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Renewable energy-based charging systems for electric bicycles: a review of solar integration, power converters, and sustainable charging solutions

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ABSTRACT

The transition toward low-carbon mobility has increased interest in renewable energy-based charging systems for electric bicycles (e-bikes). Although e-bikes require substantially less charging power than electric cars, their environmental benefits depend partly on the electricity source and the efficiency of the charging infrastructure. Solar photovoltaic (PV) technology offers a practical option for supplying clean electricity, particularly in locations with suitable solar exposure and limited grid access. This review examines the integration of PV generation with e-bike charging systems, focusing on solar-powered architectures, maximum power point tracking (MPPT), power converter configurations, energy storage, and sustainability. Conventional MPPT methods, including perturb and observe and incremental conductance, are discussed alongside more advanced approaches. The review also evaluates DC–DC conversion, battery-buffered charging, and direct-current charging arrangements in relation to efficiency, complexity, and practical deployment. Particular attention is given to the intermittency of solar generation, battery management, system cost, and environmental impacts across the technology life cycle. The review identifies design priorities for reliable, efficient, and scalable solar-powered e-bike charging infrastructure.

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1. INTRODUCTION

Electric bicycles have become an increasingly relevant option for reducing transport-related energy consumption and urban emissions. Their relatively low power requirements make them suitable for integration with distributed renewable energy systems, including small photovoltaic installations. However, the environmental advantages of electric mobility are not determined by the vehicle itself alone, because the electricity used for charging also contributes to its overall environmental footprint. Charging e-bikes from electricity generated predominantly by fossil fuels can therefore reduce, but not eliminate, the environmental benefits associated with their operation.

Solar photovoltaic (PV) technology provides an opportunity to improve the sustainability of e-bike charging, particularly in residential areas, educational institutions, workplaces, public transport facilities, and remote communities. A PV-based charging station can supply electricity directly to an e-bike battery or deliver energy through an intermediate storage system. Chandra Mouli *et al.* [1] demonstrated a solar-powered e-bike charging station supporting AC, DC, and wireless charging, with integrated battery storage for grid-connected and off-grid operation. Earlier work also investigated the design of an electric bicycle charging station using PV generation and an energy-storage-supported DC bus [2].

Despite these developments, practical solar charging involves several interconnected engineering challenges. Solar irradiance and module temperature continuously affect PV output, while the charging battery requires controlled voltage and current. The system must therefore coordinate energy harvesting, power conversion, storage, and battery protection under changing operating conditions. Although renewable-energy charging infrastructure has received substantial research attention, the specific integration of these

functions for relatively low-power e-bike applications remains less comprehensively discussed than charging systems for larger electric vehicles [3], [4].

This review addresses that gap by examining the technical relationship between solar generation, MPPT, converter selection, energy storage, and sustainability in e-bike charging applications. It distinguishes direct e-bike research from broader PV and electric-vehicle studies whose findings can inform small-scale charging design. The objective is to identify practical system configurations and explain the trade-offs that influence their efficiency, reliability, affordability, and environmental performance. The resulting discussion provides a foundation for developing solar-powered e-bike charging systems suitable for both grid-connected and standalone applications.

2. SOLAR PHOTOVOLTAIC INTEGRATION FOR E-BIKE CHARGING

PV integration can be implemented through standalone, grid-connected, or hybrid charging architectures. In a standalone arrangement, the solar array supplies the charging system without relying on the utility grid, making it appropriate for remote locations and facilities with limited grid access. A grid-connected arrangement can use solar generation as the primary daytime energy source while obtaining supplementary electricity from the utility when solar production is insufficient. Hybrid systems combine PV generation, battery storage, and grid electricity to improve charging availability and operational flexibility [3], [4].

For e-bike applications, the PV array may be installed on a charging-station canopy, building rooftop, parking shelter, or other available structure. The charging station can provide several charging outlets and may accommodate different battery voltage ratings through regulated output stages. A direct DC arrangement can reduce conversion stages by transferring PV-generated electricity to the battery through an appropriate DC–DC converter and charging controller. The solar e-bike station proposed by Mouli *et al.* [1] illustrates the potential of combining direct DC charging with AC and wireless charging options.

The main limitation of PV-based charging is the mismatch between solar generation and charging demand. Solar output varies with weather, shading, orientation, and time of day, whereas users may require charging at any time. A charging station without sufficient storage may consequently experience periods of surplus generation and periods of inadequate supply. The review of renewable-energy-based charging infrastructure by Alkawsi *et al.* [3] similarly identifies renewable intermittency, system planning, and energy management as important considerations for reliable charging services.

3. MAXIMUM POWER POINT TRACKING

MPPT is essential because a PV module has a nonlinear current–voltage characteristic, and its maximum available power changes with irradiance and temperature. An MPPT controller continuously adjusts the electrical operating point of the PV array to obtain power close to its instantaneous maximum. In an e-bike charging station, this function improves the utilization of the available solar resource and helps regulate the energy transferred to the storage or battery-charging stage. Its effectiveness is particularly important when the PV array is relatively small and unused energy represents a significant loss of the available charging capacity [5], [6].

Perturb and observe (P&O) is among the most widely used MPPT methods because it is relatively simple to implement and requires limited computational resources. The method changes the PV operating voltage or converter duty cycle and observes whether the measured output power increases or decreases. Its principal limitation is the oscillation around the maximum power point under steady-state conditions, while rapid irradiance changes may cause incorrect tracking decisions. Incremental conductance offers an alternative by evaluating changes in PV current and voltage to identify the maximum power operating condition [7], [8].

More advanced MPPT methods include fuzzy logic, neural networks, sliding-mode control, and hybrid optimization techniques. These methods may improve dynamic response or tracking performance under rapidly changing environmental conditions, although they can require more computational resources and more complex parameter tuning. Partial shading introduces an additional challenge because PV arrays can exhibit multiple local power peaks, making conventional tracking methods less reliable. Comparative studies of MPPT algorithms emphasize that the most suitable approach depends on operating conditions, implementation complexity, and the performance requirements of the PV system [9]–[11].

For low-power e-bike charging stations, algorithm selection should consider practical implementation rather than tracking accuracy alone. A simple P&O or incremental-conductance controller may be adequate for a small, uniformly illuminated array where low cost and ease of maintenance are priorities. More advanced tracking can be justified when the PV modules experience partial shading or when the system is expected to operate under highly variable irradiance. The controller should also coordinate with battery charging limits so that maximum PV power extraction does not result in excessive charging current or unsafe battery operation.

4. POWER CONVERTER ARCHITECTURES

Power converters provide the electrical interface between the PV array, energy storage, and e-bike battery. Their functions include voltage regulation, current control, impedance matching, and power-flow management. A DC–DC converter is particularly important because the voltage produced by a PV array changes with operating conditions and may not match the voltage required by the battery. Converter selection therefore influences energy efficiency, output stability, component cost, and the overall complexity of the charging station [12], [13].

Buck converters are suitable when the PV-side voltage is consistently higher than the required charging voltage. Boost converters are appropriate when the PV voltage is lower than the required DC-bus or charging voltage. Buck–boost and SEPIC converters offer wider voltage adaptability, which can be useful when PV output varies substantially during operation. However, these topologies may involve additional components, control requirements, and conversion losses compared with simpler alternatives [12].

A multiport DC–DC converter can integrate PV generation, battery storage, and the charging load within a more compact power-processing arrangement. This architecture can reduce the number of separate conversion stages and enable more flexible energy management. Nevertheless, the design and control of multiport converters are more demanding, particularly when power must be transferred between several ports under different operating conditions. Research on multi-input and three-port converters highlights their potential for renewable-energy systems while also identifying control and design complexity as important considerations [13], [14].

For e-bike charging stations, the converter should be selected according to the PV array voltage range, battery voltage, charging power, isolation requirements, and expected operating environment. A non-isolated converter may be attractive for compact, low-cost DC charging systems, whereas galvanic isolation may be desirable where electrical safety and system architecture require separation between input and output circuits. Converter efficiency should be evaluated across the expected operating range rather than at a single nominal point. Thermal performance, electromagnetic interference, component availability, and maintenance requirements should also be considered before selecting a topology.

5. ENERGY STORAGE AND BATTERY CHARGING MANAGEMENT

Battery energy storage addresses the mismatch between intermittent solar generation and user charging demand. During periods of high irradiance, surplus PV electricity can be stored and subsequently delivered when solar output decreases or charging demand increases. This arrangement improves the availability of the charging station and can reduce its dependence on grid electricity. Reviews of battery energy storage in renewable-integrated power systems identify energy balancing, power management, and operational flexibility as important functions of storage [15], [16].

Lithium-ion batteries are widely used in e-bikes because of their relatively high energy density and suitable power characteristics. However, their charging process must be controlled according to the cell chemistry, battery configuration, temperature, and manufacturer specifications. A battery management system (BMS) should provide essential protection against overvoltage, undervoltage, overcurrent, and excessive temperature. The charging controller must also coordinate with the BMS to ensure that available PV power is delivered within the permitted battery operating limits.

The storage battery used in the charging station should be distinguished from the battery installed in the e-bike. Stationary storage can buffer solar energy before it is transferred to the vehicle, while the e-bike battery stores energy for propulsion. The two batteries may have different capacities, operating cycles, and management requirements. Their combined use should therefore be evaluated in terms of conversion losses, additional capital cost, maintenance, and the potential improvement in charging availability.

Energy management can prioritize direct PV-to-e-bike charging when solar generation is sufficient, store surplus energy when immediate demand is low, and use stored or grid electricity when solar output is inadequate. Such a strategy can improve self-consumption and reduce unnecessary energy conversion. However, additional storage is not automatically beneficial because battery manufacturing, replacement, and end-of-life treatment also have environmental and economic impacts. The storage capacity should consequently be sized according to daily charging demand, solar-resource availability, acceptable autonomy, and the expected operating schedule [15]–[17].

6. SUSTAINABILITY AND ENVIRONMENTAL CONSIDERATIONS

Solar-powered e-bike charging can reduce dependence on grid electricity and support low-emission mobility. Nevertheless, sustainability should be evaluated across the complete system life cycle rather than based solely on the absence of emissions during PV operation. Manufacturing PV modules, electronic

converters, and storage batteries requires materials and energy, while maintenance and end-of-life disposal can generate additional environmental burdens. Life-cycle studies of solar PV systems emphasize that material production, energy payback, recycling, and waste management influence their overall environmental performance [18]–[20].

The environmental performance of a solar charging station also depends on the quality of its energy management. Efficient MPPT and converter operation can increase the amount of useful electricity obtained from the PV array and reduce avoidable conversion losses. Appropriate storage sizing can prevent excessive battery production and unnecessary replacement, while modular construction can simplify maintenance and component upgrades. These considerations indicate that the most sustainable design is not necessarily the system with the largest PV array or storage capacity, but the system that meets the actual charging requirement with the lowest overall resource demand.

Economic sustainability is equally important for widespread adoption. A solar charging station must balance initial investment, energy savings, maintenance, replacement costs, and charging-service availability. Shared charging infrastructure at campuses, workplaces, residential complexes, and public transport facilities may improve equipment utilization compared with isolated installations serving only a few users. Renewable-energy charging infrastructure reviews also emphasize the importance of planning, location, operational strategy, and economic feasibility [3], [4].

7. COMPARATIVE ASSESSMENT AND RESEARCH CHALLENGES

Table 1 summarizes the principal technologies and design considerations discussed in this review. The comparison indicates that each subsystem addresses a different technical problem, but the overall performance depends on their coordinated operation. Simple MPPT and converter configurations can reduce cost and control complexity, whereas more advanced architectures may improve flexibility under variable solar conditions. The table also highlights that energy storage and sustainability must be considered together rather than treated as independent design decisions.

Table 1. Comparison of key technologies for renewable energy-based e-bike charging systems

Technology	Main function	Advantages	Limitations and design considerations
Solar PV array	Converts sunlight into electrical energy	Renewable generation; modular installation	Intermittent output; area and shading constraints
P&O MPPT	Tracks the PV maximum power point	Simple, low-cost implementation	Steady-state oscillation; sensitivity to rapid irradiance changes
Incremental conductance MPPT	Tracks the maximum power point using PV electrical characteristics	Improved tracking logic under changing conditions	More sensing and control requirements
Advanced MPPT	Improves tracking under complex conditions	Potentially better dynamic or partial-shading performance	Higher computational and implementation complexity
Buck converter	Steps down DC voltage	Simple and efficient in suitable voltage conditions	Requires input voltage above the output requirement
Boost converter	Steps up DC voltage	Useful when PV voltage is below the required level	Increased voltage stress and control considerations
Multiport converter	Integrates PV, storage, and load interfaces	Flexible power flow; potential reduction in conversion stages	More complex design and control
Stationary battery storage	Buffers intermittent solar generation	Improves charging availability and energy balancing	Additional cost, losses, aging, and recycling requirements
Battery management system	Protects and supervises battery operation	Supports safe charging and battery utilization	Requires suitable sensing, protection, and compatibility

As indicated in Table 1, there is no universally optimal configuration for all e-bike charging applications. A compact residential charger may prioritize low cost and simple control, whereas a public charging station may require multiple outputs, stationary storage, and more sophisticated energy management. The selection of MPPT and converter technologies should therefore reflect the local solar resource, battery specifications, charging demand, and maintenance capability. The most effective design is one that achieves reliable charging without introducing unnecessary conversion stages or oversized storage components.

Several research challenges remain relevant to future development. First, more experimental studies are needed to evaluate complete PV–MPPT–converter–storage systems under realistic e-bike charging profiles and local weather conditions. Second, standardized approaches to interoperability and battery protection would help accommodate different e-bike battery configurations and charging requirements.

Third, long-term techno-economic and life-cycle assessments are necessary to determine whether the additional cost and environmental burden of stationary storage are justified by improvements in renewable-energy utilization. Finally, intelligent energy management could be investigated to coordinate solar forecasting, charging schedules, battery state estimation, and grid support.

8. CONCLUSION

Renewable energy-based charging systems offer a practical opportunity to improve the environmental performance of electric bicycles. Solar PV integration can provide direct or storage-supported charging through standalone, grid-connected, and hybrid architectures. MPPT improves solar energy extraction, while DC–DC converters regulate power transfer between the PV array, storage system, and e-bike battery. Battery storage can increase charging availability, but its capacity and management must be carefully matched to actual demand. The review demonstrates that the effectiveness of a solar-powered e-bike charging station depends on the integration of its electrical and energy-management subsystems. Simple MPPT and converter solutions may be sufficient for small installations, whereas public and hybrid charging facilities may benefit from more flexible power conversion and storage arrangements. Sustainability assessment must also include manufacturing, battery replacement, maintenance, and end-of-life management rather than focusing exclusively on operational emissions. Future research should prioritize experimentally validated integrated systems, robust battery protection, optimized storage sizing, and life-cycle-based design to support reliable and economically viable solar charging infrastructure for electric bicycles.

REFERENCES

[1] G. R. C. Mouli, P. Van Duijsen, F. Grazian, A. Jamodkar, P. Bauer, and O. Isabella, "Sustainable e-bike charging station that enables ac, dc andwireless charging from solar energy," *Energies*, vol. 13, no. 14, p. 3549, Jul. 2020, doi: 10.3390/en13143549.

[2] H. Chen, "The design of electric bicycle charging station based on solar photovoltaic power," in *Proceedings of the 2016 International Conference on Education, Management and Computer Science*, 2016, pp. 626–629. doi: 10.2991/icemc-16.2016.126.

[3] G. Alkawsi, Y. Baashar, U. D. Abbas, A. A. Alkahtani, and S. K. Tiong, "Review of renewable energy-based charging infrastructure for electric vehicles," *Applied Sciences (Switzerland)*, vol. 11, no. 9, p. 3847, Apr. 2021, doi: 10.3390/app11093847.

[4] G. J. Osório *et al.*, "Rooftop photovoltaic parking lots to support electric vehicles charging: A comprehensive survey," *International Journal of Electrical Power and Energy Systems*, vol. 133, p. 107274, Dec. 2021, doi: 10.1016/j.ijepes.2021.107274.

[5] R. Fachrizal, M. Shepero, D. van der Meer, J. Munkhammar, and J. Widén, "Smart charging of electric vehicles considering photovoltaic power production and electricity consumption: A review," *eTransportation*, vol. 4, p. 100056, May 2020, doi: 10.1016/j.etran.2020.100056.

[6] K. Osmani, A. Haddad, T. Lemenand, B. Castanier, and M. Ramadan, "An investigation on maximum power extraction algorithms from PV systems with corresponding DC-DC converters," *Energy*, vol. 224, p. 120092, Jun. 2021, doi: 10.1016/j.energy.2021.120092.

[7] A. B. Kebede and G. B. Worku, "Comprehensive review and performance evaluation of maximum power point tracking algorithms for photovoltaic system," *Global Energy Interconnection*, vol. 3, no. 4, pp. 398–412, Aug. 2020, doi: 10.1016/j.gloei.2020.10.008.

[8] F. F. Ahmad, C. Ghenai, A. K. Hamid, and M. Bettayeb, "Application of sliding mode control for maximum power point tracking of solar photovoltaic systems: A comprehensive review," *Annual Reviews in Control*, vol. 49, pp. 173–196, 2020, doi: 10.1016/j.arcontrol.2020.04.011.

[9] M. Lawan, A. Aboushady, and K. H. Ahmed, "Photovoltaic MPPT techniques comparative review," in *9th International Conference on Renewable Energy Research and Applications, ICRERA 2020*, IEEE, Sep. 2020, pp. 344–351. doi: 10.1109/ICRERA49962.2020.9242855.

[10] M. Derbeli, C. Napole, O. Barambones, J. Sanchez, I. Calvo, and P. Fernández-Bustamante, "Maximum power point tracking techniques for photovoltaic panel: A review and experimental applications," *Energies*, vol. 14, no. 22, p. 7806, Nov. 2021, doi: 10.3390/en14227806.

[11] M. R. S. de Carvalho, R. C. Neto, E. J. Barbosa, L. R. Limongi, F. Bradaschia, and M. C. Cavalcanti, "An overview of voltage boosting techniques and step-up dc-dc converters topologies for pv applications," *Energies*, vol. 14, no. 24, p. 8230, Dec. 2021, doi: 10.3390/en14248230.

[12] N. Zhang, D. Sutanto, and K. M. Muttaqi, "A review of topologies of three-port DC-DC converters for the integration of renewable energy and energy storage system," *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 388–401, Apr. 2016, doi: 10.1016/j.rser.2015.11.079.

[13] A. Affam, Y. M. Buswig, A. K. B. H. Othman, N. Bin Julai, and O. Qays, "A review of multiple input DC-DC converter topologies linked with hybrid electric vehicles and renewable energy systems," *Renewable and Sustainable Energy Reviews*, vol. 135, p. 110186, Jan. 2021, doi: 10.1016/j.rser.2020.110186.

[14] U. Datta, A. Kalam, and J. Shi, "A review of key functionalities of battery energy storage system in renewable energy integrated power systems," *Energy Storage*, vol. 3, no. 5, p. e224, Oct. 2021, doi: 10.1002/est2.224.

[15] S. Bin Wali *et al.*, "Battery storage systems integrated renewable energy sources: A biblio metric analysis towards future directions," *Journal of Energy Storage*, vol. 35, p. 102296, Mar. 2021, doi: 10.1016/j.est.2021.102296.

[16] K. M. Tan, T. S. Babu, V. K. Ramachandaramurthy, P. Kasinathan, S. G. Solanki, and S. K. Raveendran, "Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration," *Journal of Energy Storage*, vol. 39, p. 102591, Jul. 2021, doi: 10.1016/j.est.2021.102591.
[17] M. Tawalbeh, A. Al-Othman, F. Kafiah, E. Abdelsalam, F. Almomani, and M. Alkasrawi, "Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook," *Science of the Total Environment*, vol. 759, p. 143528, Mar. 2021, doi: 10.1016/j.scitotenv.2020.143528.
[18] M. K. H. Rabaia *et al.*, "Environmental impacts of solar energy systems: A review," *Science of the Total Environment*, vol. 754, p. 141989, Feb. 2021, doi: 10.1016/j.scitotenv.2020.141989.
[19] N. A. Ludin *et al.*, "Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review," *Renewable and Sustainable Energy Reviews*, vol. 96, pp. 11–28, Nov. 2018, doi: 10.1016/j.rser.2018.07.048.
[20] V. Fthenakis and E. Leccisi, "Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends," *Progress in Photovoltaics: Research and Applications*, vol. 29, no. 10, pp. 1068–1077, Oct. 2021, doi: 10.1002/pip.3441.