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Research paper

A comprehensive review of charging infrastructure for Electric Micromobility Vehicles: Technologies and challenges

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ABSTRACT

Micromobility electric vehicles are steadily spreading and their impact on society, technology and industry will be remarkable. Most of the factors limiting their use, like, for example, range anxiety, are somehow related to the technical limitations of current charging stations. There is a gap in the literature regarding charging stations specifically devoted to micromobility. Actually, charging stations for e-bikes are characterized by specific critical points and opportunities, related to the lower power demand with respect to an electric cars and to the absence of consolidated standards for the requested output voltage. For this reason, this article aims at filling such gap through a comprehensive analysis of the different aspects characterizing these infrastructures. At first, the electrical features of the Electrical Micromobility Vehicles (EMVs) are surveyed through a market analysis. Then, an in depth analysis of the factors influencing the design of the charging stations is conducted and the scientific literature on the subject is discussed. Particular attention is devoted to the implication of the use or renewable sources for both grid-connected and off-grid applications. Furthermore, issues related to the architecture flexibility and the selection of the transformer technology are discussed. In general, it is argued that univocal guidelines are difficult to formulate, but a certain number of factors can be identified, which are to be evaluated depending on the context where the charging station is supposed to operate. Finally, emerging scientific and technological trends are discussed: fast charging; wireless power transfer; wide band gap power semiconductors, exploitation of EMVs charging stations in the context of renewable energy communities.

1. Introduction

As cities around the globe deal with challenges like traffic congestion, air pollution, and the demand for more efficient transportation solutions, micromobility emerges as a promising alternative. This new idea of urban mobility tackles these issues effectively, encourages healthier lifestyles and enhances connectivity within communities. Micromobility refers to lightweight, typically electric-powered modes of transportation intended for short-distance travel within urban environments. This category includes electric scooters, bicycles, electric skateboards, and similar compact vehicles. In recent years, the micromobility market has experienced rapid growth: in Italy alone, for instance, approximately 300,000 units of e-bikes were registered in 2021, bringing the total in circulation to 14.9% (Energy & Strategy, 2023). The growth of the EMV market is even more crucial in the developing countries. As electric four-wheelers are still too expensive for the middle class in developing countries, the e-bike is the solution preferred by customers. The available studies in the literature deal mainly with the cases of China, India and Vietnam, For example, in Rajper and Albrecht (2020) it is reported that electric two-wheelers had sold 30 million units in China in the year 2018, leading to a total of 250 millions. The situation is similar in Vietnam (Huu et al., 2021), with the difference that electric cars are even less affordable for the middle class.

Based on this, the global e-bike market size is expected to increase at a compound annual growth rate of 14.5% from 2024 to 2030 (Grand View Research, 2022), thus resulting in a multi-faceted impact on industry, technology and society. The importance of micromobility and its potential in defining a new idea of self-transportation in an urban context is underscored by numerous national and international initiatives which incentivize the spread and use of this category of vehicles. The most recent project promoted by the European community is the *Driving Urban Transition* (DUT) (Driving Urban Transitions

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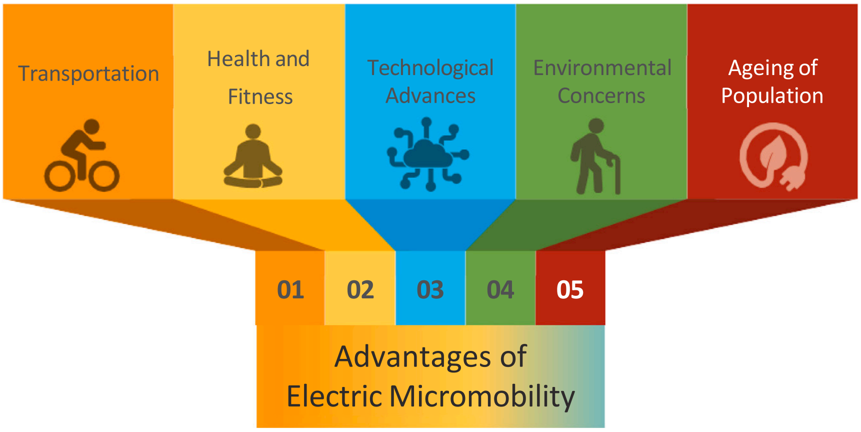


Fig. 1. Factors driving consumers to adopt electric vehicles for micromobility.

Fig. 2. Graphical representation of factors that are currently limiting the use of electric micromobility transportation systems.

Partnership, 2023). It is a European partnership aimed at supporting research and innovation projects designed to address urban changes and accompany cities in their transition towards a more sustainable economy and operation. The goal of the partnership is to provide local administrations, businesses, and society in general with the resources and means to implement the necessary urban changes for city development. As a successful example, in Murugan and Marisamynathan (2022), the Indian *National Electric Mobility Mission Plan* is cited, which was launched in the year 2013 with the aim of supporting the market in the target of selling 6–7 million of electric and hybrid vehicles from the year 2020 onwards.

Several reasons are thus moving customers towards micromobility, such as concerns related to environmental sustainability and the change in the transport habits of an aging population which resides more and more in urban environments. Nonetheless, the use of e-bikes and similar has been also growing in touristic scenarios, allowing the fruition of harsh and scenic landscapes also for elderly or not very sporty population. The use and availability of e-bikes has been becoming one of the qualifying features of green tourism (Mehmood and Zhou, 2023; Ahmad and Harun, 2023; Genikomsakis et al., 2021).

The above-summarized factors can be summarized as shown in Fig. 1 and more extensively described in Table 1.

Although Electric Micromobility Vehicles (EMVs) currently have many advantages, several aspects still limit their adoption and reduce their use in the coming years. The main six barriers are extensively described in Table 2. Most of these barriers are directly or indirectly linked to the charging infrastructure (Bridge et al., 2023; Önden et al., 2024). For example, the establishment of an extensive network of charging infrastructures can help to alleviate range anxiety and reduce the limited accessibility of EMVs. On the other hand, this is only possible if the charging infrastructure is optimized to have a low production cost. This condition is achievable only by working on urban planning and regulation (see Fig. 2).

To overcome these barriers, governments, businesses, and urban planners need to invest in the development of a robust charging infrastructure (Lo et al., 2020). This includes the strategic placement of charging stations in urban areas, along popular commuting routes, and at key destinations (Cui et al., 2019). Addressing these challenges will contribute to the growth and acceptance of EMT as a sustainable and convenient mode of transportation.

Several works in the literature are focused on electric vehicles (EVs) charging infrastructure (Pareek et al., 2020; Narasipuram and Mopidevi, 2021; Savio Abraham et al., 2021), but there is a clear gap as regards EMVs. Actually, the words “review e-bike charging station”, “review e-scooter charging station”, “review electric micromobility charging station” in the title of papers were searched in the Scopus database on the 22nd of April, 2024, and there were no matches. Indeed, it is evident that the infrastructures for EMVs have some aspects in common with charging stations for EVs in general, but there are distinctive features raising specific critical points and specific opportunities. Based on this, the objective of this paper is to fill the above gap by providing a review paper explicitly devoted to the scientific and technological challenges related to the charging infrastructures of electric micromobility.

Table 1
Advantages of electric micromobility vehicles.

Advantage	Description
Health and Fitness	Electric Micromobility Transportation (EMT) provides an option for individuals who may not be able or willing to engage in strenuous physical activity (Bourne et al., 2018). The electric assistance allows riders to pedal with less effort, making it more accessible for a wider range of people, including those with health or fitness limitations (Gojanovic et al., 2011).
Transportation	EMT offers a practical and efficient means of transportation, particularly for commuting in urban areas (Reck et al., 2022). It can help riders cover longer distances and hills with ease, reducing the overall commuting time and effort compared to traditional bikes. E-bikes are also a cost-effective alternative to cars and public transportation (Castiglione et al., 2022).
Environmental Concerns	With an increasing awareness of environmental issues and a desire to reduce carbon footprints, many people are turning to EMT as a more sustainable mode of transportation (Sun and Ertz, 2022). EMT produces fewer emissions compared to traditional vehicles, contributing to cleaner air and a smaller environmental impact (McQueen et al., 2021).
Technological Advances	Advances in battery technology and electric motors have led to more efficient and affordable EMVs (Zakaria et al., 2019). Improved battery life, lighter weights, and better performance have made EMT more appealing to a broader audience (Miao et al., 2019).
Government Incentives	In some regions, governments and municipalities are offering incentives to promote the use of EMVs (Olabi et al., 2023). This may include subsidies, tax credits, or infrastructure development to support e-bike usage (Fearnley, 2020).
Aging Population	As the population ages, EMT provides an attractive option for older individuals who may experience reduced physical capabilities (Lacey and MacNamara, 2000). The electric assistance allows them to continue cycling and maintain an active lifestyle (Papageorgiou et al., 2019).
Tourism	EMT is not only used for commuting but also for recreational purposes (Jażdżewska-Gutta et al., 2023). It enables riders to explore scenic areas and cover longer distances without the same level of physical exertion, making them popular for tourism and outdoor activities (Christoforou et al., 2023).

One of the distinctive features of EMVs is the lower power demand of, say, an e-bike with respect to an electric car. This has several implications about, for example, an augmented potential of employing distributed renewable power generation (as, for example, PV panels or micro wind turbines) and of adopting self-sufficient off-grid charging station architectures. On the other hand, the absence of consolidated standards as regards the requested output voltage raises specific issues related to the various stages of the power conversion. Actually, as an example, the review paper (Rajendran et al., 2021) about electric vehicles explicitly relates system architecture to international standards, but this is not feasible in the case of EMVs.

Furthermore, electric two-wheelers are exploited in multi-faceted scenarios, much more than electric cars, and this brings to a much more various ensemble of consumer expectations and related challenges. For example, e-cargo bikes represent a promising solution for last-mile logistics (Papaioannou et al., 2023) and thus their exploitation and related charging infrastructure needs to be conceived and optimized in urban scenarios (Narayanan and Antoniou, 2022). On the other way round, in the context of green tourism, the availability of e-bikes is an appreciated service to the customers, but its efficient implementation (Mehmood and Zhou, 2023) requires to site charging stations in possibly remote, for sure non-urban, environments.

Table 2
Factors slowing the spread of electric micromobility.

Barrier	Description
Range Anxiety	If riders are unsure about the availability of charging stations along their routes, they may be hesitant to adopt e-bikes for fear of running out of battery power during a journey (Bridge et al., 2023). A sparse charging infrastructure could limit the practicality and convenience of using e-bikes for longer trips (Parnell et al., 2023).
Limited Accessibility	The scarcity of charging stations may make it difficult for e-bike users to find a convenient place to charge their batteries, especially in urban areas where parking and charging space can be limited (Deb et al., 2018). This limitation could discourage potential users who rely on a readily available charging infrastructure (Metais et al., 2022).
Urban Planning and Regulations	Insufficient charging infrastructure may be a result of inadequate urban planning and regulations (Teixeira et al., 2023). Cities and municipalities need to proactively plan for and invest in charging stations to accommodate the growing number of e-bike users. Without supportive policies and infrastructure, the adoption of e-bikes could face obstacles (Li et al., 2022).
Cost Implications	Establishing a widespread charging network can be expensive, and if the costs are not adequately subsidized or supported by private investment, the slow expansion of charging infrastructure could be a barrier to the widespread adoption of EMVs (Avetisyan et al., 2022).
Public Perception	The perception of e-bikes may be influenced by the availability of charging infrastructure. If potential users perceive a lack of charging stations, they may view e-bikes as less practical or convenient, impacting their willingness to invest in this technology (An et al., 2023).
Manufacturing and Supply Chain Challenges	The production and distribution of e-bikes, including batteries and charging infrastructure components, may face challenges related to manufacturing capabilities and supply chain disruptions. These challenges can affect the overall growth and adoption of EMVs technology (Önden et al., 2024).

The intersection between users' utilization and expectations and technological peculiarities of the sector (*e.g.* low power demand) identifies emerging trends which are specific to EMVs, as for example fast charging and wireless power transfer.

Given the above line of reasoning, thus, the main objectives of this review can be summarized in the following points:

1. To analyse the electrical characteristics of the EMVs. An extensive market analysis is carried out to identify the characteristics of the battery packs of these systems.
2. To discuss in detail the factors which affect the design of EMV charging stations.
3. To comparatively review the current state of the art in the research regarding micromobility charging infrastructures.
4. To survey the characteristics of the main charging infrastructure solutions available on the market.
5. To address and discuss in detail the technical and scientific aspects of infrastructure design.
6. To identify emerging trends related specifically to charging stations for EMVs and to outline research direction of growing importance in the future.

As an anticipation of the collected evidence, it can be argued that it is prohibitive to define univocal guidelines for optimally designing and implementing a charging station for EMVs, but it is possible to identify some factors which should be evaluated depending on the exploitation context and related constraints. The discussion presented in this work can thus be beneficial for the various private and public stakeholders operating in the field of EMVs charging infrastructures.

1.1. Paper organization

Based on the above discussion, the paper is organized as follows. In Section 2, through a market overview, the electrical characteristics of the energy storage used on EMVs are collected. In Section 3, the main factors influencing the project and the implementation of an EMV charging infrastructure are discussed. In Section 4, a literature overview of the scientific papers related to the design of these charging stations is presented and the research gaps to filled in the future are identified. A market analysis of the main commercial solutions is presented in Section 5. In Section 6, the main technical aspects that must be taken into account during the design phase are discussed. In Section 7, some meaningful emerging trends are presented; in Section 8 a brief discussion of the main open points is presented and, finally, some concluding remarks are provided in Section 9.

2. Rechargeable electric micromobility vehicles

In this section, the main characteristics of EMVs are summarized. Since the attention of this paper is focused on the charging infrastructure, the power rating and electrical characteristics of their energy storage is hence considered. In Fig. 3, the rated voltage, the capacity and the charging power rating of the energy storage for different micromobility devices are shown. In each pie chart, the percentage of systems adopting a given feature according to the market overview is indicatively represented. These values were obtained by conducting a market survey of the main commercially available devices.

2.1. Pedelecs and E-bikes

Pedelecs feature a pedal-assist system that provides electric assistance to the rider's pedalling effort (Peterman et al., 2016). This assistance is usually activated when the rider starts pedalling and ceases when the rider stops or reaches a certain speed (Twisk et al., 2021). On the other hand, E-bikes typically have a throttle that allows the rider to control the electric motor independently of pedalling (Contò and Bianchi, 2022), meaning that the rider can choose to engage the motor without necessarily pedalling. Anyway, pedelecs are designed to assist the rider up to a certain speed, typically around 25 km/h in many regions (van der Salm et al., 2023). Once the rider reaches this speed, the electric assistance gradually decreases or completely cuts off (Cardone et al., 2016). The electric motor is usually located in the hub of one of the wheels (usually the rear wheel) or within the bike's frame, it can be rated from 250 W to 1000 W depending on the application and local regulation (MacArthur and Kobel, 2014; Ruan et al., 2013), and it is generally coupled with batteries with capacities from 100 Ah up to 1000 Ah.

2.2. E-scooter

Electric scooters have gained popularity as a convenient and environmentally friendly mode of urban transportation (Severengiz et al., 2020). They are powered by an electric motor, which is, usually, located in the hub of one or both of the scooter's wheels (Lee et al., 2017). E-scooters are equipped with a rechargeable battery that powers the electric motor. The battery capacity varies according to the model and brand, and results in typical ranges between 25 to 48 kilometres on a single charge (Aoki et al., 2019). Apart from a few exceptions, the nominal power of the engines associated with them is lower compared to e-bikes, with 68% having a power between 100 W and 200 W. The top speed and range of an e-scooter depend on various factors including the motor power, battery capacity, rider weight, terrain, and riding conditions. Common top speeds range from 24 to 40 km/h (Cano-Moreno et al., 2022).

2.3. Hoverboard, monowheel and segway

Hoverboards consist of a platform with two motorized wheels on either side. Hoverboards typically have a top speed ranging from 10 to 20 km/h (Ferro et al., 2022). The range of a hoverboard on a single charge varies, but it is usually around 16 to 24 km. Monowheels consist of a single large wheel with footrests on either side for the rider to stand on. They have varying top speeds depending on the model, but often they range from 20 to 32 km/h. The range of a monowheel on a single charge can vary but is typically around 16 to 32 km. Segways consist of a platform with two wheels and a handlebar for steering and stability. They typically have a top speed ranging from 16 to 20 km/h. The range of a segway on a single charge can vary but is usually around 20 to 40 km (Draz et al., 2012). From the perspective of nominal power, it is noticeable how segways distance themselves from the category they belong to: some models of segways are, in fact, the most used vehicles by people with motor difficulties and disabilities (Kumar et al., 2023), and to address these needs they can be equipped with motors rated up to 2500 W.

2.4. E-skateboard

E-skateboards typically feature a deck made of wood, bamboo, carbon fibre, or a combination of materials. E-skateboards are powered by a battery, which is usually housed within the deck of the board. The top speed and range of an E-skateboard depend on factors such as motor power, battery capacity, rider weight, terrain, and riding style. Common top speeds range from 10 to 20 km/h, with ranges varying from 10 to 32 km on a single charge.

2.5. Drone

Charging stations for EMVs are typically located in various places that can also be convenient for drone operators, especially those operating commercially or in urban environments where access to charging facilities can be limited (Qin et al., 2022). These devices, are not the primary targets of the infrastructure but can take advantage of its presence to increase their operability and autonomy (Huang and Savkin, 2020).

3. Factors influencing the design of charging infrastructure

In this section, the focus is placed on the charging infrastructure and on the human and technological factors that shape its design. The main features influencing the choice of one architecture over another are summarized in Fig. 4. Following, each criterion is described.

3.1. Consumers' behaviour

The recent review paper in Mina et al. (2024) is focused on the characterization of the attractiveness of the e-bikes for consumers. From that work, it clearly arises that the willingness to be e-bike users depends on several factors, among which the recharge is one of the most crucial. Indeed, the work in Van den Steen et al. (2022) reports that the infrastructure requirements of conventional cyclists vs. e-bike cyclists differ in a manner which is statistically significant only regarding one point: the charging stations infrastructure along the cycle path. The study in Kohlrautz and Kuhnimhof (2023) deals with users' willingness to employ e-bikes in relation to the provision of charging services by their employers. In particular, the users' attitude relevantly depends on the presence or not of a charging fee.

Based on the above literature review, it can be argued that there are no studies based on real-world data which establish a clear relation between the characteristics of the charging station and the users' behaviour. Most studies are based on surveys, which investigate potential users' behaviour. Furthermore, despite several works dealing

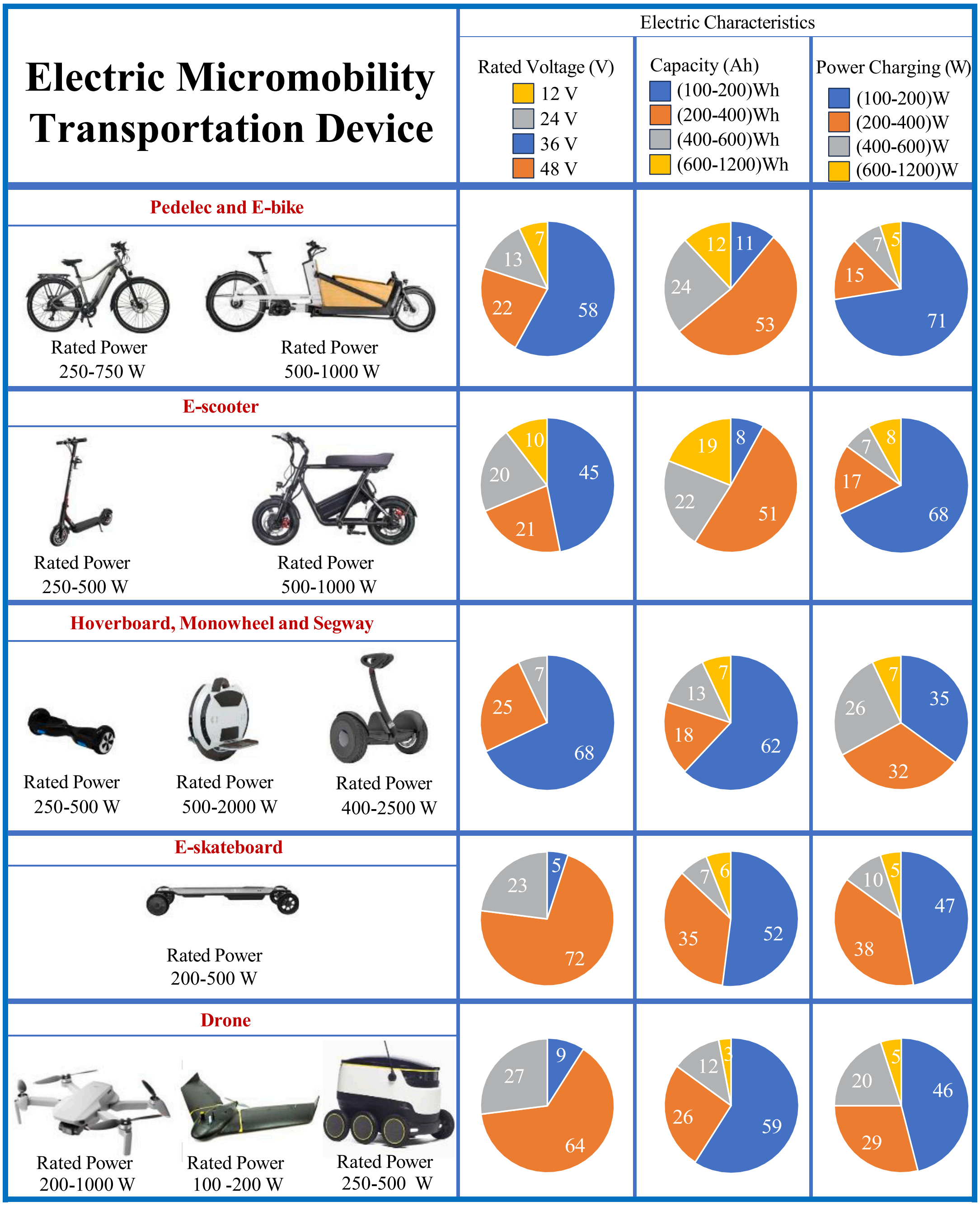


Fig. 3. Electrical characteristics of micromobility transportation devices.

with optimizing the siting of electric vehicles charging stations (Liu et al., 2022; Zeng et al., 2024; Xu et al., 2020), there are no studies which are explicitly devoted to the siting of e-bikes charging stations.

Nevertheless, also considering the limitations of the current literature, some indications of interest for the present study can be drawn:

- The availability of charging stations along the routes is requested by the users;
- Given that range anxiety is one of the most important factors limiting the benevolence towards e-bikes, it is fundamental that the charging stations are capable of providing the service as efficiently as possible. Thus, in order to satisfy consumers' expectations, it might be preferable to select grid-connected charging station architectures because they can employ power from the grid for charging the e-bikes, if necessary. On the other way round, this choice would have several drawbacks related to the necessity of connecting to the utility grid, as well as safety and regulatory issues. It might then be more appealing to select in any case off-grid architectures, especially in remote or touristic areas. In order to find an adequate balance between being off-grid and providing adequate services to the customer, the power flows of the system need to be evaluated carefully in order to appropriately tune, for example, the rated power of the employed PV panels or the nominal battery storage capacity.
- As supported by studies like Huang et al. (2021) and Murugan and Marisamynathan (2022), the advances in battery technology

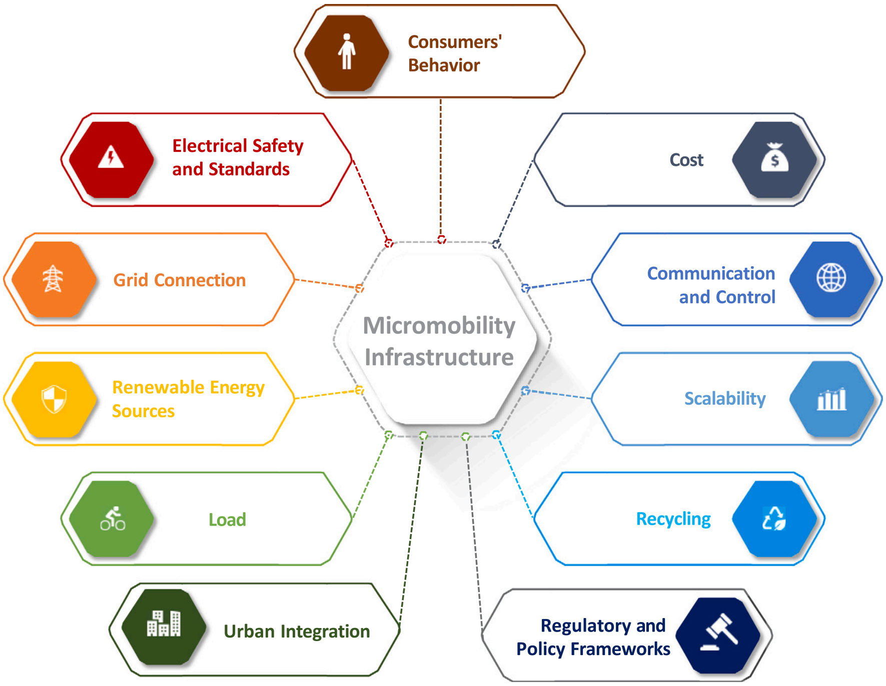


Fig. 4. Infrastructure features that affect the characteristics of the charging station.

and the availability of fast charging services are important drivers of consumers' benevolence towards e-bikes.

3.2. Electrical safety and standards

Mitigating electrical risks at charging stations for electric micromobility transportation systems involves the implementation of various safety measures and best practices. Electrical safety provided by a charging station can be characterized as the probability that it will consistently perform its functions without generating hazardous voltages on accessible surfaces as a result of random faults. The increase in complexity of the architecture and offered services leads to an overall reduction in reliability and, consequently, increases the electrical risk for users. Therefore, in selecting the features of the station, it is crucial to carefully evaluate its specific use cases and implement appropriate safety systems. This topic has been already widely analysed for the electric vehicle charging infrastructure (Wang et al., 2019). For example, in Rajendran et al. (2021), a comprehensive review of system architecture and international standards for electric vehicle charging stations is proposed, focusing on the various methodologies of protection for the different components involved.

The commercialization of charging infrastructure for e-bikes involves adhering to various standards and regulations to ensure safety, compatibility, and compliance with legal requirements. Some key standards and regulations that may be necessary to follow for the commercialization of e-bike charging infrastructure are summarized in Table 3.

3.3. Grid connection

Choosing between grid connection and off-grid solutions depends on factors like location, availability of infrastructure, and energy demand. Grid-connected stations offer high reliability and energy availability but may require significant upfront investment and, in some cases, they can have significant impacts from a power flow management perspective (Das et al., 2020). Off-grid solutions, such as solar-powered stations, provide flexibility and sustainability ensuring the supply of energy even in remote or with low load density areas. As a drawback, they often have a constrained capacity for electricity supply compared to the traditional grid, which may limit their ability to meet high-demand situations or support multiple users simultaneously. These systems may also exhibit lower power quality compared to the grid, leading to issues such as voltage fluctuations, harmonics, and frequency variations, thus requiring careful planning and management (Ortega-Arriaga et al., 2021).

3.4. Renewable energy sources

As above anticipated, the use of Renewable Energy Sources (RES) aligns with sustainability goals and reduces the environmental impact of charging stations. Integrating solar, wind or other renewable sources can reduce reliance on fossil fuels and decrease greenhouse gas emissions, contributing to a more sustainable transportation infrastructure (Puertas and Marti, 2022). Although related, this aspect should be considered separately from the status of the station's connection. The installation of an autonomous generation system, in fact, does not exclude the possibility of direct power supply from the electrical grid, a fact that makes these two frameworks distinct and to be evaluated individually.

3.4.1. Lifecycle assessment

For a comprehensive understanding of the environmental impact of the infrastructure, from manufacturing to disposal, Life Cycle Assessment (LCA) is essential. LCA enables the recognition of hot spots and sectors that could use improvement within the entire life cycle, also offering insights into choices between other environmental indicators, such as greenhouse gas emissions, resource depletion, and ecosystem impacts. When it comes to electric vehicles, various studies show that the environmental impact over the entire life cycle heavily depends on the generation source used. The sustainability of the charging infrastructure, therefore, cannot be separated from the renewable energy source. Without it, the overall impact over the entire life cycle may even be worse compared to internal combustion counterparts (Pasetti et al., 2022; Bucher et al., 2019). In addition, significant differences also seem to emerge regarding the properties of the charging point: according to Zhang et al. (2019), public mix chargers and public AC and

Table 3
Standards and regulations for the commercialization of e-bikes charging infrastructures.

Standard	Field	Description
UL 2849	Electrical Safety	Standard for Electrical Systems for e-Bikes, for the electrical system of any powered bicycle
UL 2271	Electrical Safety	Standard for Batteries for Use in Light Electric Vehicle Applications, of any storage battery for a powered bicycle or mobility device
UL 2272	Electrical Safety	Standard for Electrical Systems for Personal E-Mobility Devices, for all powered mobility devices, including e-scooters
IEC 60038	Electrical Safety	standard voltage values which are intended to serve as preferential values for the nominal voltage of electrical supply systems, and as reference values for equipment and system design
IEC 60664	Electrical Safety	Insulation coordination for equipment having a rated voltage up to AC 1 000 V or DC 1 500 V connected to low-voltage supply systems. This document applies to frequencies up to 30 kHz
IEC 62196	Electrical Safety	Plugs, socket-outlets, vehicle connectors and vehicle inlets — Conductive charging of electric vehicles
IEC 61851	Electrical Safety	for EV conductive charging systems, parts of which are currently still under development
ISO 17409	Electrical Safety	its international standard provides guidelines for the installation and operation of electric vehicle charging stations, including requirements for safety, accessibility, and environmental considerations. It covers aspects such as location, signage, and user information.
ISO15118	Communications	regulates bidirectional communication between electric vehicles and charging stations
ISO 14001	Environmental and Sustainability	best practices for organizations that wish to reduce their environmental footprint by adopting an effective environmental management system (EMS)
ISO9001	Quality Management	requirements for a quality management system (QMS). Organizations use the standard to demonstrate the ability to consistently provide products and services that meet customer and regulatory requirements

DC chargers have the highest energy consumption and greenhouse gas emissions, in contrast to home chargers having the lowest. Indeed, it is important not to underestimate the impact of onboard electronics and Vehicle-to-Grid (V2G) integration programs: according to Wohlschlager et al. (2022), the environmental impact throughout the entire lifecycle of a standard charging point is up to 69% lower compared to V2G points, raising the issue of optimizing ICT resources for charging.

3.4.2. Efficiency of charging stations powered by renewables

In the case of EMVs, there is a lack in the literature as regards the investigation of the quality of service of off-grid architectures powered by renewables. This limits the comprehension of the challenges and opportunities related specifically to this kind of application. To the best of the authors' knowledge, the only available study is (Nkounga et al., 2021).

If the architecture is off-grid and powered solely by renewables, which have an intermittent nature, it is fundamental to tune the size of the battery storage and that of the renewable power source in order to provide the charging service when requested. It is evident that this kind of optimization problem is multi-faceted, since on the one hand it is desirable to have the minimum rated renewable power and battery capacity, in order to minimize the costs and the size of the charging station, and on the other hand it is desirable to always provide the charging service when it is requested. In the charging station design phase, the charging demand scenarios are unknown and can only be hypothesized. Yet, their daily distribution is fundamental, as it makes a great difference, for example, if they occur when there is PV power production or not. Moreover, the results are highly site-specific, as they are dependent on the irradiance and-or wind distribution.

Based on the above considerations and given the lack of similar analyses in the literature for the specific case of EMVs, in the following, a realistic estimate of the achievable Quality of Service (QoS) for an off-grid charging station powered by PV panels is provided by considering a simplified scenario of urban charging demands. Namely, the following assumptions are made and the following steps are pursued:

- Suppose that each e-bike arrives at the charging station with a partial State of Charge comprised between the 30% and the 40% and, thus, that the power demand for a single e-bike recharge can be estimated to be 135 W constant for two hours (Pasetti et al., 2023).
- Suppose that the charging demand occurs with patterns typical of workers: thus in the morning, at lunch break and in the evening. The hypothesized scenario is two recharge demands from 7 a.m. to 11 a.m., two from 1 p.m. to 3 p.m., and two from 7 p.m. to 9 p.m.
- Simulate the annual DC power supply, with a minimum time resolution of 1 h, for the PV system considering assumed values of the location, tilt condition, and orientation. Use lumped parameter models of PV modules in the PVGIS tool along with historical data on solar irradiance and ambient temperature. A sample location in the city of Brescia (Italy) is selected and data from the PVGIS-SARAH2 database for the year 2020 with a time step resolution of 1 h are employed.
- Assume an architecture of the charging station with a hybrid inverter and thus assume typical values of the various conversion efficiencies: a. Combined DC/DC and MPP tracking efficiency 87%. b. DC/AC efficiency values 88%.
- Assume a constant power demand profile of 12 W for the electronic and ICT components.
- Assume that the charging is allowed if the power demand of the e-bikes does not exceed the DC PV power summed to the available power of the battery storage.
- Consider three cases of rated PV power: 500 W, 1000 W and 1500 W.
- Let the capacity of the battery storage vary with steps of 100 Wh from a minimum of 100 Wh to a maximum of 3000 Wh.
- Compute the QoS, which is the annual rate of power outlet unavailability with respect to the total requested recharging time.

The obtained results are reported in Fig. 5. Several considerations arise from Fig. 5, as for example that a QoS higher than 70% cannot

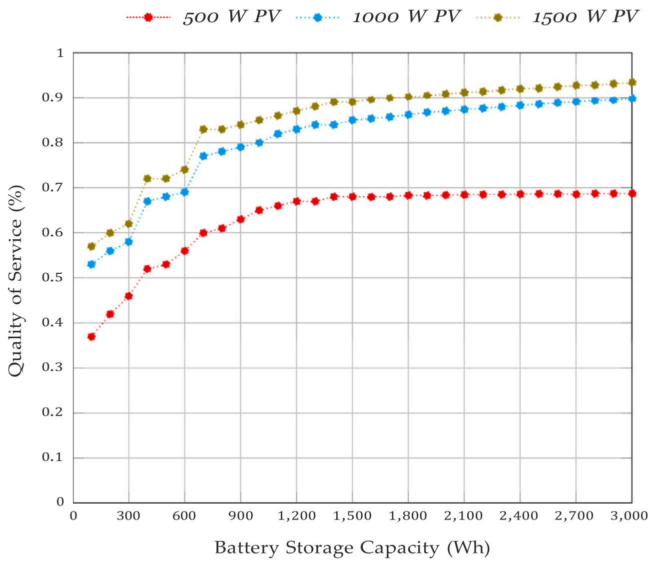


Fig. 5. Quality of Service as a function of E_{BESS} for 500, 1000 and 1500 W of installed rated PV power, supposing urban recharge demand scenarios.

be achieved in managing the above scenario of demands (6 recharges of 2 h each) with a rated PV power of 500 W, whatever the battery storage. The ratio between the total daily power recharge demand and the rated PV power is likely the most important factor determining in general the QoS, although there might be particular effects related to the daily distribution of the power demand. For example, for the scenario considered in this analysis, the total daily energy demand of the e-bikes recharge is 2160 Wh and it results possible to serve them with at least 80% QoS if the rated PV power is 1000 W. For a rated power of 1000 W or higher, the effect of the size of the battery storage is more evident. The possible surplus production of the PV which is not employed for directly recharging the e-bikes can be stored and employed for managing future demands. With 1500 W of PV power and 3000 Wh of storage capacity, it is possible to reach 90% QoS. If one wants to double the size of the PV with respect to the best case in Fig. 5, thus selecting 3000 W, and also the highest considered battery capacity (3000 Wh), in any case, the estimated QoS is in the order of 95%. Thus, for the case of off-grid architectures, it should be expected that, with a reasonably sized or even reasonably oversized system, in any case, the QoS does not reach 100%. This matter of fact should be taken in consideration in relation to the desired level of users' satisfaction.

3.5. Load

The type of micromobility vehicle to be charged significantly influences the design and functionality of the charging infrastructure. Different types of vehicles, such as electric scooters, bicycles, electric skateboards, and similar compact vehicles, have varying power requirements, charging port configurations, and charging times. This is due to several key factors such as battery capacity, rated power charging, or connectors. It is essential to include the necessary devices to make the service accessible to the target vehicles while also predicting the number of vehicles that can be recharged simultaneously (Hasib et al., 2021).

3.6. Costs

Cost considerations are paramount for the widespread adoption of charging stations and the overall feasibility of electric micromobility transportation systems (Madina et al., 2016).

Operational costs for EMV charging infrastructure can vary depending on factors such as the size of the network, the type of charging equipment deployed, and the geographic location. Some common operational costs associated with EMV charging infrastructure include:

1. Maintenance and Repairs: Regular maintenance is essential to ensure the proper functioning of charging stations. This includes tasks such as cleaning, inspecting equipment for wear and tear, replacing damaged components, and conducting software updates. Maintenance costs can vary depending on the complexity of the charging infrastructure and the frequency of use (Madina et al., 2016).
2. Network Connectivity: Charging stations may require network connectivity for remote monitoring, payment processing, and software updates. Operational costs associated with network connectivity include subscription fees for cellular or Wi-Fi services, as well as maintenance of network infrastructure (Pardo-Bosch et al., 2021).
3. Site Rental or Leasing: If charging stations are located on leased or rented premises, operational costs may include rental or leasing fees paid to property owners. These costs can vary depending on the location and duration of the lease agreement (Hardinghaus et al., 2022).
4. Insurance: Charging infrastructure operators may incur insurance costs to protect against liabilities such as property damage, theft, or personal injury. Insurance premiums can vary depending on factors such as coverage limits, deductibles, and the operator's claims history (Wu, 2019).
5. Customer Support and Administration: Providing customer support services, such as troubleshooting assistance and billing inquiries, may incur operational costs. Additionally, administrative tasks such as billing, accounting, and regulatory compliance may require dedicated staff or third-party services.
6. Marketing and Promotion: Operational costs may also include marketing and promotional expenses to raise awareness of the charging infrastructure among potential users. This can include advertising campaigns, promotional events, and partnerships with local businesses or community organizations (Bowermaster et al., 2017).

Although there are many costs associated with building and maintaining the infrastructure, it is possible to return economically from the investment in a short period of time due to the economic revenue. Nonetheless, realizing a return on investment in this sector may require time, prompting many to employ various revenue streams to optimize earnings from charging stations. The three key revenue streams for EMV charging infrastructure are:

1. Collect Direct Charging Fees: One primary revenue stream for EMV charging infrastructure is the collection of direct charging fees from users. EMV riders may be charged a fee for accessing and using the charging stations, either on a per-use basis or through subscription plans (Mercan et al., 2020). These fees can contribute to covering the operational costs of the charging infrastructure, including electricity consumption, maintenance, and administrative expenses. By implementing a transparent and competitive pricing structure, charging station operators can attract users while ensuring a steady flow of revenue (Rabiee et al., 2018).
2. Collaborate with Businesses, Property Owners, and Government Bodies: Collaboration with various stakeholders, including businesses, property owners, and government bodies, presents another avenue for generating revenue from EMV charging infrastructure. Businesses and property owners may be willing to host charging stations on their premises in exchange for rental fees or revenue-sharing arrangements (Bagherzadeh et al., 2020). Government bodies may offer subsidies, grants, or incentives

to support the deployment of charging infrastructure, thereby offsetting some of the initial investment costs. Strategic partnerships with local businesses, tourist attractions, or transportation hubs can also enhance the visibility and utilization of charging stations, leading to increased revenue opportunities (Wang et al., 2018).

3. Leverage Increased Customer Spend: EMV charging infrastructure can serve as a catalyst for increasing customer spending at nearby businesses or establishments (Genikomsakis et al., 2021). By strategically locating charging stations in commercial areas, shopping centres, or tourist destinations, operators can attract EMV riders who may subsequently patronize adjacent businesses while waiting for their bikes to charge (Suripto et al., 2022).

3.7. Communication and control

Effective communication and control systems are necessary for managing charging infrastructure, optimizing energy usage, and providing a seamless user experience (Dhianeshwar et al., 2016). The implementation of smart charging solutions (Pasetti et al., 2023) with robust communication protocols enables remote monitoring, scheduling, and billing functionalities, enhancing the efficiency and convenience of charging stations (Rinaldi et al., 2017, 2023).

3.8. Scalability

As micro-mobility becomes more and more popular, it is essential to consider the scalability of the infrastructure. Scalability refers to the network's propensity to grow in order to accommodate an increasing number of vehicles. This can be accomplished by installing new stations in areas with rising demand and enhancing the number of existing charging stations. A scalable network must necessarily exhibit a high degree of flexibility, interoperability and modularity: to cope with the various needs of EV owners, the infrastructure should provide a wide range of charging options, ensuring the availability of the service between different charging networks and EV models. Modular charging infrastructure allows for expansion and customization, with the possibility to add or remove single modules as needed and guaranteeing simple and fast upgrades. However, while constituting a necessary requirement, scalability poses several challenges that do not always find an immediate resolution. Foremost among these is the issue of integration with the existing network, which was created based on different assumptions and is not always predisposed to more or less substantial changes (Zhang et al., 2016; Barulli et al., 2020). No less important is the issue of urban spaces. Several studies highlight the challenges in integrating charging infrastructure into urban environments, with solutions often diverging from the optimal technical-economic outcome for reasons unrelated to strictly electrical concerns (Metais et al., 2022). Indeed, a scalable station must necessarily have smart capabilities that allow it to interact actively with existing infrastructure. The ability, for example, to intelligently manage power flows could be an additional parameter in positioning charging points to meet power flow management needs (Liu and Ouyang, 2024).

3.9. Recycling

Considering the end-of-life disposal and recycling of charging station components is crucial for minimizing environmental impact and promoting sustainability. Incorporating recyclable materials, designing for disassembly, and implementing responsible end-of-life management practices are essential for reducing waste and maximizing the environmental benefits of charging stations (Ma et al., 2018).

3.10. Urban integration

Light mobility has a significant impact on urban spaces. It can reduce the number of vehicles on the roads, thus improving traffic flow. This leads to less road congestion, reducing travel times, and improving air quality. Promoting micromobility can contribute to the regeneration of urban areas, making spaces more livable and attractive for residents and visitors, and fostering local economic development by stimulating commerce and similar activities (Vizmpa et al., 2023). Despite the numerous advantages of light mobility, there are also some negative impacts to consider. The increase in the number of bicycles and scooters on the streets can raise the risk of road accidents, especially if there are no dedicated and safe infrastructures for them. Furthermore, in some cities, the introduction of reserved lanes for bikes and scooters can cause space conflicts with other road users, such as cars, buses, and taxis (Candiani et al., 2024). The excessive reduction in available space for traditional vehicular traffic can lead to congestion and delays, especially if not managed effectively.

3.11. Regulatory and policy frameworks

Even though not directly related to the technical aspects, the regulatory framework drastically influences its diffusion, thus indirectly impacting the charging infrastructure. The almost sudden emergence of micro-mobility in the urban landscape of numerous European metropolises caught lawmakers by surprise (Fearnley, 2020; Herrman, 2019). Indeed, they proposed a series of initiatives to regulate its deployment, despite with much slower timing compared to technological/commercial developments (Shaheen and Cohen, 2019). The legislative drafting process, in fact, has been influenced by numerous problems arising from the absence of clear and precise regulations, such as accidents, improper use of spaces and general city decay (Janikian et al., 2024). The result has been, in many cases, the issuance of excessively stringent models that not only risk to severely limit the diffusion of this new mobility concept but also affect business models related to vehicle sharing or light delivery (Aba and Esztergár-Kiss, 2024; Button et al., 2020). On the other hand, it is essential to ensure an adequate level of safety, both for the users who use these vehicles and for all stakeholders in urban mobility. The role of the legislator is therefore crucial in the dissemination of light mobility, balancing between the two extremes of dissemination on one hand and safety on the other.

4. Charging infrastructure scientific literature overview

The fundamental demarcation in the charging station architecture is between grid-connected and off-grid operation. In the former case, the AC power from the grid necessarily must be converted to DC to charge the EMVs. As discussed for example in Khalid et al. (2019) and Deb et al. (2017), the increasing demand for distributed power requested for charging EVs might affect the smooth performance of the grid. This is the reason why the interest in the off-grid architecture for EV charging stations has been growing (Rituraj et al., 2022; Schelte et al., 2021). An intermediate solution is conceivable, which is the hybrid architecture, meaning that the charging station can operate standalone or grid-connected. The literature is ambiguous about the use of the term hybrid. Indeed, the term is also referred to the use of multiple power sources for the charging station. In this work, the use of the term hybrid is strictly referred to the charging infrastructure. As discussed for example in Pasetti et al. (2022), Ali et al. (2023), the contribution of e-powered mobility in diminishing Green House Gas (GHG) emissions depends heavily on the choice of the power source employed for charging the EVs. In a nutshell, a sensible GHG emissions reduction is achievable only if the power source is renewable (Miraftabzadeh et al., 2024). This motivates why there is a wide literature on the exploitation of RES for feeding EV charging stations (Alkawsi et al.,

Table 4
Relevant papers regarding micromobility charging station.

Ref.	Grid	Renewable source	WPT	Energy storage	Power rating	DC–DC converter	Experimental test
Chandra Mouli et al. (2020), Mouli et al. (2018)	Grid	PV	Yes	220 Ah	200 W AC	Flyback	Yes
Mishra et al. (2022)	Off-Grid	PV	No	24 V 60 Ah Li-ion	116, 84, 52 kW	Bidirectional	No
Bugaje et al. (2021)	Off-Grid	PV	–	104 kWh	900 W	–	No
Bhatti and Singh (2020)	Grid	PV	No	No	–	Boost	No
Huu et al. (2021)	Grid	PV	No	No	–		No
Yin and He (2023)	Grid	PV	No	No		Buck-Boost	No
Nguyen et al. (2020)	Off-Grid	PV+Wind	No	167 W	1 kW	Bidirectional	No
Afzal et al. (2023)	Grid	PV+Wind	No	No			

2021). This point is strictly intertwined with the grid architecture selection. In general, the architecture of the charging station can be simplified in the case of off-grid operation if the employed power source is photovoltaic (PV), possibly coupled with Battery Energy Storage Systems (BESS). In such a case, the AC–DC conversion and vice versa might be unnecessary. This consideration explains why, practically, all the papers selected as most relevant, discussed in Table 4, include PV power generation.

As can be seen, the research is equally distributed between grid-connected and off-grid systems. The totality of grid-connected systems, however, involves the use of RES, both to power the utilities and for auxiliary systems. The power size of the infrastructure is highly variable depending on the type and amount of vehicles to be simultaneously recharged, ranging from 100 W up to tens of kW. For systems involving renewables, much attention is placed on the use of bidirectional converters. Bidirectional converters can regulate the power flow from the battery to the load when charging vehicles are present and from the renewable source to the battery when energy is generated but no electric loads are connected to the infrastructure. It is worth pointing out that the DC–DC conversion is a critical technological point, given that the EMV market is very far from the adoption of one-size-fits-all standards. Therefore, the DC–DC conversion stage is fundamental to regulating the output voltage for the particular EMV battery. Wireless power transfer is also an emerging and important technological aspect. The balance of the pros and cons is non-trivial. On the one hand, the wired charging might be discouraging for the user. On the other hand, the efficiency of wireless power transfer via the principle of magnetic induction has a lower efficiency and the safety issues related to the exposure to magnetic fields are non-trivial. Nevertheless, it is significant to point out that this aspect has been attracting a vast amount of research in the latest years (Bi et al., 2016; Mahesh et al., 2021; Triviño et al., 2021), and, thus, this is discussed in Section 7.

The works in Chandra Mouli et al. (2020) and Mouli et al. (2018) provide a comprehensive picture of the scientific and technological challenges related to e-bike charging stations. In those works, the detailed design of a solar-powered e-bike charging station is presented. The architecture is hybrid and the core of the system is a 48 V DC nano-grid powered by a PV array and equipped with a storage. The charging station provides AC, DC and wireless charging for the e-bike. In the case of DC charging, the power is transferred directly from the PV panels (or the storage) to the e-bikes, thus avoiding unnecessary conversion to AC. The power rating of the PV system is 2.6 kW and the employed storage is constituted by four lead–acid gel batteries of 220 Ah capacity each, series-connected to 48 V, proving a useable capacity in the order of 10 kWh. The connection between the DC nano-grid and the 50 Hz AC grid is realized via a bi-directional inverter: one output is connected to the single-phase AC grid and the other output powers the e-bike AC charging with a single 230 V 50 Hz schuko wall socket through a charging adapter, up to 3.7 kW of power. The DC charging can be regulated in current and voltage via a dual interleaved quasi-resonant converter with digital current-mode control, such that the user does not need to carry a power adapted. For safety reasons, the power rating of the DC charging is limited to 100 W. Wireless charging is possible via inductive coils, with the transmitter coil located under the floor of the charging station, up to 200 W. This is a critical point, in that the radiated magnetic field associated to the wireless power transfer can reach undesired levels. At the moment the work was written, the design of the charging station was tested in the laboratory and there were preliminary assessments indicating that the radiated magnetic field was in the limit for general public exposure.

The objective of the work in Mishra et al. (2022) is a provide a robust solar PV based off-grid design for charging e-bikes. The PV array is sized in order to have 1 kW at an ambient temperature of 25 °C with a 1000 W/m^2 irradiance. The battery storage is a 24 V 60 Ah Li-Ion. Particular attention is devoted as well to the DC-DC converters, which are an important part of a PV-powered off-grid charging station. The solar PV array is connected to the unidirectional boost converter, while the energy storage is connected to the bi-directional converter. The simulations are conducted by discussing the cases of 12, 24 and 36 V required for the e-bike, thus addressing one of the critical aspects related explicitly to e-bike charging.

In Bugaje et al. (2021), the objective is integrating e-bike charging into an off-grid photovoltaic Water-Energy Hub located in the Lake Victoria Region of Western Kenya. Such hub is PV-powered (30 kWp) and includes energy storage (capacity in the order of 104 kWh). A 30 kVA inverter converts the PV power into AC to either cover the electrical load profile or charge the battery storage. The produced power is employed for traditional usages and also for purifying drinking water. The focus of the paper is on the analysis of the load cycles of the energy hub and on the identification of the energy surplus, which can be employed for charging e-bikes. Thus, the load profile is optimized in order to minimize the energy deficit. The work is composed mainly of numerical simulations, with an experimental campaign aimed at determining the distance-related energy consumption of the e-bikes. The main result is that, upon optimization of the load cycles, it is possible to charge four OpiBus e-bike batteries per day.

The work in Bhatti and Singh (2020) deals with the design of a micro-grid for charging e-bikes. The architecture is hybrid, in that the power for charging the e-bikes can be taken from the utility 50 Hz AC grid, or from a 6 kW local PV array, or from a 30 kW solar farm. A three-phase AC-DC converter is employed in case the power is taken from the grid, and a boost DC-DC converter is employed to regulate the DC power from the PV generation at the voltage level needed for the battery of the e-bike. No battery storage is contemplated (see Fig. 1) The study is constituted by numerical simulations. A similar approach is pursued in Huu et al. (2021), where a hybrid PV-based architecture is investigated for the installation at a University campus in Vietnam.

The study in Yin and He (2023) deals with an off-grid PV-powered hybrid charging station. The overall idea for sizing the system is one PV array unit to one battery and the batteries are stored in cabinets, in order to allow battery swapping. This, indeed, represents a promising solution for improving the self-consumption from renewable sources while feeding their power directly to e-bike batteries. The work in Yin and He (2023) is more specifically devoted to charging station design and architecture and thus it is considered the most relevant for the purposes of this work. The selected architecture is hybrid and the charging station can thus employ the PV power or take it from the AC grid. Therefore, the charging station is equipped with an AC-DC converter (for AC grid to e-bikes battery power flow) and a DC-DC buck-boost converter (for PV power to e-bikes battery power flow).

The works in Nguyen et al. (2020) and Afzal et al. (2023) are, to the best of the authors' knowledge, the only ones devoted to the integrated use of PV and wind turbines to feed an e-bike charging station. In this case, there is an augmented complexity with respect to the only PV-powered charging station, due to the fact that the wind turbines produce AC power. In the case of Nguyen et al. (2020), the architecture is explicitly off-grid. In the case of Afzal et al. (2023), from Fig. 3 one would argue that power could be injected into the grid, but the focus of the paper is on the use of PV + wind + storage to feed the load (e-bikes) without power exchanges with the grid. Indeed, Fig. 5 practically refers to an off-grid architecture.

The architecture described in Nguyen et al. (2020) (Fig. 1) is composed of four blocks: a wind power sub-system, a PV power sub-system, an energy storage composed of second-life batteries, and the load. The wind power sub-system is composed of a Savonius vertical-axis wind turbine and an AC-DC converter. The Savonius wind turbine is selected due to its low start-up and the minimal requirement of maintenance. Another interesting aspect of the study is that the storage is composed of second-life batteries obtained from Alizeti's e-bike conversion system manufacturer once its state of health dropped below 70%. The focus of the work is on numerical simulations aimed at sizing the system based on a cost function which takes into account the number of wind turbines, PV panels and second-life batteries.

The focus of the work in Afzal et al. (2023) is on the estimation of how many e-bikes can be charged depending on the wind/solar properties of the installation site. Two wind turbines with a rated power of 1 kW and a PV array with a rated power 1.2 kW feed power to the charging station. It is argued that a near-shore installation provides a remarkable increase of the wind Annual Energy Production, which in turn translates into a higher capability of charging e-bikes. The study is based on numerical simulations, done with Simulink.

5. Commercial solutions available in the market

In Table 5, the main solutions available on the market are summarized and compared. Different architecture solutions are available in the market. The comparison has been performed in terms of the type of infrastructure, number of EMVs chargeable simultaneously, information about the power outlet, presence of renewable sources and followed standards.

In Fig. 6, the main structural solutions of charging infrastructure are shown. The main structure can be divided into four categories: rack, pillar, wall box and hub. The rack represents the simplest and cheapest solution. As shown in Fig. 6(a), it allows reducing the required space, and it can be easily expanded or adjusted to accommodate more bikes as needed, making these charging solutions suitable for locations with varying levels of demand. In Fig. 6(b), Fig. 6(c) Fig. 6(d) the pillar solution is shown. This solution is more expensive than the simple rack as it usually provides additional services such as instrumentation for vehicle maintenance. A pillar can often be used to charge 1 to 4 vehicles at the same time. One of the less bulky solutions is the wallbox, shown in Fig. 6(e). In this case, the system consists of a box equipped with outlets used to recharge the electric vehicle. Finally, the most comprehensive structure is the hub, as shown in Fig. 6(f), Fig. 6(g) and Fig. 6(h). This structure can use racks or wallboxes within a sheltered structure. The structure can also be covered by photovoltaic panels and/or wind turbines. This solution is the most cumbersome and expensive, but it is also the solution that can provide more ancillary services. The solution shown in Fig. 6(g) consists of a series of lockers in which pre-charged battery packs are stored. The user can then go to the facility and, by means of an identification key, collect the recharged battery pack. This solution falls within the logic of battery swapping. This approach allows for a fast replacement of depleted batteries with fully charged ones, minimizing downtime for users. It is especially beneficial in densely populated urban areas where users may not have enough time to wait for their vehicle to be charged. The system allows the users to quickly swap batteries at designated swapping stations without having to monitor the charging process or wait for extended periods. On the other hand, managing the logistics of collecting, transporting, and maintaining a fleet of batteries adds complexity and cost to operations. It requires regular maintenance of batteries, swapping stations, and vehicles to ensure seamless service. In addition, battery swapping involves the production, transportation, and disposal of batteries, which can have environmental implications if not properly managed (Yang et al., 2022; Zhou et al., 2023). Almost all commercially available structures are designed to be used in connection with the electricity grid. The hub solutions, such as Bike Energy (2024) and Charmax (2024), allow to be designed for off-grid operation. The off-grid operation is more suitable for a hub facility as it provides the necessary space for the placement of the renewable energy generation system. Since if operating in off-grid mode the renewable source must guarantee sufficient autonomy, the off-grid is not compatible with smaller structures such as simple racks or pillars. Rather, the renewable resource can be exploited for the construction of a shelter in combination with racks and/or pillars, as shown in Fig. 5(h). The most commercially used renewable source is photovoltaics. This is because, once installed, PV systems result in relatively low operating costs, therefore, solar energy becomes an economically attractive option for micromobility charging infrastructure, especially when compared to conventional grid electricity with ongoing utility bills (Kornelakis and Koutroulis, 2009). In addition, advances in PV technology, such as increased efficiency and reduced costs of solar panels, have made solar energy more accessible and cost-effective for various applications, including micromobility charging infrastructure (Spertino et al., 2013). Only (Biciway, 2024) proposes a system based on wind power in combination with photovoltaics, as shown in Fig. 5(d). The main limitation of this solution is that mini-wind turbines require suitable wind conditions for effective operation. They are most efficient in areas with consistent and strong wind speeds. Site selection is crucial, and turbines may not be viable in areas with insufficient wind resources (Suripto et al., 2022). In addition, turbines can be visually obtrusive, especially in urban or residential settings, impacting aesthetics and potentially facing opposition from local communities (Garcia et al., 2019). Additionally, some turbines produce noise during operation, which may be perceived as disruptive in certain environments (Iannace et al., 2020).

6. Technical aspects for infrastructure design

Starting from the state of the art presented above, a set theory representation of the possible solutions for the charging infrastructure taking into account different technical solutions is shown in Fig. 7.

The development of charging infrastructure for micromobility presents a critical aspect of sustainable urban transportation systems. From the technical and energy autonomy point of view, the focus must be placed on key decisions regarding grid connectivity, safety, transformer type, and integration of RES. In the following, each aspect is discussed.

Grid Connectivity The choice between grid-connected or off-grid charging infrastructure holds significant implications for reliability, scalability, and cost-effectiveness. Grid-connected systems offer a reliable power supply, leveraging existing infrastructure to ensure consistent charging availability (Twaha and Ramli, 2018). Conversely, off-grid solutions provide independence from the grid, enhancing resilience against grid failures and disruptions in service. Yet, they entail higher initial setup costs and limited scalability, particularly in remote or underserved areas (Jafari et al., 2018).

Isolation The decision to employ isolated or non-isolated charging systems influences safety, complexity, and compliance considerations.

Table 5
Commercial charging infrastructure available on the market.

Ref.	Company	Type	N. of EMVs	Electrical information	Renewable source	Standard
Ibombo (2024)	E-PRS-LV2 by IBOMBO	Rack	4	250 V Sockets	No	EC/EN 61439-1 IEC/EN 61439-4 Plug IP54 6A RCBO protection
E-traction (2024)	Solar E-charger by Etraction	Rack	3	230V AC Socket	PV	–
Saris Infrastructure (2024)	Saris Infrastructure	Rack	1	120 V/230 AC Socket	No	–
Kemmlit (2024)	Kemmlit PowerBox	Rack	1	230V AC Socket (13 A)	No	IP66 Sockets
Biciway (2024)	Tulip Power Solar+Wind	Pillar	2	30 W Solar panel and 300 W wind turbine, Battery 110 Ah	PV+WIND	IP55 and IK10 Sockets
Scame (2024)	Scame Pillars	Wall Box	6	7.4 kW	No	–
Spelsberg (2024)	Spelsberg TG BCS 3	Wall Box	3	230V AC Socket	No	IP44 and IK08 Sockets, IK08, Double Insulation 400V
Bike Energy (2024)	Bike Energy Charge Cube	Hub	8	–	PV	–
Charmax (2024)	Mobile E-Charging by Charmax	Hub	4	Off-grid	PV 1.3 kW	–

Fig. 6. Different types of charging infrastructure available in the market.

Isolated charging systems offer enhanced safety by providing electrical isolation between the vehicle and the grid, reducing the risk of electric shock (Khan et al., 2019). They also comply with safety standards and minimize electromagnetic interference. However, they involve an increased complexity and cost compared to non-isolated systems. Non-isolated systems are simpler in design and potentially more cost-effective, however, they lack electrical isolation, and, therefore, they raise safety concerns and compliance challenges (Bhatti et al., 2016).

Transformer Type The choice between high-frequency and low-frequency transformers affects size, efficiency, and power handling capacity (Al-Hanahi et al., 2021). High-frequency transformers offer compact designs and higher efficiency, so they are suitable for space-constrained installations and achieve lower energy losses during conversion (Yilmaz and Krein, 2012). Nonetheless, they may incur higher costs and lower power handling capacity than low-frequency transformers. In contrast, low-frequency transformers excel in power handling capacity and reliability, albeit at the expense of larger size, weight,

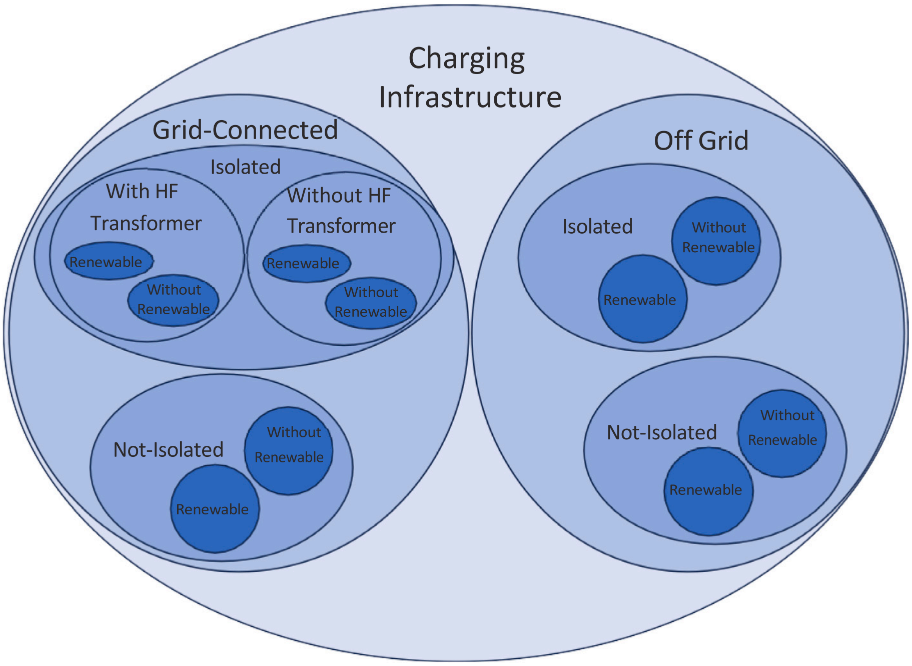


Fig. 7. Set-theory representation of charging infrastructure characteristics.

and potentially lower efficiency. This concept has already been widely analysed for fast charger stations of electric vehicles in Tu et al. (2019). For example, in Fig. 7, a comparison in terms of encumbrance between high-frequency and low-frequency transformers is shown.

Integration of RES Integrating RES into charging infrastructure aligns with sustainability goals but introduces considerations related to intermittency, cost, and location constraints. Renewable sources such as solar or wind energy reduce greenhouse gas emissions and offer long-term cost savings. However, they are subject to intermittency, depending on weather conditions, which may impact charging station reliability. Additionally, the initial setup costs for integrating RES can be higher, and their suitability varies based on geographic location (Krozer, 2013).

In conclusion, the design and implementation of charging infrastructure for micromobility require careful consideration of technical factors such as grid connectivity, isolation, transformer type, and the integration of RES. Each decision carries its own set of advantages and disadvantages, impacting safety, reliability, scalability, and sustainability. By comprehensively evaluating these considerations, stakeholders can develop charging infrastructure solutions that effectively meet the needs of micromobility users while contributing to sustainable urban transportation systems.

According to the previous analysis, five main different electrical structures of charging stations can be identified, as shown in Fig. 8. The arrows indicate the power flows within the circuit. The black colour is used for unidirectional flows, and the red one for bidirectional flows. If a converter can be chosen with both unidirectional and bidirectional power flows, according to the system's requirements, both the colours and arrows are shown.

The structure shown in Fig. 8(a) does not have a grid connection. A renewable resource is present to ensure autonomy (in Fig. 8(a), photovoltaic power sources were assumed to be used). In general, the DC–DC converter interfacing with the Renewable Energy Source (RES) is unidirectional, with power flowing from the source to the load or battery. On the other hand, the converter connected to the Energy Storage (ES) must be bidirectional. This allows the ES to be recharged when RESs generate power but no loads need to be supplied. It also allows the energy stored in the ES to be used to supply loads when RESs do not generate enough energy. The architecture shown in Fig. 8(b) provides the connection to the grid via a low-frequency (LF) transformer, usually at 50/60 Hz. These transformers are typically characterized by large weights and volumes. The amplitude of the grid AC voltage is reduced and subsequently rectified by means of an AC–DC converter. The power flow of this converter can be unidirectional or bidirectional. The choice of bidirectionality allows energy to be fed into the grid if it is more cost-effective than keeping it in the battery. This possibility plays a key role, especially in the emerging energy communities (Lowitzsch et al., 2020). The architecture shown in Fig. 8(c) has the same characteristics as the structure shown in Fig. 8(b) but a renewable energy generation system is present. This complicates energy flow management but increases the autonomy of the entire system. The structure depicted in Fig. 8(d) exploits a high-frequency transformer. As discussed in Tu et al. (2019), this results in a higher power density and allows the size of the whole system to be smaller. Finally, the structure shown in Fig. 8(e) has the main characteristics of Fig. 8(d) with the addition of the renewable energy source. To perform a comparison between different solutions, five aspects have been identified as follows so that the best solution depending on the scenario in which the charging infrastructure will have to operate is identified. Fig. 9, shows a radar plot which visually summarizes the characteristics of each solution.

- Efficiency: All the schemes shown in Fig. 8 consist of a cascade of blocks. Each block is characterized by a conversion efficiency, therefore, the system efficiency results as the product of chain of efficiency. It is therefore apparent that a structure that employs more converters operates at a lower overall efficiency than those with a lower converter number. For this reason, architectures (a), (b) and (c) result in higher efficiencies than solutions (d) and (e).
- Flexibility: This parameter considers the ease with which a certain infrastructure can be deployed in different scenarios. Architecture (a) turns out to be the most flexible solution as it does not require connection to the power grid and its dimensions are usually contained. For this reason, it is easily implemented even in hard-to-reach environments, such as mountainous environments. Architectures (d) and (e) turn out to be less flexible than architecture (a) because they require grid connection, but the presence of the high-frequency transformer allows a significant reduction

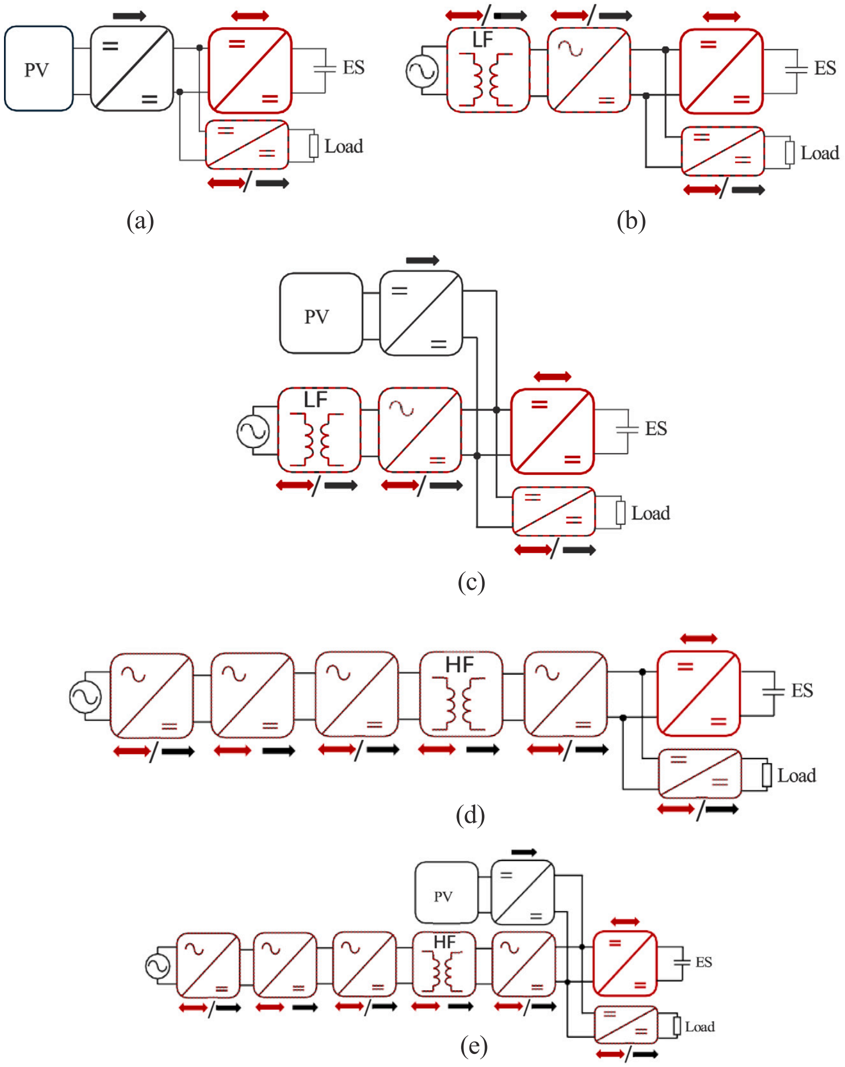


Fig. 8. Different architectures. (a) Non-isolated infrastructure with renewable source.(b) Low-frequency transformer isolated infrastructure. (c) Low-frequency transformer isolated infrastructure with renewable source. (d) High-frequency transformer isolated infrastructure. (e) High-frequency transformer isolated infrastructure with renewable energy source.

in footprint, enabling their use even in remote areas. Finally, the most bulky and difficult-to-place solutions are architectures (b) and (c).

- Energy Autonomy: This parameter takes into account each architecture availability. The grid connection provides greater assurance of service continuity (Zha et al., 2022). If production from a renewable source is added to this, one can make up for any blackouts by taking advantage of the energy that has been produced and stored (Chobanov, 2016). Therefore, solutions (c) and (e) are the most robust, followed by solutions (b) and (d), which have no renewable generation. The architecture that provides the least energy autonomy is the solution (a) since, it does not present a grid connection. In case of failure of the renewable energy production system, service continuity is lost.
- Low Cost: This parameter takes into account the cost of the entire infrastructure. Given its simplicity, the least expensive solution is definitely Solution (a). Solution (b) is more expensive than (a), but less expensive than solution (c), as it does not include the use of the renewable source. Finally, the most expensive solution is represented by solution (e).
- Safety: Electrical safety is crucial, therefore, assuming that all architectures must ensure adequate levels of security which is assumed to be ensured by all the architecture, referring to international standards. However, one can identify in architecture (a) the architecture that requires more risk countermeasures.

Table 6
Score assignment to each configuration analysed.

Scheme	7(a)	7(b)	7(c)	7(d)	7(e)
Efficiency	5	4	4	3	3
Safety	1	3	3	3	3
Costs	5	3	2	2	1
Energy Availability	1	3	4	3	4
Flexibility	5	3	3	4	4

Each of the five aspects has been assigned a score from 1 to 5, where increasing values correspond to better performance based on the aspect under consideration. Table 6 shows the results obtained from the various configurations while Fig. 9 shows a radar plot which visually summarizes the characteristics of each solution. As shown by the analysis performed, none of the architectures is unequivocally better than the others, indicating that the choice must be evaluated on a case-by-case basis depending on the scenario and conditions.

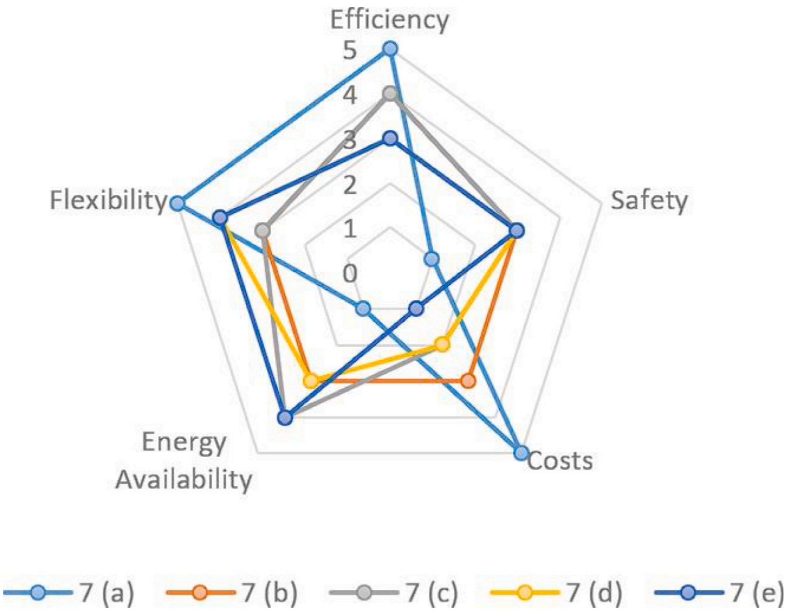


Fig. 9. Comparison between different infrastructures.

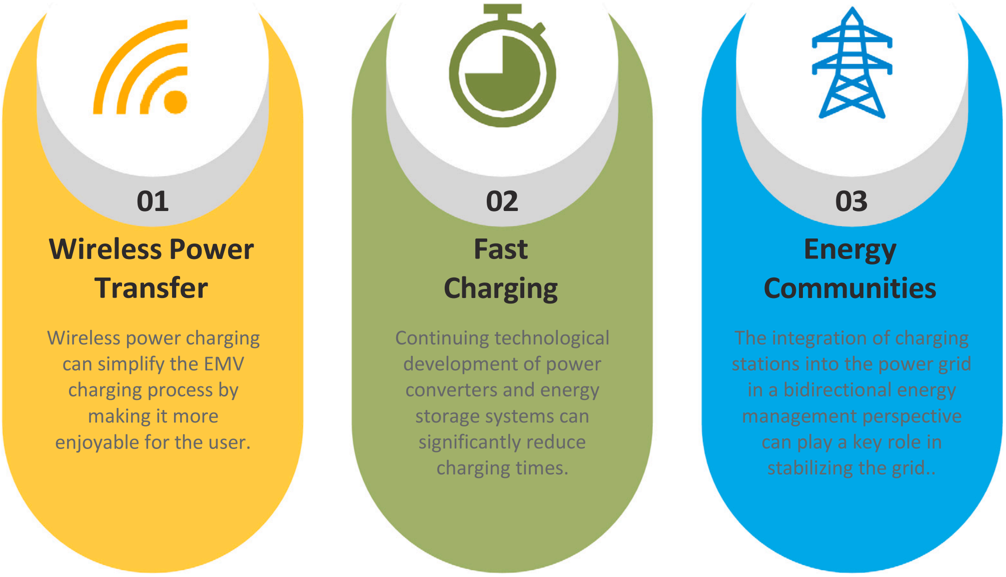


Fig. 10. Emerging trends for micromobility.

7. Emerging trends

In this Section, the emerging trends for micromobility charging infrastructure are discussed. In Fig. 10, the three main emerging trends for EMVs charging stations are shown.

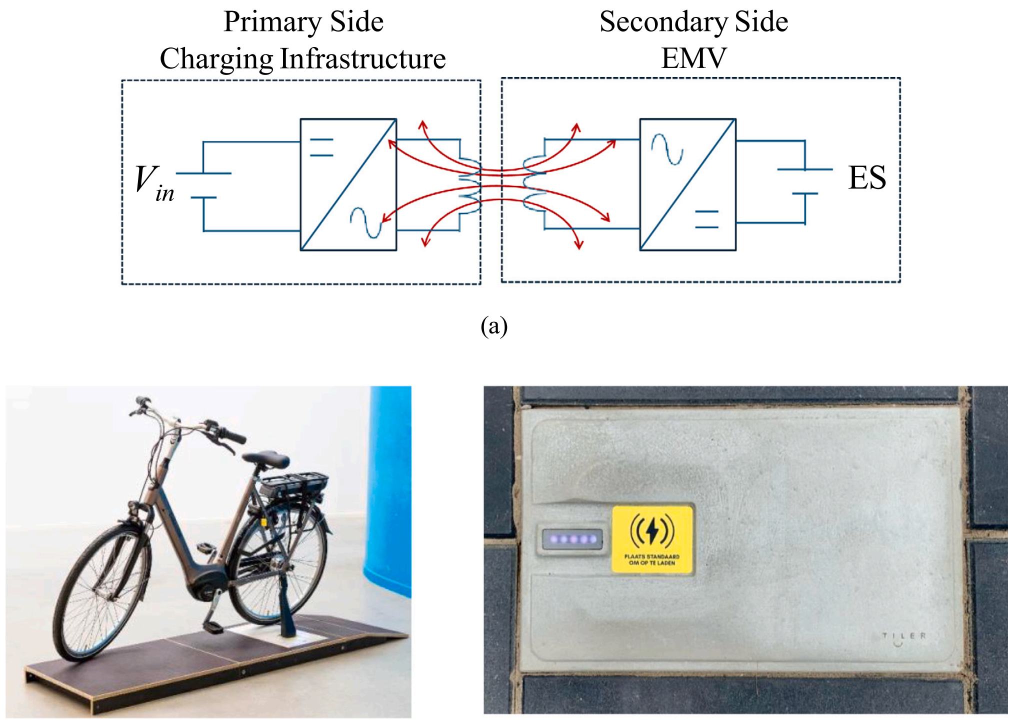
7.1. Wireless power transfer

Analysing recent work available in the literature, it is possible to understand that wireless charging of EMVs is rapidly gaining momentum. WPT eliminates the need for physical connectors and plugs, resulting for users in a much more useable charging system for micromobility. Users can simply park their vehicles over a charging pad or within a designated area and have them automatically charged without any manual intervention. In Fig. 11(a) the principle of operation is shown. A primary coil is supplied by an alternating current generating a variable magnetic field. When a secondary coil is placed close to the primary coil, a voltage is induced, allowing for the power transfer.

Since there are no physical connectors involved, WPT can help increase the availability, durability, and longevity of micromobility devices. Physical connectors are prone to wear and tear over time, leading to potential damage or malfunctions. WPT technology reduces the maintenance costs for charging infrastructure over time and makes the system particularly beneficial for municipalities or businesses managing large fleets of micromobility devices (Corti et al., 2020; Reatti et al., 2017).

This interest is confirmed by several works available in the literature. In Table 7, papers that propose a wireless charging infrastructure for EMVs are summarized. This topic is relatively new and is still in the research phase, but several works already prove the WPT feasibility through experimental prototypes. Some solutions are already available in the market, as the system proposed by Tiler and shown in Fig. 11(b) and (c).

Yet, in this regard, several aspects related to low-power electric vehicles like e-bikes need to be more accurately addressed. A comprehensive discussion is given in Joseph et al. (2020). The use of PV



(a)

(b)

(c)

Fig. 11. Wireless power charger for e-bikes. (a) Principle of operation. (b) The system proposed by Tiler, accessed on 05.03.2024 https://www.tilercharge.com/product. (c) Primary side proposed by Tiler.

power for the charging station is assumed. This entails the necessity of converting the DC PV-generated input power into high-frequency AC on the transmitter side. In the paper, it is stated that the requests of high tolerance to misalignment and high distance effective wireless power transfer lead to adopt the series-series (SS) compensation for the inductions in the coupled coils. However, this topology is affected by reverse current flow in the system. To prevent this, a reverse blocking diode can be used, but this affects the power transmission efficiency, which is a major drawback in the case of low-power applications, such as e-bikes. Based on this, in Joseph et al. (2020), a coil tuning mechanism is proposed to mitigate the reverse current flow and a linear closed-loop control mechanism is used to regulate the output at the desired voltage (which is fundamental in the case of e-bikes).

There are several studies in the literature which are specifically devoted to advances in the system design (which is one of the topics addressed as well in Joseph et al. (2020)). Some meaningful examples are the following: they are focused on the analysis of the overall efficiency of the system, which is well known to be a critical point for WPT. In Triviño-Cabrera et al. (2021), the focus is on the design of a wireless power transfer, which might be appealing in the market for an e-bike. Firstly, weight and physical stability are critical for an e-bike and thus heavy power components should be avoided in the secondary structure. Furthermore, the effect of the surrounding materials should be taken into account. Finally, the control should be effective and simple and the maintainability must be minimized. Experimental validation of the proposed design is conducted, and it is concluded that interfering materials impact the efficiency during the complete charge. The work in Pellitteri et al. (2020) deals with a wireless power transfer for e-bike charging based on induction. Modelling, design, simulation and experimental results of this prototype are provided. A maximum total power transfer efficiency of 79% is achieved. In Genco et al. (2019), an analysis of the design of the coupled coils is conducted through the Ansys Maxwell software. The addressed issues are the number of turns of the coils, then the response of the system at a variable frequency is analysed, and finally, the behaviour of the system in case of misalignment is studied. An overall efficiency in the order of 95% is achieved with a 0.7 cm air gap and 8 turns for each coil. Another important issue for the WPT technology is how to switch from a constant output current to a constant output voltage operation, depending on the state of charge of the e-bike battery. In Chen et al. (2019), the selected solution is a hybrid two-/three-coil topology, which is designed through the Ansys Maxwell software and then tested in the laboratory. The rationale is that the system realizes constant current output with the two-coil topology and constant voltage output with the three-coil topology. In Liu et al. (2019), a three-coil topology is proposed and the switching from constant current to constant voltage mode is achieved with two AC switches utilized at the transmitter side. Furthermore, the work in Liu et al. (2019) deals also with the load identification in order to switch appropriately from constant current to constant voltage and a method based on the active power calculation is proposed.

The work in Afonso et al. (2020) deals with a technological challenge related to the dynamic inductive power transfer for e-bike charging stations: namely, a wireless communication and management system which serves for vehicle authentication, energy consumption accounting, and user account management.

Finally, we refer to some meaningful review papers addressing specifically the challenges related to WPT applications for e-bike charging stations. The work in Joseph and Elangovan (2018) deals in general with light electric vehicles. Most critical aspects are common to the specific case of e-bikes, but some are peculiar to the case of e-bikes and in that review, those are briefly discussed. As mentioned also above in this Section, a critical point for low-power WPT applications is the trade-off between system efficiency and transfer distance. The discussion conducted in this Section highlights that relevant progress on this point are ongoing since the review in Joseph and Elangovan (2018) was conducted and published (year 2017). In Shrestha et al. (2023), a more recent review on wireless power transfer applications for e-bikes is conducted. An interesting consideration in this paper is that most studies focus on inductive power transfer, while a capacitive power transfer might be convenient for e-bikes because of its inherent

Table 7
Papers regarding wireless power transfer for e-bikes charging stations.

Ref.	Architecture	Renewable energy source	WPT	Power rating	DC–DC converter	Experimental test
Joseph et al. (2020)	Off-grid	PV	Yes	96 W	–	Yes
Triviño-Cabrera et al. (2021)	Grid-connected	No	Yes	84 W	–	Yes
Pellitteri et al. (2020)	Grid-connected	No	Yes	300 W	–	Yes
Genco et al. (2019)	Grid-connected	No	Yes	–	–	Numerical simulations
Chen et al. (2019)	Grid-connected	–	Yes	–	–	Yes
Liu et al. (2019)	Grid-connected	–	Yes	190 W	–	Yes
Afonso et al. (2020)	–	–	Yes	–	–	–
Joseph and Elangovan (2018)	–	Yes	Yes	–	–	–
Shrestha et al. (2023)	Grid-connected	Not specified	Yes	–	–	–
Shanmugam et al. (2022)	Grid-connected	PV	Yes	–	–	–
Gomaa et al. (2023)	Grid-connected	PV and Fuel Cell	Yes	–	Review on DC–DC converters	–

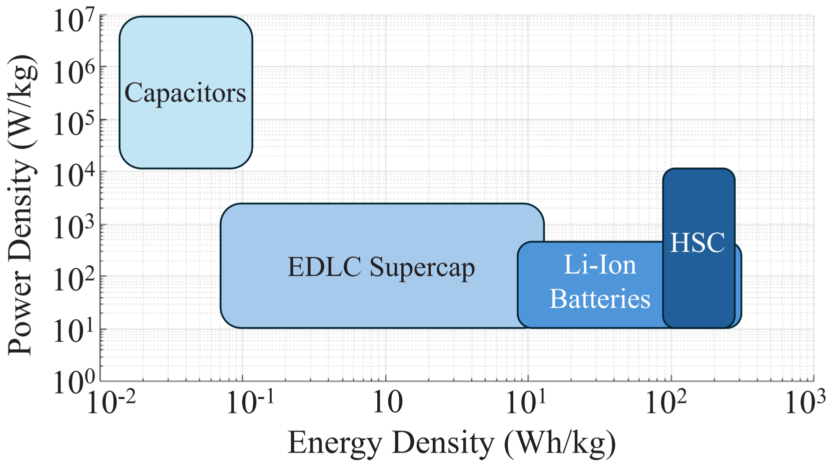


Fig. 12. Energy density and power density of different energy storage technologies.

low costs and low weight. The main drawback is the lower efficiency and the lower power capacity than inductive power transfer. However, the balance between pros and cons might be favourable in low-power applications like e-bikes. In Shanmugam et al. (2022), a systematic review of dynamic wireless charging systems for electric vehicles, in general, is conducted. The parameters involved in grid-connected and PV-powered systems are discussed, through a step-by-step discussion.

7.2. *Faster charging technologies*

One of the main limitations of electric micromobility infrastructure and transportation systems is the long charging time, which is due to the energy storage technology. In Fig. 12 the energy density and the power density of the main energy storage technologies currently available in the market are shown.

The limited power density of the energy storage does not allow fast battery charging because this would lead to significant cell overheating. Currently, most of the energy storage exploits Lithium-Ion batteries. Industries and academia currently aim to research alternative battery chemistry, such as solid-state batteries (Deng et al., 2020) or Lithium-Sulphur batteries (Manthiram et al., 2015), that could potentially lead to faster charging times than traditional Lithium-Ion batteries. In addition, enhancements in thermal management systems within batteries can improve their efficiency and allow for faster charging without overheating. Implementing intelligent charging algorithms that optimize charging protocols based on factors like battery health (Pelosi et al., 2023), temperature and power delivery capabilities can both reduce charging times and ensure battery longevity. Other studies are currently proposing Electric Double-Layer Capacitors (EDLC), also called Supercapacitors, as an alternative solution to Lithium Ion batteries (Berrueta et al., 2019). Supercapacitors deliver and store energy much faster than batteries, and, therefore they represent an ideal solution for applications requiring rapid energy discharge and recharge, such as regenerative braking in electric vehicles (Reddy et al., 2023). Moreover, they have a longer life cycle than batteries, with hundreds of thousands to millions of charge–discharge cycles available (Kim et al., 2016). This durability makes them suitable for applications where frequent charging and discharging are required. Supercapacitors do not suffer from the same degradation issues as batteries, such as capacity fade or memory effect. This means that they require minimal maintenance over their lifetime, reducing operational costs. One of the main limitations of nowadays supercapacitors is their limited power density (Morandi

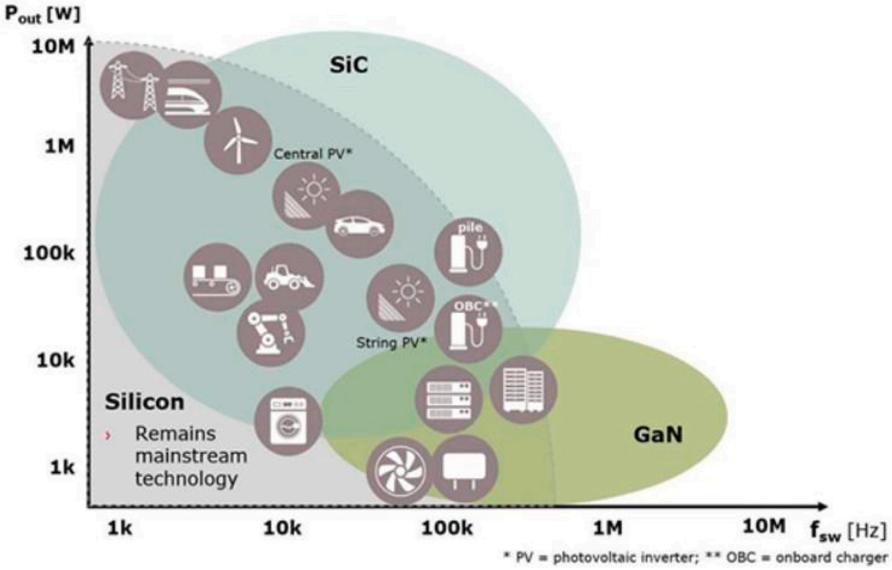


Fig. 13. Potential applications of Si, SiC, and GaN devices.
Source: Image Courtesy: Infineon. Source: https://www.digikey.com/en/articles/wide-bandgap-semiconductors-are-reshaping-the-transportation-world.

et al., 2021). To overcome this limitation and obtain performance similar to Li-Ion batteries, hybrid supercapacitors have been recently developed (Catelani et al., 2023; Corti et al., 2023b). For example, their use to speed up the charging process has already been analysed in Corti et al. (2023a), highlighting their promising performance. Therefore, in the near future, the use of different technologies could be used as a replacement for Li-Ion batteries or in combination with them to speed up the charging process.

Furthermore, the above issues need to be conceived in the presence of high penetration of renewables. This advocates non-trivial efforts in the optimal sizing of the BESS and PV systems (Leone et al., 2022).

7.3. Wide bandgap devices

At the core of contemporary power electronics converters lie power semiconductor devices. Contrasted with the mature and deeply entrenched silicon (Si) technology, which has undergone numerous generations of refinement over the past five decades and is nearing its material theoretical boundaries, the emerging wide-bandgap (WBG) power semiconductor devices hold the potential to transform forthcoming generations of power electronics converters (Waheed et al., 2024). WBG devices, such as silicon carbide (SiC) and gallium nitride (GaN) transistors, offer several advantages for power-switching converters compared to traditional silicon-based devices. WBG devices typically have lower switching losses and reduced conduction losses compared to silicon-based devices. This leads to higher overall efficiency in power conversion systems (Buffolo et al., 2024). The higher efficiency and higher frequency operation of WBG devices enable the design of smaller and lighter power converters, which is particularly advantageous in applications where size and weight constraints are critical, such as in electric vehicles and aerospace systems. WBG devices often exhibit better reliability and durability characteristics compared to silicon-based devices, especially in harsh operating environments such as high temperatures, high voltages, and high switching frequencies. This can lead to longer system lifetimes and reduced maintenance requirements.

As illustrated in Fig. 13, certain applications demonstrate optimal performance with SiC and GaN, while others exhibit characteristics that align with silicon. Frequently, GaN devices prove most effective in high-frequency applications, while SiC devices show significant potential in high-voltage scenarios.

These emerging technologies offer several benefits specifically tailored to micromobility electric charging stations:

- Compact Design: Space is often at a premium in urban environments where micromobility charging stations are located. WBG devices allow for the design of smaller and more compact charging stations due to their higher power density, enabling more charging points to be installed in limited spaces (Buffolo et al., 2024).
- Fast Charging: Micromobility charging stations may need to support fast charging to accommodate the short turnaround times demanded by users. WBG devices, with their ability to switch at higher frequencies, facilitate the design of fast-charging systems that can quickly replenish the batteries of electric vehicles without compromising efficiency or reliability (Ertugrul, 2024).
- Reduced Cooling Requirements: Cooling is essential for maintaining the optimal operating temperature of power electronics components in charging stations. WBG devices, with their ability to operate efficiently at higher temperatures, can reduce the cooling requirements of charging stations, leading to smaller and more cost-effective cooling solutions (Shenai, 2019).
- Lower Operating Costs: The higher efficiency and reliability of WBG-based charging stations result in lower operating costs over the lifetime of the infrastructure. Reduced energy losses and maintenance requirements contribute to overall cost savings, making WBG devices an economically viable choice for micromobility charging infrastructure (Lencwe et al., 2024).

In summary, WBG devices offer tailored advantages for micromobility electric charging stations, including higher efficiency, compact design, fast charging capabilities, high reliability, scalability, reduced cooling requirements, and lower operating costs, making them an ideal choice for powering the next generation of urban transportation solutions.

7.4. Energy communities

The emerging use of grid-connected micromobility charging infrastructure within energy communities offers several benefits and can be highly useful. Energy communities often leverage RES such as solar or wind power (Caballero et al., 2023; Amato et al., 2022).

Grid-connected micromobility charging infrastructure can be integrated with these renewable energy systems, allowing for cleaner and more sustainable charging of electric micromobility vehicles (Deng et al., 2023).

By incorporating micromobility charging infrastructure into energy communities, operators can implement load management strategies and demand response mechanisms. This enables them to schedule charging during off-peak hours or when renewable energy generation is high, optimizing energy usage and reducing strain on the grid during peak times (Soeiro and Dias, 2020).

Micromobility vehicles equipped with V2G technology can not only draw power from the grid but also feed excess energy back into the grid when needed. This bidirectional energy flow helps to stabilize the grid (Saldarini et al., 2023), supports renewable energy integration, and provides additional revenue streams for vehicle owners within energy communities (Manso-Burgos et al., 2022).

Integrating micromobility charging infrastructure into energy communities enhances overall energy resilience by diversifying energy sources and promoting decentralized energy generation and distribution. This can help to mitigate the impact of grid disruptions or outages, ensuring continued access to charging facilities for micromobility users (Guo et al., 2022).

8. Discussion

The conducted analysis shows the specific points which are explicitly related to the charging stations for electric micromobility rather than to electric mobility in general. Two of such most important points are the different order of magnitude of the requested power and the lack of standards as regards the requested output voltage. These two matters of fact on the one hand imply an advantage, in the sense that the impact of EMVs on the distribution grid is in general modest. On the other hand, from the users' point of view, there can be dissatisfaction related to the quality of the service, which might be insufficient due to the inefficiency brought by the various stages of power conversion, especially in the case of high penetration of renewables.

Actually, the concept of EMV is strictly intertwined with that of environmental sustainability. The acceptance of EMV technology by a considerable amount of users is strictly related to how evident the reduction of carbon footprint is. This advocates an exploitation of RES which should be as massive as possible to sensibly diminish GHGs emissions. Yet, the exploitation of RES poses several issues, related to their intermittent nature, the architecture of the charging station, the design of the charging station, and the efficiency of the various stages of the power flow.

The studies in the literature deal quite symmetrically with off-grid and grid-connected architectures, while most commercial solutions at present in the market are grid-connected. Grid-connected stations are expected to provide a stabler availability of the service, but in general, require significant upfront investment and infrastructure to connect to the electricity grid. Furthermore, although e-bikes in general constitute a modest electrical load, an over-exploitation of grid-connected charging station architectures might affect the smooth functioning of the electrical grid (Miraftabzadeh et al., 2023; Ali et al., 2022). Off-grid solutions, such as PV-powered stations, result in lower costs because they are not connected to the grid and are suitable to be employed in remote areas. However, they require storage devices and accurate planning and management of energy. A recent relevant trend is the integration of EMVs charging station into energy communities, which has been discussed in Section 7.3. The advantage is that operators can implement load management strategies and demand response mechanisms, but this calls for even more judicious planning of the system operation and for the development of adequate ICT technologies and smart charging algorithms (Afonso et al., 2020).

The limited power demand of the EMV technology opens specific perspectives on the selection of the transformers. The use of high-frequency transformers is more appropriate in the context of EMVs than EVs in general. Actually, their main drawback is the limited power handling capacity. However, this might not be an excessive problem if the electrical load as well is limited (as in the case of e-bikes). Furthermore, they are attractive because of their high efficiency, which means improved sustainability. Low-frequency transformers, instead, are more versatile in load management but result in large volumes which limits their applications in restricted areas.

The above issues regarding transformer technology are connected to one of the most important factors limiting the diffusion of EMVs, which is the charging time, as demonstrated by the growing scientific literature on fast charging technology (Section 7.2). Another crucial point related to EMV charging is the users' experience when wired connections are compared with wireless power transfer-based solutions. It is reasonable to expect that wireless power transfer will become the leading technology for EMV charging in the upcoming years. The literature is still at an early stage and there are no consolidated standards dealing, for example, with the switching from constant current to constant voltage charging mode. The low power demand of EMVs opens scientific and technological perspective which are peculiar to this sector of EV, which have been discussed in Section 7.1.

9. Concluding remarks

In this paper, the main aspects that characterize a charging station for EMVs were comprehensively analysed, filling a gap in the literature. It was argued that further development of charging station technology is fundamental to overcome the barriers which have been limiting the spread of EMVs.

From the review of the scientific literature, it has been highlighted that there are two main aspects which in the near future should be analysed more in deep:

- The real-world assessment of fully sustainable charging stations powered by renewables, especially in the case of off-grid architecture.
- The development of a comprehensive framework which effectively assesses the EMV charging infrastructure from the point of view of environmental and financial sustainability, users' satisfaction or dissatisfaction, and impact on the traffic and on the electrical grid. Actually, the literature review conducted in this paper leads to argue that mainly only one aspect at a time is analysed.

Differently, with respect to the scientific literature, which explores various types of charging station architectures, the survey of the commercial solutions shows that the grid-connected architecture is by far the most exploited for real-world applications. Furthermore, it has been observed that the renewable energy source mostly exploited in the context of EMV charging stations is PV, while there are very few examples of micro-wind systems integration. This is mainly due to the fact that the wind resource is not uniformly distributed in the territory, and it is nearly unavailable in urban environments, while the solar irradiance is more uniformly distributed.

This matter of fact has practical implications in the structure design of the charging station. The typical structure which can host a sufficient amount of PV panels, especially in the case of off-grid operation, is the hub, although its cost is evidently higher than simple racks.

Despite the above summarized common ground, from some points of view, it can be argued that there is no one-size-fits-all solution for the design of EMV charging stations. Indeed, the selection of most of the technical options depends on the exploitation scenarios, which are considerably different, say, in the case of green tourism or in the case of commuting to the workplace. Based on the conducted analysis, in any case, the following criteria for charging station design can be identified:

- At first, achieving the desired Quality of Service (which primarily means users' satisfaction) in the various scenarios, which by itself requires a non-trivial analysis;
- Secondarily, satisfying the diversified users' expectations, which might deal with financial returns or, on the other way round, with explicitly full sustainability.

Differently with respect to what might appear at first glance, a common ground connecting the above-listed diversified scenario of priorities can be identified, which is the development of fully sustainable smart charging stations powered by renewables. Despite the real-world implementations still do not belong to such a paradigm, it is straightforward to argue that it will dominate in a few years, provided that the emerging scientific and technological trends (discussed in Section 7) related specifically to the low power demand of EMVs will have been successfully addressed.

CRediT authorship contribution statement

Fabio Corti: Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Salvatore Dello Iacono:** Visualization, Formal analysis, Conceptualization. **Davide Astolfi:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Marco Pasetti:** Supervision, Resources, Methodology. **Antony Vasile:** Writing – original draft, Visualization, Supervision. **Alberto Reatti:** Writing – review & editing, Validation, Supervision, Resources. **Alessandra Flammini:** Supervision, Resources, Project administration.

Data availability

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

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fabio Corti, Salvatore Dello Iacono, Davide Astolfi, Marco Pasetti, Antony Vasile, Alberto Reatti, Alessandra Flammini reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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