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Smart and connected charging systems for electric bicycles: a review of IoT monitoring, predictive charging, and grid integration

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ABSTRACT

The growing adoption of electric bicycles (e-bikes) creates opportunities for connected charging services, but also raises questions about battery visibility, charging demand uncertainty, communication reliability, and distribution-grid coordination. Internet of Things (IoT) technologies can connect sensors, chargers, users, operators, and energy-management platforms to support remote monitoring and controlled charging. This review examines smart and connected e-bike charging through five linked themes: IoT architectures, remote battery and charger monitoring, predictive charging, communication technologies, and grid integration. Direct e-bike studies demonstrate the feasibility of networked energy monitoring and solar-assisted charging stations, while much of the forecasting and grid-control literature is derived from larger electric-vehicle applications. The review evaluates how state-of-charge estimation, usage histories, travel patterns, weather, tariffs, and local grid conditions can inform charging predictions and scheduling. It also discusses communication interoperability, cybersecurity, privacy, and the limits of vehicle-to-grid operation for small e-bike batteries. The analysis identifies a need for standardized e-bike charging interfaces, validated low-cost prediction models, and coordinated control strategies that reflect the dispersed and relatively small loads of e-bike fleets. These priorities provide a pathway toward safer, more reliable, and grid-responsive charging services.

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1. INTRODUCTION

Electric bicycles (e-bikes) have become an important component of sustainable urban mobility because they provide electrically assisted transportation with relatively low energy requirements. Their increasing use creates a corresponding need for accessible, reliable, and safe charging facilities. Conventional charging arrangements generally provide limited information about battery condition, charging progress, energy consumption, and charger availability. These limitations can make it difficult for users and charging operators to coordinate charging activities efficiently.

Smart and connected charging systems offer an opportunity to address these problems through the integration of sensing devices, communication networks, cloud platforms, and intelligent control. Internet of Things (IoT) technologies enable charging equipment and battery-monitoring devices to exchange operational information with users and service providers. Research on a CANopen-based gateway for e-bikes demonstrates how communication and energy monitoring can be integrated into an e-bike system [1]. Similarly, a solar-powered e-bike charging station incorporating AC, DC, and wireless charging illustrates the potential for combining charging infrastructure with more advanced energy-management functions [2].

Despite these developments, the research landscape remains fragmented across vehicle monitoring, charging-demand forecasting, communication protocols, and grid coordination. Many predictive charging and smart-grid studies focus on passenger electric vehicles, whose charging power, battery capacity, and usage patterns differ considerably from those of e-bikes [3]–[5]. Directly transferring these methods to e-bike

applications without adapting their assumptions may produce unsuitable charging schedules or unnecessary system complexity. This review therefore examines the technical relationships among IoT monitoring, remote supervision, predictive charging, communication, and grid integration, while identifying the specific research needs of connected e-bike charging systems.

2. IOT ARCHITECTURE FOR CONNECTED E-BIKE CHARGING

An IoT-based charging system can be organized into four functional layers: sensing, communication, data processing, and application. The sensing layer collects electrical and operational parameters, including battery voltage, current, temperature, charging status, and estimated state of charge (SoC). The communication layer transfers these measurements between the charger, bicycle, gateway, and remote platform. The processing and application layers analyze the received information and present useful services through dashboards, mobile applications, or charging-management interfaces.

At the device level, microcontrollers and embedded communication modules can collect measurements from battery-management systems and charging circuits. A gateway can combine information from multiple bicycles or charging outlets and transmit it to a local server or cloud platform. Bui *et al.* [1] demonstrated a CANopen-based gateway and energy-monitoring system specifically for electric bicycles, showing the relevance of structured communication within the vehicle ecosystem. Broader IoT-based smart-grid research also identifies layered architectures as an effective way to connect distributed devices with monitoring and energy-management applications [6], [7].

The architecture should distinguish between functions that require immediate local responses and those that can be performed remotely. Protection against excessive current, abnormal temperature, and unsafe voltage conditions should remain operational even when internet connectivity is interrupted. Cloud services are more appropriate for historical analysis, user notifications, charging forecasts, and coordination among multiple stations. This separation improves operational resilience because communication failure does not automatically disable essential battery-protection functions.

3. REMOTE MONITORING AND OPERATIONAL MANAGEMENT

Remote monitoring allows users and charging operators to observe charging conditions without continuously accessing the physical charger. Important parameters include charging voltage, current, power, accumulated energy, battery SoC, temperature, charging duration, and charger availability. These measurements can be displayed through a mobile application or web dashboard, allowing users to estimate charging progress and identify abnormal operating conditions. For operators, aggregated monitoring data can support maintenance planning, equipment utilization analysis, and identification of recurring charging problems.

The quality of remote monitoring depends on measurement accuracy, sampling frequency, data transmission reliability, and the correct interpretation of battery information. Voltage and current measurements can describe charging behavior, but they do not independently provide a complete assessment of battery health. More advanced systems can combine electrical measurements with temperature, operating history, and battery-management-system information to improve condition assessment. Research on electric-vehicle IoT monitoring and charging-station recommendation demonstrates how connected measurements can support real-time information services and user-oriented charging decisions [3].

Remote monitoring also introduces cybersecurity and privacy requirements. Unauthorized access to charging equipment could potentially alter charging commands, expose user information, or interrupt charging services. Communication channels should therefore use authentication, access control, encrypted data transmission, and secure device configuration. Smart-grid communication reviews identify security, interoperability, reliability, and network performance as important considerations when connecting distributed energy devices [6]–[8].

4. PREDICTIVE CHARGING AND DEMAND FORECASTING

Predictive charging uses historical and real-time information to estimate when, where, and how much charging energy will be required. For e-bikes, useful input variables include battery SoC, previous charging sessions, travel distance, daily usage patterns, user departure times, and expected journey requirements. Weather conditions and local electricity tariffs can provide additional information when charging facilities are connected to renewable generation or time-dependent electricity pricing. These variables can help a charging controller determine suitable charging times and reduce unnecessary energy consumption.

Statistical forecasting, time-series analysis, machine learning, and deep learning are potential approaches for predicting charging demand. Statistical methods can provide interpretable forecasts when charging behavior is relatively stable, while machine-learning methods can identify more complex relationships among user behavior, time, location, and charging demand. Zhu *et al.* [9] compared deep-learning methods for short-term EV charging-load forecasting using real charging-station data. Calearo *et al.* [10] reviewed EV load datasets and modeling approaches, emphasizing the importance of data availability and model selection for reliable forecasting.

For e-bike applications, prediction should operate at both individual and station levels. Individual prediction estimates the remaining energy requirement of a particular bicycle, while station-level prediction estimates the aggregate demand expected across several charging outlets. The two forecasts can support different decisions, such as notifying a user when charging is recommended or allocating available power among connected bicycles. IoT-based forecasting and charging-station recommendation research provides a foundation for such services, although its methods require adaptation to e-bike travel patterns and smaller charging loads [3], [11].

Predictive charging should not be confused with simply delaying charging until electricity demand is low. A useful system must respect user departure times, minimum required battery energy, battery charging limits, and the availability of charging outlets. Forecast errors should also be considered because inaccurate predictions may leave users with insufficient battery energy or cause unnecessary charging during peak periods. Consequently, e-bike charging models should be evaluated using real operating data from different users, battery types, locations, and seasons.

5. COMMUNICATION TECHNOLOGIES AND INTEROPERABILITY

Communication technologies connect e-bikes, charging stations, cloud services, and electricity-system operators. Short-range technologies such as Bluetooth and Wi-Fi can support communication between a bicycle, a smartphone, and a nearby charging controller. Cellular networks are useful when bicycles or charging stations require remote connectivity across wider geographic areas. For distributed charging facilities, low-power wide-area communication may also be considered when the data rate is modest and long communication range is important.

The communication protocol should be selected according to range, latency, energy consumption, reliability, network coverage, and implementation cost. MQTT and CoAP can support lightweight IoT messaging, while HTTP-based interfaces are widely used for web applications and cloud services. CANopen is relevant to communication among embedded components in an e-bike system, as demonstrated by Bui *et al.* [1]. Broader smart-grid communication research emphasizes that protocol selection must account for device constraints, network topology, interoperability, and security [7], [8].

Interoperability is particularly important when charging stations serve bicycles from different manufacturers. Proprietary connectors, inconsistent data formats, and incompatible battery-management interfaces can prevent charging equipment from exchanging essential operational information. Research on electric-vehicle charging communication identifies the need for coordinated information exchange among vehicles, charging infrastructure, and network operators [12]. For e-bikes, a practical interoperability framework should define minimum requirements for battery identification, charging status, electrical limits, authentication, and fault reporting.

6. INTEGRATION WITH THE ELECTRICITY GRID

Connected e-bike charging stations can become manageable electrical loads when their operating status and expected demand are communicated to an energy-management system. Uncontrolled charging may create simultaneous demand peaks when many users connect their bicycles at similar times. Coordinated charging can distribute this demand over available time periods while respecting user requirements and equipment constraints. Research on distributed EV charging control shows that centralized, decentralized, and hierarchical scheduling approaches can be used to coordinate charging decisions among users, aggregators, and grid operators [13].

Smart charging can also respond to electricity prices, local transformer loading, renewable-energy availability, and building energy consumption. For example, a workplace charging facility may prioritize charging during periods of high rooftop PV generation or low building demand. A residential charging system may schedule non-urgent charging during off-peak tariff periods while preserving a minimum battery level for the next journey. Reviews of EV charging integrated with photovoltaic generation highlight the importance of coordinating vehicle demand with local energy production and consumption [14].

Vehicle-to-grid (V2G) operation allows electric vehicles to return stored energy to the electricity network through bidirectional power conversion and suitable control systems. However, V2G should not be assumed to be immediately practical for ordinary e-bikes because their battery capacities, charging interfaces, power electronics, and user requirements differ from those of larger electric vehicles. Bidirectional operation would require compatible chargers, battery-management systems, grid protection, communication arrangements, and appropriate commercial incentives. Previous V2G studies identify battery degradation, infrastructure costs, grid requirements, and communication as important factors affecting practical implementation [15]–[18].

For e-bike fleets, controlled unidirectional charging may therefore be a more realistic initial grid-support strategy than bidirectional energy export. Charging stations can reduce peak demand by adjusting charging start times and limiting aggregate power when the local network approaches its operating constraints. Aggregated e-bike charging loads may also provide flexibility for buildings, campuses, and commercial facilities. These applications require coordination between local charging controllers and building or distribution-level energy-management systems [13], [19].

7. COMPARATIVE ASSESSMENT AND RESEARCH CHALLENGES

Table 1 summarizes the principal functions, benefits, and implementation challenges of connected e-bike charging technologies. The comparison highlights that monitoring, prediction, communication, and grid coordination are interdependent rather than isolated functions [20]. A monitoring platform without reliable communication may provide incomplete information, while a prediction model without accurate battery data may generate unsuitable charging recommendations. The table also shows why local protection and user requirements must remain central to the system architecture.

Table 1. Key technologies and design considerations for smart and connected e-bike charging

Technology	Main function	Potential benefits	Main challenges
IoT sensors	Measure battery and charger parameters	Real-time operational visibility	Sensor accuracy and calibration
Remote monitoring	Display charging status and energy data	User convenience and maintenance support	Network availability and data security
Predictive charging	Estimate future energy demand	Improved scheduling and reduced peak demand	Data availability and forecast uncertainty
Machine learning	Identify usage patterns and charging behavior	Adaptation to complex demand patterns	Training data quality and model validation
CANopen, MQTT, CoAP, HTTP	Enable communication among devices and platforms	Data exchange and system connectivity	Interoperability and protocol selection
Smart charging control	Coordinate charging with user and grid requirements	Load management and improved energy utilization	User flexibility and distribution constraints
V2G capability	Enable bidirectional energy exchange	Potential grid-support services	Compatible hardware, battery impacts, and regulation

As shown in Table 1, the main research challenge is not simply connecting a charger to the internet, but developing a coordinated system that converts reliable data into safe and useful charging decisions. First, more direct experimental studies are required to evaluate IoT-enabled charging systems specifically designed for e-bikes rather than adapting passenger-EV models without validation. Second, shared communication and battery-interface requirements are needed to improve compatibility among chargers and bicycles from different manufacturers. Third, predictive models should be tested with diverse real-world e-bike datasets, including differences in battery chemistry, travel behavior, charging location, and user schedules [21].

Cybersecurity and data governance also require greater attention as charging infrastructure becomes increasingly connected. Charging operators should collect only the data necessary for service delivery and should protect personal travel information from unauthorized access. Local control should remain capable of enforcing electrical safety limits during communication interruptions or cloud-service failures. Future research should therefore combine embedded protection, edge computing, secure communication, and predictive energy management within a scalable architecture [22].

8. CONCLUSION

Smart and connected charging systems can improve the usability, safety, and operational efficiency of electric-bicycle charging infrastructure. IoT monitoring provides visibility into battery and charger conditions, while remote platforms support user notifications and maintenance management. Predictive

charging can use battery information, travel patterns, and historical charging records to improve scheduling and estimate future demand. Communication protocols provide the connectivity required to coordinate bicycles, charging stations, cloud platforms, and energy-management systems. Grid integration offers further opportunities through controlled charging, demand management, and coordination with renewable energy sources. However, V2G operation for e-bikes requires additional technical and economic validation and should not be treated as a standard capability of existing systems. The review identifies three priorities for future development: interoperable e-bike charging interfaces, validated prediction methods based on real e-bike data, and secure coordination between charging stations and local electricity networks. Addressing these priorities can support the development of reliable, user-oriented, and grid-responsive charging infrastructure for electric bicycles.

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