efficiency of the batteries and electric motors when compared to fuel cells and internal combustion engines [17].
(2) Battery electric buses provide the highest total well-to-wheel GHG emissions reduction relative to diesel buses among all other alternative technologies [17].

Based on the carried-out literature review, below Table 1 illustrates the recent studies comparing alternative fuel and power train buses.

IV. BUS CHARGING INFRASTRUCTURE

Transitioning from diesel to BEBs is a big step towards more sustainable transportation. But this change has its own set

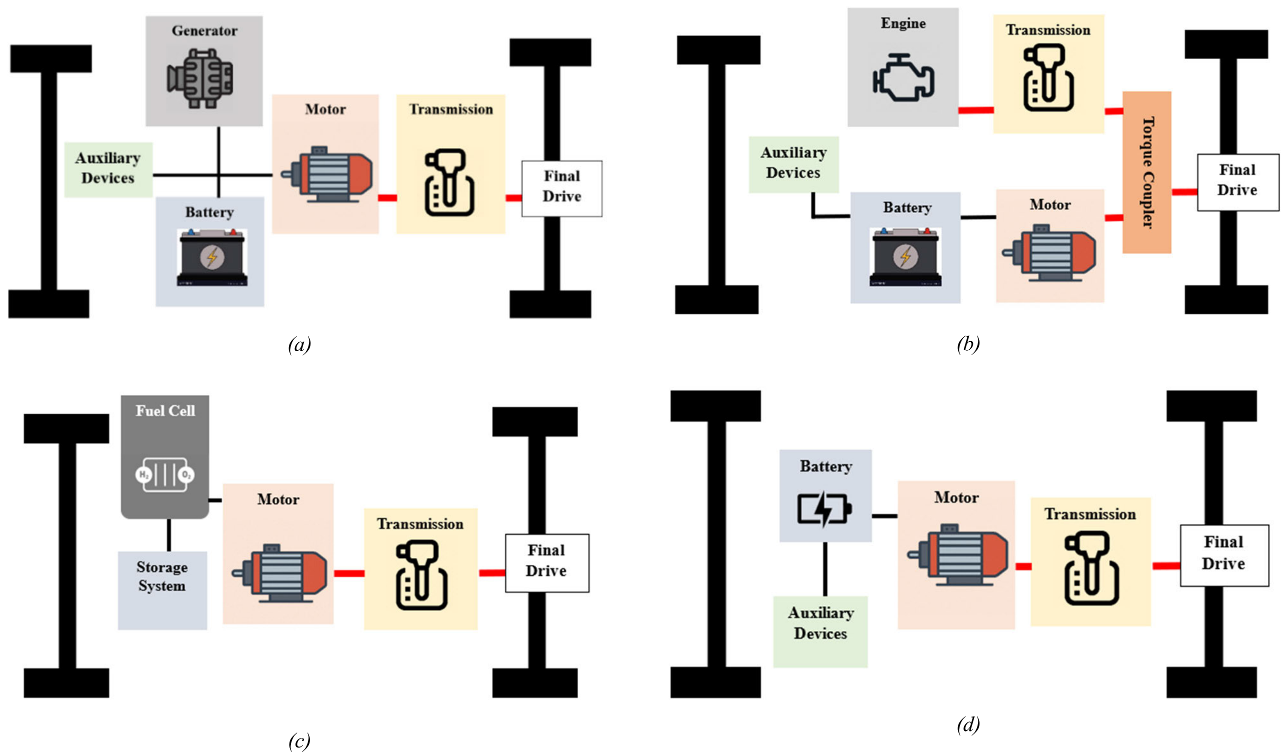

FIGURE 2. The configuration (a) series hybrid buses, (b) parallel hybrid buses (c) fuel cell buses, and (d) fully electric buses.

of challenges, especially when it comes to setting up the proper electric charging infrastructure. Acknowledging the extensive discourse present in current literature regarding BEBs' charging infrastructure, this section aims to build upon and contextualize these discussions within the specific framework of hot climate conditions encountered in regions such as the GCC. Unlike diesel buses, BEBs provide significant environmental benefits, but they often can't travel as far on one charge compared to diesel buses, especially under heavy energy use like in extreme weather or tough terrains. One of the main differences between BEBs and diesel buses is the refueling or charging time [29]. A diesel bus takes about 5 to 10 minutes to refuel. BEBs, however, can have varied charging times depending on the type of charger used. Slow charging systems might take up to 10 hours, while fast charging can be significantly quicker but still longer than refueling a diesel bus, usually between 2 to 5 hours, depending on the battery capacity and the charging rates [30]. This means BEBs operators need a mix of both slow and fast charging stations to cater to different needs and situations. To make BEBs work effectively, stakeholders must think about several factors when setting up their charging systems. This includes considering the length of bus routes, how far BEBs can travel on one charge, the time available for charging buses, electricity costs, bus schedules, local weather effects, and the potential use of overhead electric lines, known as catenary networks. There are two general categories of the heavy vehicles charging infrastructure type: (1) depot charging and

TABLE 2. US adopted charging specifications [29].

Charging Levels	Voltage Rating (V)	Current Range (A)	Power Range (kW)
Level 1	120	15-20	1.4 - 2.4
Level 2	240	20-100	4.8 - 24
Level 3	480	60-400	50 - 350

(2) opportunity charging. Depot charging takes place at the bus depots, mainly overnight during the bus off service hours while opportunity charging takes place at the bus stop stations along its line of operation, or during the bus dwelling time at its depot if possible. Regarding the charger's technology, the charging power source can either be Alternative Current (AC) or Direct Current (DC), where DC charging is mainly associated with high power charging above 30 kW. Another thing to keep in mind is that different countries have distinct standards for charging electric vehicles. The US, Europe, and China, for example, each have their unique approaches [19]. The following elaborates the adopted standards and charging types:

United States: EV industry in the US adheres to specific standards defined by the National Electric Code Committee for Electric Vehicle Supply Equipment (EVSE). As presented in Table 2, these charging standards are delineated into three primary levels: Level 1, Level 2, and Level 3. Levels 1 and 2 operate on Alternating Current (AC) and utilize a single-phase voltage power supply, which is typically available in

TABLE 3. Europe adopted charging specifications [29].

Levels	Details	Voltage Rating (V)	Maximum Current (A)	Power Range (kW)
Level 1	Household AC charging (slow)	250/480	16	3.7 - 11
Level 2	AC charging with safety	250/480	32	7.4 - 22
Level 3	AC Charging with safety & communication between charger & EV	250/480	32	14.5 - 43.5
Level 4	DC fast charging, including depot DC and opportunity charging	800	500	38 - 350

residential homes and commercial establishments. In contrast, Level 3 leverages either three-phase AC voltage or Direct Current (DC) power supply, offering rapid charging capabilities. A pivotal protocol in both the US and European contexts is the Combined Charging System (CCS). The CCS stands out due to its comprehensive compatibility and ease of use. Universally embraced by a myriad of EV manufacturers, the CCS protocol encompasses options for 1-phase AC charging with Type 1 and Type 2 inlets, 3-phase AC charging via a Type 2 inlet, and high-power DC charging (exceeding 350 kW) through dedicated pins available in Combo 1 and Combo 2 connectors. This system presents a formidable alternative to other charging technologies such as Japan's CHAdeMo, China's GB/T, and Tesla's proprietary Supercharger. Table 2 illustrates the EV charging standards adopted in the US along with their specifications [29].

Europe: In Europe, the EV sector adheres to specific charging standards as determined by the European electricity industry, which are outlined in Table 3. These standards define four distinct charging levels. The initial level, Level 1, is designed for household AC charging, predominantly found in residential and commercial settings. This method, however, is not broadly adopted due to its inherent limitations [29]. The slow charging process associated with Level 1 can result in power sockets becoming heated over extended periods, raising potential safety concerns. Levels 2 and 3 are more common choices for EV charging across Europe. These levels have been conceived with a strong emphasis on safety [31]. Level 3 further incorporates a communication mechanism between the charger and the vehicle, ensuring optimal charging efficiency and user experience. Lastly, Level 4 provides DC fast charging capabilities. This level facilitates rapid charging sessions, marking it as a preferred choice for users in need of swift energy replenishment for their vehicles. Notably, within the context of electric buses, depot DC charging and opportunity charging are widely recognized technologies. Depot DC charging typically takes place at centralized locations, allowing for buses to charge overnight or during extended periods of downtime. Conversely, opportunity charging is strategically placed at bus stops or terminals,

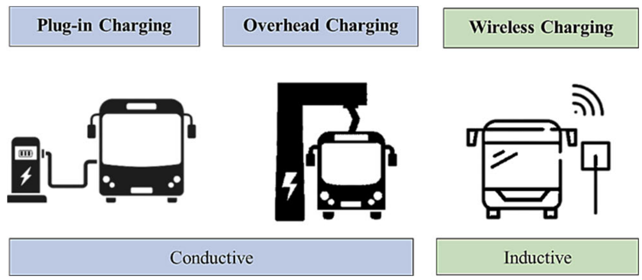

FIGURE 3. BEBs charging types illustration.

permitting buses to top up their batteries during short layovers, thus ensuring continuous operation throughout the day [32]. Table 3 shows the EV standards adopted in Europe region.

China and Japan: China and Japan have both played pivotal roles in the standardization of EV charging systems. Historically, China adhered to European charging standards, but starting in 2018, there was a notable shift. Both China and Japan began a collaborative endeavor to establish a unified charging standard for EVs [10].

At the forefront of this collaboration is CHAdeMo, a prominent association responsible for the creation of DC fast chargers. Boasting a network of 50 manufacturing companies globally, CHAdeMo has been instrumental in spearheading advancements in the EV charging arena. Both China and Japan under the banner of CHAdeMo jointly introduced a new charging protocol, CHAdeMo 3.0, specifically tailored for expeditious charging of Electric Transit Buses (ETBs). This protocol facilitates a power rating of 500 kW and a maximum current rating of 600 A. Table 4 shows the evolution of CHAdeMO charging protocols.

Depot charging takes place at the bus depots, mainly overnight during the bus off service hours while opportunity charging takes place at the bus stop stations along its line of operation. In terms of charging technology options for BEBs, there are four types of primary charging methods available currently in the market [31]; elaborated below and in Fig. 3.

1. **Plug-in Charging**: Conductive charging method designed for fast charging, with advantages like reduced CI costs, robustness, stability, reliability, and user-friendliness.
2. **Overhead Charging**: Opportunity charging is provided to charge the BEBs while on-route, where these chargers come with high power charging capacity between 150-600kW. There are two types of overhead or opportunity chargers, elaborated below:

Off-board Top-Down Pantograph (OBTDP): Top-down pantographs are designed so that BEBs don't need to be equipped with pantograph arm within the bus. These pantographs, set to a specific DC power level, are strategically placed along the roadside. When a BEB approaches a designated charging spot, marked by road indicators or speed humps, the driver can initiate the charging process using a switch on the dashboard. Upon activation, the pantograph descends to connect

TABLE 4. Evolution of CHAdeMO charging protocols [29].

CHAdeMO Protocols	Release Year	Power Rating (kW)	Max Current (A)	Voltage Rating (V)	Key Features
CHAdeMO 0.9	2010	62.5	125	500	Most popular DC fast charging globally
CHAdeMO 1.0	2012	62.5	125	500	Enhanced vehicle protection, compatibility, and reliability
CHAdeMO 1.1	2015	62.5	125	500	Inclusion of emergency stop and dynamic current change during charging
CHAdeMO 1.2	2017	200	400	500	First high-power charger with temperature, overload protection, and fault detection
CHAdeMO 2.0	2018	400	400	1000	Optimized for quick charging of trucks and ETBs
CHAdeMO 3.0	2020	500	600	833	Enhanced quick charging for trucks and ETBs
CHAoji	2021	900	600	1500	Ultra quick charging, tailored for trucks and ETBs

with the BEB battery terminals, facilitating the charging process. Examples of these are elaborated in Fig. 4 and 5.

On-board Bottom-Up Pantograph (OBBUP): In this scheme, the BEB will need to be equipped with the necessary pantograph arm to be used for charging. The pantograph is mounted on the bus, which the driver raises to the DC power supply catenary wires for charging. Fig. 6 and 7 shows examples of implemented Bottom-Up pantographs.

The Top-Down Pantograph, lighter by around 50kg and more cost-effective, offers distinct advantages in reliability, especially due to its robust design. Maintenance is also more streamlined, often managed by infrastructure operators. In terms of flexibility, this design is versatile, accommodating a range of bus sizes without any height limitations. However, its central drawback is the potential to disrupt the entire bus line if a failure occurs. In contrast, the Bottom-Up Pantograph, though heavier and costlier, presents its own set of merits and challenges. While it might be affected by vehicular

FIGURE 4. Example of top-down pantograph – Qatar [33].

FIGURE 5. Example from top-down pantograph – Netherlands [34].

conditions, thus posing reliability issues, its design ensures that a single failure usually affects only one bus. However, complications could arise if a malfunction happens during the charging process [37]. Table 5 offers a comparative analysis of both pantograph designs, highlighting their strengths and weaknesses.

3. Inductive Charging: Also referred to as wireless charging, this technique utilizes a cutting-edge method to transmit power. Embedded within the pavement is a transmitter, which sends power directly to a receiver mounted on the undercarriage of the BEB. Instead of relying on direct physical connections, this technology harnesses the principle of electromagnetic fields. As the bus moves or stops over the charging zone,

FIGURE 6. Bottom-up pantograph example – Netherlands [35].

FIGURE 7. Bottom-up pantograph example – USA [36].

TABLE 5. Comparison between top-down & bottom-up pantographs.

Feature/ Aspect	Top-Down Pantograph	Bottom-Up Pantograph
Weight and Cost on Vehicle	Lighter by around 50kg. Cost-effective.	Heavier by approximately 50kg. More costly.
Reliability and Maintenance	Higher reliability due to robust design. Reduced maintenance handled by infrastructure owners.	Subject to vehicular conditions, which might affect reliability. Increased maintenance needs.
Flexibility and Working Range	Suitable for various bus heights, from single to double Deckers. No height restrictions.	Challenges with double Deckers due to height, and on midi/minibuses due to size.
Overall System Reliability	More robust design. Failure could affect the entire bus line.	A single Failure typically affects only one vehicle. However, a failure during charging might cause more disruption.

TABLE 6. Comparison between charger types.

Feature/Aspect	Plugin Charging	Pantograph (Overhead) Charging	Wireless Charging
Charging Speed	Varies (Slow & Fast)	Fast	Slow
Vandalism Risk	High (due to exposure)	Moderate	Low
Weather Damage Risk	High	Moderate	Low
Risk of Electric Shock	Present	Present	Minimal or None
Maintenance Frequency	Moderate	High (moving parts involved)	Low
Driver Involvement	Required	Required	Hands-free, none required
Operational Flexibility	Limited	Moderate	High

power is seamlessly transferred, eliminating the need for traditional plug-in methods. This cutting-edge method presents three main variants: Static Wireless Charging (SWC), Quasi Dynamic Wireless Charging (QDWC), and Dynamic Wireless Charging (DWC).

From the traditional Plugin Charging to the innovative Pantograph (Overhead) and Wireless Charging methods, each system has its own advantages and potential setbacks. While some methods promise faster charging speeds, others prioritize safety by minimizing the risk of electric shock or offer operational flexibility. Additionally, factors such as exposure to vandalism, susceptibility to weather damage, maintenance frequency, and the degree of driver involvement play crucial roles in determining the feasibility and practicality of each charging system. The subsequent Table 6 provides a succinct comparison of these three prevalent charging techniques, detailing their respective strengths and challenges.

Many studies across recent literature tackled the charging infrastructure investment costs. Reference [38] investigated the charging infrastructure needs for BEBs operating in Stockholm, focusing on their cost and energy consumption by performing a network simulation. The study proposes an optimization model using mixed linear programming to minimize the costs and energy consumption of BEBs by optimally locating the chargers across the public transport network in Stockholm. Reference [22] conducted a lifecycle cost analysis of BEBs with different charging methods. The author concluded on the importance of properly choosing the battery size and charging infrastructure on the total investment costs. Reference [39] focused on the operational expenses of BEBs utilizing opportunity charging infrastructure with high-power chargers; the study aims at minimizing the demand charges of BEBs, where demand charges are a significant element of the electricity bill related to the peak power demand and independent of the electric energy consumption. The authors concluded that a smart charging strategy could help reduce the demand charges and, thus, the total operational expenses of BEBs.

Other studies focused on charging infrastructure planning from an operation feasibility perspective. Reference [40] focused on opportunity charging infrastructure and proposed a simulation-based methodology to determine the optimal number and location of fast charging stations along the bus line based on the BEBs' energy needs. Reference [41] proposed a methodology to properly deploy the charging infrastructure to ensure a reliable bus service without disruption in the transport network operation, and other studies tackled BEBs' opportunity charging from infrastructure planning and operation feasibility [42], [43]. Other studies investigated the impact of BEB charging on power grids stability. Reference [44], emphasized that the extensive growing charging load may lead to significant stability issues at the level distribution grid, and thus, it is essential to plan the charging load of BEBs properly while considering the grid constraints. Similarly, [45] concluded that the large-scale deployment of EV charging stations would increase the power demand drastically, causing instability in the power grid supply. In addition, studies such as [32] directly link the charging infrastructure planning to the BEB fleet charging load and impact on the electric utility grid. Considering the prevalent examination of charging technologies and infrastructure in existing studies, our analysis further delves into the adaptation of these systems under extreme heat, assessing their reliability, efficiency, and overall impact on BEB operational viability.

V. ENERGY STORAGE TECHNOLOGIES FOR BUSES

BEBs are becoming increasingly relevant in our eco-conscious era. The battery is a predominant factor that determines the efficiency, cost, and usability of BEVs. The journey towards the broader adoption of BEVs is deeply intertwined with advancing battery technologies that can offer high capacity, durability, affordability, and safety. Over time, several types of batteries, like nickel-based, lead, and lithium-based, have been used in these buses. Examples include nickel-cadmium (Ni-Cd), nickel metal hydride (Ni-MH), lead-acid (Pb-acid), and lithium-ion batteries (LIBs) [46]. Expanding on this, at the heart of every battery lies electrochemical processes that transform chemical energy into electric power. This transformation occurs as electrons move from one electrode (the cathode) to another (the anode) within an electric circuit. Intriguingly, a battery's inherent energy potential or voltage is fundamentally dictated by its chemical composition, particularly the materials constituting the electrodes. Within the scope of BEBs, traction batteries, specifically designed to energize electric drivetrains, often necessitate lofty voltage levels, sometimes reaching up to 400 V. To meet such demands, manufacturers often deploy modular battery packs of lower voltages coupled with integrated DC-DC systems. The resultant voltage and performance are then contingent upon the system's design and architecture [46].

Traction batteries distinguish themselves on several fronts:

1. Energy density (both gravimetric and volumetric) signifies the energy amount they can store and release relative to their weight or volume.

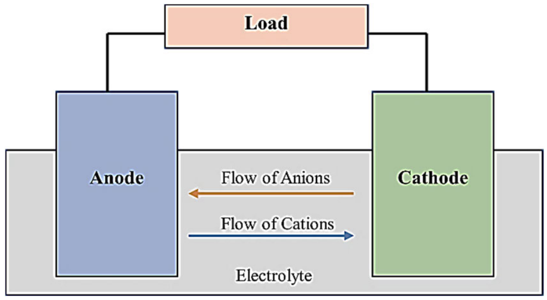

FIGURE 8. Generic battery structure.

2. Power density (again, both in terms of weight and volume) denotes the electric power they can deliver or draw per unit of weight or volume.
3. Safety remains paramount, particularly in ensuring batteries are resilient against thermal runaways, especially during overload scenarios.
4. Their cycle stability and longevity, known as calendar life.
5. Operational viability under diverse temperature conditions, whether extremely cold or hot.

It's worth emphasizing the profound influence of temperature on battery performance. For instance, as temperatures drop beneath 25°C, the electron flow in batteries decelerates, diminishing their energy output. Specifically, under temperatures like -20 °C, the recharging process for lithium batteries becomes excruciatingly prolonged, 20 times slower than at a comfortable +20°C. Addressing this, many BEBs are equipped with thermal management systems to maintain battery temperatures withing an optimal desired range. However, this solution isn't without its trade-offs. The energy used by these systems can significantly affect the overall driving range of the vehicle. Fig. 8 presents a schematic of a typical battery chemistry.

Over the years, the evolution of battery technology for battery electric buses has been marked by a consistent pursuit of efficiency, safety, and sustainability. The industry transitioned from heavy lead-acid batteries, shifted to nickel-based batteries, and eventually settled on advanced lithium-based batteries, prominently lithium iron phosphate [39]. This trajectory underlines a pivotal quest: a balance between safety, longevity, storage capacity, and charging efficiency. When delving into lithium-based technologies, three major contenders emerge: LFP (Lithium Iron Phosphate), NMC (Lithium Nickel Manganese Cobalt Oxide), and LTO (Lithium Titanate). LFP batteries have increasingly become a staple in BEBs.

These batteries exhibit remarkable attributes like high cycling life, consistent voltage profile, and outstanding power capability. The safety, minimal toxicity issues, and abundant availability of materials make them even more attractive. However, despite their specific characteristics, which make them ideal for slow charging scenarios such as depot charging, the rise of NMC batteries with higher energy densities might impact their future dominance [47]. As a formidable

TABLE 7. Battery types and specifications, reproduced from [46].

Battery Types	Specific Energy (Wh/Kg)	Energy/Volume (Wh/L)	Power/Weight (W/Kg)	Recharging Cycles
Pb-acid	40	70	180	500
Ni-Cd	60	100	150	1350
Ni-MH	70	250	1000	1350
Li-ion	200	270	1800	1000

competitor to LFP, NMC batteries have a higher energy density, allowing for either an extended driving range or a more compact battery pack. They also display commendable longevity. However, safety concerns due to potential toxic and flammable leakages after collisions and the cost implications associated with cobalt are challenges that need addressing. Yet, with an aptitude for both slow and rapid charging and decreasing costs, they could soon dominate the BEB market [46]. LTO batteries, despite certain challenges like a lower cell voltage, shine in applications demanding high-stress cycling profiles, especially ultra-fast charging, and regenerative braking regimes. Their capacity to support high charging and discharging current peaks sets them apart. The LTO technology is also gaining traction owing to its declining price, making it an attractive option for niche applications within the BEB sector [48].

As elaborated in Table 7, Lithium-ion (Li-ion) batteries in electric bus applications boast an energy storage capacity per weight of 200 Wh/Kg and an energy density by volume of 270 Wh/L. This makes them simultaneously lightweight and space efficient. Their power-to-weight ratio of 1800 W/Kg ensures electric buses, which necessitate frequent halts and accelerations, operate optimally. Although Li-ion batteries might have a marginally lower recharging cycle count compared to Ni-Cd and Ni-MH batteries, their low self-discharge rate is a testament to their efficiency. All these attributes, in unison, earmark Li-ion batteries as the front-runner for electric bus applications. Fig. 9 shows a summary of the available Li-Ion battery properties.

BEBs rely solely on battery systems for energy storage, the nuances of battery behavior, performance, and degradation mechanisms hold paramount importance. In the preceding discussion on different battery technologies, key metrics like specific energy, energy per volume, power per weight, and recharging cycles were dissected. However, delving deeper into the operational dynamics of these batteries reveals more intricate details that can significantly influence a BEV's performance and the battery's lifespan [13].

The way a battery is utilized in BEVs, especially concerning its discharge profile, has profound implications for its health and longevity. It's worth noting that while a battery's state of charge (SoC) might indicate sufficient energy storage to achieve the desired range, it's seldom prudent to deplete this charge fully. To avoid accelerated degradation, a safety margin of approximately 20% is usually maintained and advised by the OEMs, implying that the depth of discharge (DoD) should ideally remain below 80% [49]. Moreover, after a full charge cycle, an additional buffer, typically around 5%, is advisable to accommodate energy recuperation through processes like regenerative braking. Thus, when designing battery systems for BEVs, engineers often aim to operate within a window defined by a maximum SoC of 95% and a DoD of 80% [50].

However, these operational constraints don't exist in isolation. The discharge rate, especially when it deviates from the designed norms, can influence battery health. Typically, batteries optimized for high capacity exhibit a continuous discharge rate of about 1C. Yet, in certain demanding scenarios, these cells might encounter pulse currents surging to 3C. Such deviations from the optimal discharge rate can lead to incomplete transformations of active chemicals within the battery. This not only influences the battery's internal impedance but can also induce capacity reductions over time [51].

Furthermore, battery degradation is an inevitable consequence of time and usage. The frequent charge and discharge cycles invariably lead to wear and tear, both physically and chemically, within the battery [51]. Factors such as harsh cycling profiles exacerbate the rate of this degradation. In the world of BEBs, a traction battery is generally considered to be on its decline when its capacity retention drops below the range of 80% to 60% of its original capacity. Interestingly, even as the battery degrades in terms of energy storage, its minimum allowable SoC remains relatively consistent, akin to that of a newer battery. Fig. 10 shows the battery operational window.

In addressing the varied demands of BEBs, particularly in challenging environments, the design and selection of battery packs necessitate a multifaceted approach. Factors such as the cooling system employed, the underlying battery technology, the physical size and weight of the battery, and its total energy capacity critically dictate a BEB's operational efficiency and viability. For instance, lithium-ion batteries, favored for their high energy density and efficiency, may employ liquid cooling systems to mitigate thermal risks, particularly in hot climates [12]. Conversely, more robust battery technologies like Lithium Iron Phosphate (LFP) might utilize air cooling due to their inherent thermal stability, offering a balance between safety and cost-effectiveness [18]. The size and capacity of these battery packs are then tailored to the specific operational needs of the bus, considering factors such as route length, anticipated energy consumption, and charging infrastructure availability. Specifically, in regions with extreme weather conditions like Qatar, the combination of LFP battery packs with liquid cooling systems emerges as a preferred choice. These battery packs are selected for their resilience to high temperatures and their ability to maintain performance and safety under the thermal stress common in such climates. Furthermore, a dedicated Battery Management System (BMS) operates continuously, 24/7, to ensure optimal monitoring and management of the batteries. This system plays a crucial role in maintaining the battery within its ideal operational parameters, thereby prolonging its life and

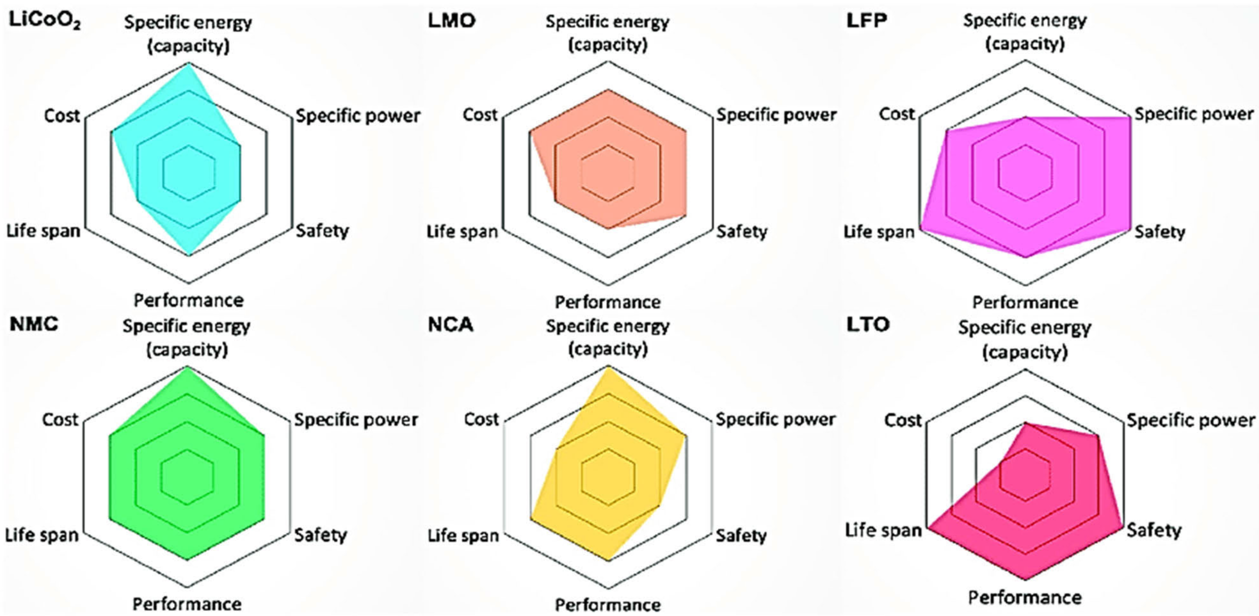

FIGURE 9. Li-ion chemistry traction battery properties, adapted from [13], [46].

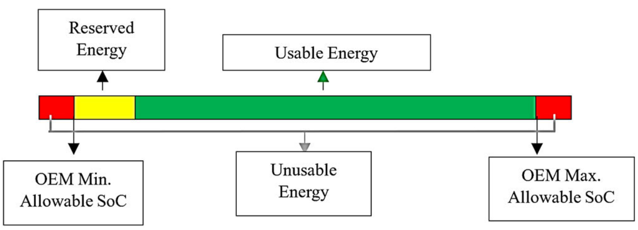

FIGURE 10. Battery operational window.

enhancing the overall reliability of BEBs in harsh weather conditions [12].

VI. ENERGY CONSUMPTION OF BEBs

The energy consumption of BEBs has a direct impact on the bus driving range, costs, and choice of charging infrastructure. Bus manufacturers usually provide fleet operators with the bus maximum driving range under specific operating conditions. These conditions don't reflect the real-world energy consumption and driving range of BEB, presenting uncertainties for bus fleet operators regarding the fleet energy and charging needs. On the contrary, the energy consumption and driving range of BEBs in real-world conditions strongly depends on their operating conditions such as the speed profile, elevation profile, weather conditions, and many other factors [52]. Hence, a precise estimation of BEB's energy needs in day-to-day operation is essential to evaluate and adapt the BEBs into a public transport ecosystem.

Over the past decade, several studies evaluated the energy consumption and driving range of BEBs. [53] proposed a BEB energy consumption model to estimate the BEB energy needs. The study mainly models the bus longitudinal dynamics, focusing on the main powertrain components, including the battery and electric drive system, in addition to other electric auxiliaries, where their energy consumption was estimated by collecting data from more than 3,200 trips with BEBs operating in China and Norway. Reference [54] investigated the energy performance of several electric machine typologies in BEB powertrains, focusing on the electric motor efficiency and the brake energy recovery feature using a detailed physical modeling approach. Reference [55] estimated the energy needs of electric city buses using a modeling-experimental hybrid approach. Reference [56] evaluated the energy performance of electrified powertrains at the system and component level based on detailed physical modeling. Reference [57] developed a BEB simulator, which is a tool for modeling energy consumption analysis of electrified buses, where the authors adopted a forward modeling approach using MATLAB to estimate the powertrain energy consumption.

While most of the studies focus on assessing the powertrain energy consumption of BEBs, ignoring the energy consumption of the other auxiliary systems - specifically the HVAC unit - results in an underestimated BEB energy consumption. Some studies in the literature solely focus on the vehicle energy needs related to the HVAC unit. Reference [58] designed and performed and experimental analysis of an efficient HVAC systems including heating, ventilation and air-conditioning for on an electric bus. Reference [59] investigated the energy needs and performance of cabin thermal management in BEBs, where a simulation model of cabin heating and cooling system was developed in the Amesim software. The author concluded that the BEB driving range

TABLE 8. Energy consumption literature review.

Ref.	Method	Geographic Context	Operational Factors Ambient Temp.	Speed	Driving Profile	Route Topology	Passenger Load	Design Factors HVAC System	Propulsion System	Auxiliaries Systems
[52]	Simulation	NA	Y	Y	Y	Y	Y	Y	Y	Y
[53]	Real-World	China	N	Y	Y	Y	Y	Y	N	N
[55]	Real-World & Simulation	Finland	N	Y	N	N	Y	N	Y	Y
[56]	Real-World & Simulation	USA	N	Y	Y	Y	Y	Y	Y	N
[57]	Real-World	Norway	Y	Y	N	N	Y	Y	N	Y
[58]	Simulation	Belgium	N	Y	Y	N	N	N	N	N
[59]	Simulation	NA	Y	Y	Y	N	Y	Y	Y	Y
[60]	Simulation	USA	N	Y	N	Y	N	Y	Y	Y
[61]	Real-World & Simulation	Korea	Y	Y	N	N	N	Y	N	N
[62]	Simulation	NA	Y	Y	N	Y	N	Y	N	N
[63]	Simulation	Blair (Antoona)	Y	Y	Y	Y	Y	N	N	N
[64]	Real-World	Singapore	N	Y	Y	Y	Y	N	N	Y
[65]	Simulation & Real-World	Paris	Y	Y	Y	Y	Y	Y	Y	Y

can be reduced by more than 50% in extreme cold conditions. Reference [60] examines the energy needs of electric bus HVAC unit through detailed thermal modelling for the bus heat transfer phenomena and concluded on the importance of a proper system design and control to reduce the impact of the HVAC unit energy needs on the BEB driving range. Reference [61] evaluated the energy efficiency and economic performance of several heating technologies in BEBs due to their significant impact on the bus driving range. The presented studies clearly show how significant the impact of cooling and heating needs on the BEB energy consumption and driving range.

Very few studies assess the BEB energy consumption while considering the powertrain energy consumption and the auxiliaries energy needs including the HVAC unit, electronics, and pneumatic auxiliaries, to assess the BEB comprehensive energy needs. Reference [20] provides a detailed forward-simulation modeling approach considering the bus powertrain, HVAC, and auxiliaries quantifying the BEB comprehensive energy needs using a simulation tool developed in the software Dymola. In addition, [52] studied the real-world energy performance of BEB by conducting several on-road testing campaigns in China, mainly focusing on the bus powertrain and HVAC unit consumption, ignoring the other secondary auxiliaries.

In addition, the operating conditions of BEB have a significant impact on its energy consumption. Reference [20] studied the impact of traffic and weather conditions on the energy needs of BEB operating in the city of Paris, France. Reference [52] tested battery electric buses under a variety of driving conditions in Macao-China, and under different air conditioning loads. Reference [56] considered several day-to-day routes and synthesized bus driving cycles to reflect on the impact of bus driving conditions on its energy needs. Reference [62] studied the BEB energy consumption under 15 driving cycles in cold and warm weather conditions using non-linear simulation models. Reference [63] assess the energy needs of several types of electric bus service, such as city, intercity, and shuttle buses, and conclude on the impact of bus use-case and driving behavior on its total energy needs and driving range. Reference [64] studied the energy needs of buses operating in Kuala Lumpur – Malaysia, focusing on the impact of the bus line route and passenger utilization.

The numerous studies presented based on recent literature clearly show the high sensitivity of BEB energy consumption and driving range to its operating conditions, namely driving and weather conditions.

The studies assessed BEB's energy consumption. As seen in Table 8, most of the studies focus on one specific energy system, such as the powertrain or the HVAC unit, while most of the assessments lack a comprehensive evaluation of the BEB energy needs with all energy systems included. In addition, the studies mainly rely on simulation models that estimate the BEB energy needs under pre-defined operating conditions such as synthesized driving cycles and fixed weather and passenger conditions. Thus, those studies do not reflect the real-world energy needs of the buses under real operating conditions, which can be best captured through a variety of on-road testing campaigns.

VII. IMPLICATIONS OF OPERATING BEBS IN HOT ENVIRONMENT

A. WEATHER IMPLICATIONS

Understanding the impact of extreme weather conditions, particularly high temperatures, on operating BEBs is crucial. This section delves into the impact of hot temperatures on three primary components: the BEBs themselves, the supporting charging infrastructure, and the energy storage systems.

Influence of Hot Temperatures on BEBs: Almost none of the studies have delved into the performance of BEBs under harsh climate conditions. However, few have explored the implications of such conditions on Electric Vehicles (EVs) in general. The results from these studies highlight that temperature plays a substantial role in the performance and efficiency of various EV components such as motors, inverters, and energy storage systems [67], [68], [69]. Reference [67] investigated the effect of temperature on battery- and ultracapacitor-powered EVs, where the temperature ranges considered were -20 °C to +20°C. The authors found that motor operating efficiency varies with ambient temperature. For instance, with an ambient temperature increase from -20 °C to +20°C, the efficiency of the motor predominantly decreases due to the increased copper losses, which are critical components in motor operation. In addition, the authors found that in certain operational regimes, such as high speed and low torque, increased temperatures can improve efficiency, as iron losses - another form of energy dissipation with motors - decrease with rising temperature.

Reference [68] developed a detailed systems-level approach to connect HVAC technologies and usage conditions to consumer-centric metrics of vehicle performance, including energy consumption and range, where factors such as local ambient temperature, local solar radiation, local humidity, length of the trip, and thermal soak have been identified as primary drivers of cabin conditioning loads. The authors found that the inverters are affected by temperature fluctuations, where the temperature rise decreases the inverter efficiency due to the increased conduction losses. Reference [69] investigated the fuel efficiency of plug-in hybrid electric vehicles and compared their performance with respect to standard gasoline vehicles under harsh Canadian cold urban environments. The authors found that the fluctuation of temperature directly impacts key performance indicators such as driving range, energy consumption, and the efficiency of battery charging and discharging. In synthesizing the existing literature on the performance of electric vehicles under varying temperature conditions, several salient research gaps become evident:

1. A significant proportion of extant research focuses on temperature ranges up to +20°C. There is a conspicuous paucity of studies addressing the implications of extremely high temperatures, specifically those exceeding 45°C.
2. While the body of research on electric vehicles is growing, there remains a dearth of studies centered specifically on Battery Electric Buses (BEBs). This niche yet crucial category demands further academic attention.
3. As urban centers increasingly adopt BEBs in their transit systems, particularly in climates with pronounced temperature extremes, the urgency for comprehensive research in this domain becomes ever more pressing.

Influence of Hot Temperatures on Charging Infrastructure: Several studies found temperature has profound effect not only on the BEBs technologies but also on the charging infrastructure of EVs in general [70], [71], [72]. Reference [70] studied the large-scale deployment of electric taxis

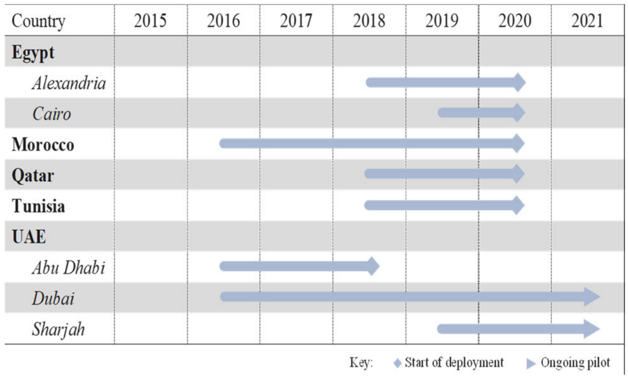

FIGURE 11. Progress of pilots and deployment in MENA.

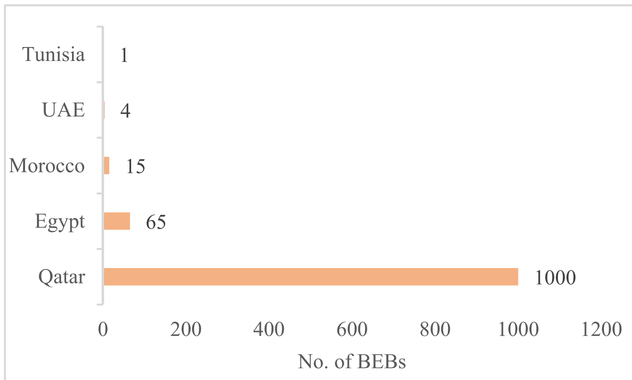

FIGURE 12. No. of BEBs in MENA as of 2022.

in Beijing by a real-world data analysis, where the authors investigated the characteristics of the large-scale EVs for a deep understanding of operational status such as energy consumption and battery charging patterns. The authors found that cold weather is significantly slowing down the charging rates. The chemical reactions pivotal for efficient battery charging, especially within lithium-ion batteries, are subdued during colder temperatures, where as a result, the charging infrastructure struggles to deliver a rapid charging experience. In addition, the authors found that extended charging times during cold weather will decrease the utilization of public charging facilities, as users might prefer charging their vehicles at home over longer durations or might be discouraged from using their EVs altogether. In addition, [71] found that public charging facilities' material and electronic components might be susceptible to damage or reduced functionality in extreme temperatures, leading to reduced reliability and increased maintenance costs. Reference [72] investigated the impact of temperature on adopting electric vehicles based in 20 provinces in China. The authors found that extreme weather conditions, particularly cold temperatures, can adversely affect public charging facilities, where these climatic conditions often result in slower charging speeds and reduced utilization of these facilities. In addition, the authors also found that charging lithium batteries involves a series of chemical reactions within the

FIGURE 13. Charging infrastructure deployed in qatar.

electrode and electrolyte, where these reactions are less at lower temperatures. The influence of harsh climatic conditions on the performance of charging facilities has been underscored in real-world infrastructure designs across various regions. A notable example is the infrastructure deployed in Qatar. Characterized by its extremely high temperatures, innovative strategies have been implemented to combat the deleterious effects of heat on charging efficiency. Recognizing the adverse influence of excessive heat on AC-DC inverters, the Qatari approach, which is visualized in Fig. 13, entailed constructing air-conditioned kiosks to house these inverters. Such a measure aims to ensure a regulated and conducive temperature environment, optimizing inverter efficiency and prolonging its operational lifespan. For instance, overnight chargers or plug-in chargers in Qatar are strategically housed under complete shades and the inverters are within air-conditioned kiosks to shield them from direct sun radiation, preventing overheating during charging. This measure ensures that the charging process is not compromised by high ambient temperatures, maintaining efficiency, and prolonging the operational lifespan of both the charging infrastructure and the batteries. Furthermore, for pantograph charging, or opportunity charging, efficiency during the summer months is a crucial consideration. The high ambient temperatures typical of summer in regions like Qatar can impact the charging speed and efficiency of these systems. Innovative cooling solutions and heat-resistant materials are often incorporated into the design of opportunity charging stations to maintain performance even under extreme temperature conditions. These adaptations are essential for ensuring the reliability and effectiveness of BEBs' charging infrastructure in hot climates, addressing both the immediate challenges of thermal management and the longer-term sustainability of electric bus operations [12].

In reviewing the existing literature and infrastructural practices, two prominent research gaps emerge:

1. Impact of cold temperature on charging infrastructure has received considerable attention, the specific repercussions of exceedingly high temperatures remain relatively under-researched. This is especially significant for regions that predominantly experience torrid conditions, necessitating studies to investigate the high-temperature impact better.
2. The current literature largely overlooks design considerations that address the extremes of both high and low temperatures. This underscores the urgent need for research into design enhancements and recommendations tailored to such challenging environments.

Influence of Hot Temperatures on Energy Storage Systems: Multiple studies investigated the influence of temperature fluctuations on energy storage systems [46], [51], [69], [73]. Reference [69] found that both high and low temperatures can degrade the efficiency of the energy storage components. While high temperatures might provide a slight efficiency boost, they can simultaneously decrease the overall lifespan of the battery. The authors also found that cold temperatures can drastically reduce the charging and discharging efficiency, which ultimately affects the battery performance and degradation. Reference [46] studied the global advancements and current challenges of electric vehicle batteries, where the authors found that extended exposure to high temperatures can lead to the degradation of the battery and other energy storage components, thereby reducing their overall lifespan. Reference [51] reviewed a number of studies on the influence of temperature on the capacity and life cycle of lithium-ion accumulator storage batteries. The authors found that at high temperatures, the service life and efficiency are reduced. In addition, the authors also found that the initial storage capacity of Li-Ion energy storage devices is reduced by up to 60% when used at low ambient temperatures, and at high temperatures, the capacity reduces by around 10%, although hot operation degrades the battery performance faster. In [73], the authors explored public perception barriers to the widespread adoption of EVs in Tianjin. Based on a sample of 476 urban respondents collected by questionnaire. The authors found that high temperatures elevate the risk of spontaneous combustion, especially if the battery experiences a rapid energy surge, like during charging. Such conditions can lead to lithium precipitation, heightening the risk of short circuits within the battery pack.

The specific challenges posed by extreme temperatures, especially in Middle East regions, have spurred innovative design solutions tailored to ensure battery longevity and safety. Notably, the BEBs in Qatar have incorporated an advanced design feature: a specialized liquid cooling system for their batteries [74]. This system operates continuously, 24 hours a day, regardless of whether the ignition is on or off. This continuous cooling provision ensures that the batteries remain within safe operational temperature limits, which is especially vital when the BEBs are parked in extreme ambient temperatures. Such a design is a testament to the forward-thinking approach needed to ensure the longevity and safety of BEB batteries in harsh climates [75].

However, the body of research on this topic presents several gaps:

2. There's a noticeable absence of studies specifically targeting design improvements for batteries, especially for those subjected to consistently high temperatures.

TABLE 9. Summary of buses purchase cost.

Bus Type	Purchase Cost $	Cost per kWh $	Reference
BEB (Average)	$650,000	$500	[13]
BEB (350 kWh)	$750,000	N/A	[78]
BEB Battery Cost	N/A	$300 - $500	[79]
BEB Battery Cost	N/A	$150	[80]
BYD-BEB	$686,000	$N/A	[80]
BEB (Proterra)	$550,000	N/A	[81]
BEB (250 kWh)	$570,000	N/A	[82]
BEB (Range)	$530,000 - $590,000	N/A	[83]
BEB (Average)	$550,000	$500	[84]

TABLE 10. Summary of findings on BEBs operating costs.

Reference	Key Findings
[18]	Indicates BEBs have potential to reduce CO2 emissions and are economically competitive with diesel and natural gas counterparts when considering purchase and operating costs
[29]	Finds end-station charging strategy could be economically competitive with diesel in the best-case scenario
[79]	Predicts that green hydrogen advancements may make BEBs more competitive as battery prices decline
[12]. [85]	Assesses the increased maintenance costs due to the heavier BEBs required for operation in hot climates, linking vehicle weight with road wear

3. General studies on the effects of high-temperature environments on energy storage systems are limited, indicating a significant area that requires exploration.
4. Another noticeable gap is the limited research on large-capacity batteries, specifically those of 200kWh and above, which are commonly used in BEBs. Understanding their behavior and performance nuances in both standard and extreme conditions is pivotal for the broader adoption of BEBs, especially in temperature-sensitive regions.

B. ECONOMIC IMPLICATIONS

Initial Investment: Average purchase prices for Battery Electric Buses (BEBs) were examined, considering variations influenced by the manufacturer's region. Notably, BYD, a high-end Chinese manufacturer, emerged with an average price point of $686,000, reflecting the influence of labor rates in different regions. Chinese manufacturers offered prices ranging from $530,000 to $600,000, while beyond this range, European (EU) and United States-based manufacturers presented their BEBs with correspondingly higher price tags. For instance, Proterra BEBs were reported at an average cost of $550,000 [76], while Bloomberg [77] indicated costs of $570,000 and $750,000 for BEBs with 250 kWh and 350 kWh battery capacities, respectively. These variations in cost estimates were complemented by considerations of battery expenses. Schmidt et al. [78] noted a cost range of $300 to $500 per kWh for battery storage, while Blynn [79] reported a rate of $150 per kWh for electric vehicle batteries. An average battery cost of $500 per kWh was assumed, resulting in a calculated average BEB cost of $650,000. This analysis underscores the multifaceted nature of BEB economics, influenced by regional manufacturing factors, and offers insights into sustainable urban mobility.

Operating Costs: The upfront costs for Battery Electric Buses (BEBs) encapsulate a range of factors, including variations stemming from the region of manufacture and battery pricing. Transitioning to operating expenses requires a thorough assessment of the enduring economic performance [18]. Operating costs are not merely a matter of energy consumption and charging logistics; they also encompass maintenance, which can differ markedly between countries [82]. This variation can often be attributed to environmental conditions; for instance, in warmer climates, operators may opt for BEBs with larger battery capacities to circumvent range challenges during summer months. This necessary adjustment leads to an increase in vehicle weight, thereby elevating road wear and subsequent maintenance costs [12]. These findings reflect the fuel savings potential of BEBs, making them an attractive option, especially in countries like Lebanon, where home-to-work commutes often occur in highly congested traffic [52]. Moreover, in hot environments like Qatar, where electricity costs are notably low at $0.04 per kWh, BEB operating costs are further reduced, enhancing their economic viability [12]. The table below collates critical insights from scholarly research, offering an in-depth perspective on the operational cost spectrum for BEBs.

VIII. BENCHMARKING AND SITUATION ANALYSIS

With the increased global effort and attention towards environmental protection and air pollution avoidance, the need for eco-friendly transportation options has increased rapidly. Attention shifted towards e-mobility in governments' efforts to reduce emissions and provide environmentally friendly solutions. Several countries in the MENA region opted for an electric fleet to meet their environmental goals. Opting for e-buses to attain emission targets has clear benefits that contribute directly to the environment. However, this solution was faced with a set of challenges, especially in the implementation stage [83].

Based on the Union International Public Transport (UITP) reports (i.e., [83]), Tunisia, Morocco, Egypt, Jordan, and Iran are all countries with significant attempts to shift their fleets to electric. Piloting commenced in 2018, with most countries remaining in the piloting phase due to challenges with the unique characteristics of the MENA region, ranging from weather conditions to other operational difficulties. Most MENA countries announced their plans to grow their electric fleet either through deployment or local manufacturing. However, the number of buses on the road is still insignificant while piloting is still ongoing, as illustrated in Fig. 11.

GCC countries are among those countries aiming for a greener and healthier city through the introduction of BEB in efforts to provide an enhanced lifestyle and living conditions that are pollution and noise free. The piloting for e-buses in the UAE has been ongoing since 2015 to test all aspects and performance under several conditions.

Among GCC countries with strong directions towards electrification of buses is the State of Qatar. After commencing the pilot in 2018, Qatar's fleet has grown to 741 in 2020 and 1000 in 2022 with a plan to convert 100% of the fleet to electric by 2030. Fig. 12 shows the numbers of BEBs as of 2020 in MENA countries [83].

IX. MARKET ACCEPTANCE

In the realm of BEB adoption, market acceptance plays a pivotal role in shaping the future of sustainable urban mobility. Competitions and innovative technology have proven to be effective incentives for future vehicle designers, driving equipment improvements in BEBs while focusing on reducing costs and enhancing efficiency. Notably, some studies like [81] have shed light on the perceptions of potential consumers, highlighting the ongoing progress in BEB improvements as a critical factor influencing the transition from conventional vehicles to BEBs. Manufacturers are increasingly positioning their BEBs as more efficient vehicles rather than just greener alternatives, aligning with market studies that indicate a growing preference for technology advancements and fuel savings among new generations, even when higher costs are involved. Qatar's commitment to reducing CO2 emissions by 2030, as outlined in the National Development Strategy 3 (NDS3) launched in January 2024 [84]. Which underscores the country's dedication to environmental sustainability and green mobility. In line with these ambitions, the Investment Promotion Agency (IPA) of Qatar has been proactive in attracting investors to establish their operations within the country, signaling a robust push towards fostering a sustainable automotive sector [85]. A landmark development in this endeavor was Tesla's inauguration of its showroom and service center in Qatar in January 2024 [86]. In addition, in Qatar's case, the Ministry of Transport has taken proactive measures to foster the market acceptance of electrified public transport, specifically BEBs [87]. Through a series of campaigns and initiatives, the Ministry is actively promoting the benefits of BEBs, emphasizing their efficiency, reduced fuel consumption, and low maintenance costs compared to traditional combustion engine vehicles. While it is acknowledged that the upfront cost of BEBs can be relatively high, the overall economic advantages, coupled with the Ministry's efforts to raise awareness, aim to reshape consumer mindsets toward zero-emission products. Qatar has also started to implement free charging schemes, as announced by Kahramaa [88], and attractive financing programs offered by local banks to further incentivize BEB adoption [89]. Furthermore, in countries like the United Arab Emirates (UAE), significant incentives are offered to BEV users, including free parking, free charging infrastructure, road tax exemptions, and even free maintenance services offered by dealerships [90]. These proactive measures in both Qatar and the UAE are indicative of the growing commitment to promoting BEBs as a sustainable and economically viable mode of urban transportation, further accelerating their market acceptance in the region.

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