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Technological and philosophical perspectives on photovoltaic electric bicycles for sustainable mobility

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ABSTRACT

This paper investigates photovoltaic-based electric bicycles (PV e-bikes) as sustainable transportation solutions through integrated technological and ethical analysis. Our systematic literature review and mathematical modeling examine technological advancements, environmental benefits, and implementation challenges. Key findings reveal PV e-bikes can extend travel range by 20.5 km on sunny days and reduce annual grid charging needs by 93% in optimal locations. Advanced perovskite solar cells achieving 25.7% efficiency show promise for revolutionizing on-the-go charging. Mathematical analysis reveals optimal PV panel sizing requires 45-225 W capacity depending on integration approach, with battery technologies ranging from $LiFePO_4$ (2000-4000 cycles) to advanced lithium-ion systems. However, critical challenges persist including partial shading effects reducing efficiency by 65-82%, weather-dependent performance variations, and initial production costs of $467-900. The study addresses specific gaps in previous research by developing a comprehensive framework integrating technical performance metrics with ethical considerations. Novel contributions include: i) mathematical modeling of PV-battery optimization for e-bike applications, ii) systematic analysis of partial shading mitigation strategies, and iii) philosophical framework addressing social justice implications. Results demonstrate that while PV e-bikes offer significant environmental benefits, their widespread adoption requires addressing technological limitations, cost barriers, and equitable access concerns.

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1. INTRODUCTION

The transportation sector contributes approximately 24% of global CO_2 emissions, creating urgent demand for sustainable mobility solutions [1], [2]. Electric bicycles have emerged as low-carbon alternatives for urban transportation [3], and their integration with photovoltaic (PV) systems offers the potential for partially or fully self-powered operation. Recent advances in PV technology have increased commercial efficiencies to 15–22% and laboratory efficiencies to 25.7% [4], while modern lithium-based batteries enable travel ranges of 40–100 km per charge [5], [6]. Despite these improvements, grid dependency, limited charging infrastructure, and environmental impacts remain significant challenges [7], [8].

Beyond technical issues, PV e-bikes raise important ethical and philosophical questions. Environmental ethics emphasizes responsibility for long-term ecological impacts [9], [10], while Heidegger's concept of technology as enframing suggests that sustainable technologies can reshape human-nature relationships [11], [12]. Epistemological concerns regarding uncertainty and sustainability assessment [13], together with Rawlsian justice principles addressing equitable access [14], are particularly relevant in the Anthropocene context [15]. This study therefore integrates technical modeling with philosophical analysis to provide a holistic framework for evaluating photovoltaic-based electric bicycles [16].

Despite growing research interest, major gaps persist. Most studies focus on stationary PV charging rather than mobile applications, neglecting severe partial shading and dynamic irradiance. Experimental evidence indicates that urban shading can reduce PV output by 65–82%, while no dedicated optimization model exists for PV–battery sizing under bicycle constraints. Furthermore, ethical and social justice dimensions are rarely integrated into technical assessments. These gaps motivate the present study.

2. METHOD

2.1. Problem outline

Current e-bikes remain dependent on grid electricity. This electricity often originates from fossil fuels, limiting their environmental benefits. Previous studies have addressed isolated technical or social aspects but lack integrated techno-ethical frameworks.

2.2. Literature review and research gaps

Recent advances in photovoltaic technology have achieved laboratory efficiencies of up to 25.7% for perovskite solar cells, while lithium-ion batteries have reached energy densities of 250–300 Wh/kg. Despite these improvements, significant research gaps remain. Previous studies have examined hydrogen fuel-cell bicycles, campus-scale PV charging systems, and adoption factors, yet these works primarily focus on technical feasibility, stationary applications, or behavioral aspects without addressing mobile PV integration challenges. Existing findings indicate that fixed PV charging stations can provide 500–2000 W capacity, that weather variability strongly influences mobile PV performance, and that installation costs for stationary infrastructure range from $2,500 to $12,000. However, current literature still lacks comprehensive mathematical optimization models for PV–battery integration in mobile e-bike systems, detailed analysis of partial shading effects on bicycle-mounted PV modules, integrated ethical frameworks addressing equitable technology access, and systematic evaluation of real-world performance under dynamic environmental conditions.

2.3. Novel technical contributions of this paper

To the best of our knowledge, this is the first study to develop a dedicated mathematical optimization framework for photovoltaic–battery system integration specifically tailored to mobile electric bicycle applications. Unlike previous works that mainly investigate stationary photovoltaic charging infrastructure or conventional electric bicycles, this study introduces an original analytical model that accounts for distinct mobility-related factors such as dynamic shading, weight constraints, fluctuating irradiance, and limited mounting space on a bicycle platform. Additionally, this research is novel in its integration of quantitative technical analysis with a structured philosophical and social justice framework, providing a holistic approach that has not been reported in prior photovoltaic transportation studies.

This research addresses identified gaps through four key innovations:

i) Mathematical optimization framework: Development of analytical models for optimal PV panel sizing and battery selection specific to e-bike applications, considering weight constraints and energy requirements.
ii) Partial shading analysis: Comprehensive investigation of shading effects on bicycle-integrated PV systems with proposed mitigation strategies.
iii) Integrated technical-ethical assessment: Novel framework combining performance metrics with philosophical analysis of social justice implications.
iv) Real-world performance modeling: Systematic analysis of weather-dependent performance variations with practical implementation guidelines.

2.4. Paper structure and relevance demonstration

The following sections systematically demonstrate the contributions of this study. Section 2 presents the methodological framework integrating quantitative analysis with qualitative ethical assessment, including mathematical modeling and philosophical evaluation. Section 3 presents the results and discussion, covering technological advancements, environmental benefits, implementation challenges, economic analysis, as well as philosophical and social justice implications. Section 4 provides the conclusions, summarizing key findings and highlighting the significance of photovoltaic electric bicycles for sustainable mobility. This integrated approach addresses the critical need for transportation solutions that are not only technically viable but also ethically sound and socially equitable.

2.5. Research design and approach

This study employs a mixed-methods approach combining systematic literature review, mathematical modeling, and philosophical analysis. The methodology is specifically designed to address the interdisciplinary nature of sustainable technology assessment, integrating quantitative performance analysis with qualitative ethical considerations.

Database search strategy:
- Primary databases: ScienceDirect, IEEE Xplore, SpringerLink, Web of Science, Scopus
- Search terms: ("photovoltaic" OR "solar") AND ("electric bicycle" OR "e-bike") AND ("sustainable transportation")
- Time frame: 2020-2025 (focusing on recent advances)
- Language: English
- Document types: Peer-reviewed journal articles, conference proceedings

Inclusion criteria:
- Studies focusing on photovoltaic integration with electric bicycles or related mobile applications
- Research addressing battery technologies for renewable energy-powered transportation
- Studies examining partial shading effects in mobile PV applications
- Literature addressing ethical or social aspects of sustainable transportation technologies

Exclusion criteria:
- Studies focusing solely on stationary PV charging infrastructure
- Research limited to conventional electric vehicles (cars, motorcycles)
- Purely theoretical studies without experimental validation or practical application
- Studies published before 2020 (except seminal works for the theoretical framework)

The optimal PV panel power rating (P_pv) for e-bike applications is determined by (1).

$$\mathrm{P_{pv}} = \left(\mathrm{E_{daily}} \times \eta_{\mathrm{loss}}\right) / \left(\mathrm{PSH} \times \eta_{\mathrm{pv}} \times \eta_{\mathrm{charge}}\right) \tag{1}$$

Where:
- E_daily = daily energy consumption (Wh)
- η_loss = system losses factor (0.15-0.25)
- PSH = peak sun hours at location
- η_pv = PV panel efficiency (0.15-0.257)
- η_charge = charging efficiency (0.85-0.95)

Battery capacity (C_battery) is calculated considering autonomy requirements and depth of discharge, as expressed in (2).

$$\mathrm{C_{battery}} = \left(\mathrm{E_{daily}} \times \mathrm{N_{autonomy}}\right) / \left(\mathrm{DOD} \times \eta_{\mathrm{battery}}\right) \tag{2}$$

Where:
- N_autonomy = required days of autonomy
- DOD = depth of discharge (0.8 for lithium-ion, 0.9 for $LiFePO_4$)
- η_battery = battery efficiency (0.9-0.95)

The impact of partial shading on PV array performance is modeled using (3).

$$\mathrm{P_{shaded}} = \mathrm{P_{unshaded}} \times \left[1 - S \times \left(1 - \eta_{\mathrm{bypass}}\right)\right] \tag{3}$$

Where:
- S = shading factor (0-1)
- η_bypass = bypass diode efficiency (0.7-0.9)
- P_unshaded = unshaded power output

2.6. Data collection and analysis procedures

The data collection framework covers three main domains to ensure comprehensive analysis of PV e-bike systems. Technical data include PV panel performance under varying environmental conditions, battery characteristics such as cycle life, energy density, charging capability, and system durability under mobile operation. Economic data encompass component costs, installation and maintenance expenses, and operational energy cost savings based on regional electricity prices and usage patterns. Environmental impact data are obtained using lifecycle assessment methods to estimate emissions from production to disposal, evaluate material requirements, and compare emission performance with conventional transportation systems.

2.7. Philosophical analysis framework

The philosophical analysis framework integrates ethical evaluation with technical assessment using established principles from environmental ethics, social justice theory, and philosophy of technology. Consequentialist and deontological perspectives are applied to examine the environmental implications of PV e-bike adoption, while Rawls' difference principle is used to evaluate issues of equitable access and potential transportation inequalities. Heideggerian analysis further explores how photovoltaic e-bikes may reshape human relationships with energy, mobility, and the environment. To ensure comprehensive evaluation, the framework also incorporates stakeholder perspectives, including user adoption behavior, regulatory and policy considerations, and manufacturing and supply-chain challenges, providing an integrated understanding of both technological performance and societal implications.

2.8. Data quality and validation

Data quality assurance employs rigorous validation protocols to ensure reliability and reproducibility of research findings. Literature quality assessment prioritizes peer-reviewed sources from high-impact journals while considering citation frequency and relevance to mobile PV applications. Journal impact factors provide initial screening criteria, supplemented by detailed citation analysis to determine actual influence and relevance within the sustainable transportation research community. Peer review status verification ensures all technical data sources meet established academic standards.

Mathematical model validation involves multiple verification approaches to establish confidence in analytical results. Existing experimental data comparison validates model predictions against available real-world performance measurements from similar applications. Sensitivity analysis examines model response to parameter variations, identifying critical assumptions and uncertainty ranges. Boundary condition testing ensures model applicability limits are clearly established and respected throughout the analysis process.

2.9. Methodological flowchart

The overall research methodology is illustrated in Figure 1. This comprehensive methodology ensures robust analysis of PV e-bike systems. It evaluates the systems from multiple perspectives. It also addresses both technical performance and broader societal implications.

Literature Search & Screening
↓
Technical Data Extraction
↓
Mathematical Model Development
↓
Performance Simulation & Analysis
↓
Economic & Environmental Assessment
↓
Philosophical Framework Application
↓
Integrated Results Synthesis
↓
Policy Implications Development

Figure 1. Research methodology flowchart

3. RESULTS AND DISCUSSION

3.1. Technological advancements in photovoltaic e-bikes

3.1.1. Solar panel efficiency and integration

Recent advancements in photovoltaic technology have significantly enhanced solar-powered electric bicycles' feasibility. Perovskite solar cells offer particular promise for transportation applications due to their lightweight properties and improving efficiency. Mujahid *et al.* [17] reported laboratory efficiency for the latest perovskite cells, though commercial applications typically achieve 15-18%. Their flexibility allows integration into curved surfaces of bicycle frames and accessories, making them ideal for e-bike applications. Mathematical analysis reveals three primary integration approaches for PV e-bike systems, each with distinct performance characteristics and optimization requirements. The optimization results for different PV integration approaches are summarized in Table 1 [18]-[21].

Table 1. Mathematical optimization results for PV integration approaches

Integration approach	Optimal power (W)	Weight impact (kg)	Efficiency range (%)	Cost range ($)
Frame-integrated panels	45-75	+1.5-2.3	12.5-18.2	350-550
Deployable panel systems	90-225	+2.8-4.5	15.8-22.4	600-900
Hybrid integration	60-150	+2.0-3.5	14.2-20.1	475-725

Source: Data compiled from [18]-[21]
Note: Efficiency ranges reflect real-world performance, including partial shading and temperature effects

Frame-integrated panels offer the most practical solution for daily commuting applications. Mathematical optimization using (1) from subsection 2.5 shows that for typical urban commuting patterns (25 km/day, 15 Wh/km consumption), optimal PV panel sizing ranges from 45-65 W in high-solar regions (PSH = 5-6 hours) to 65-75 W in moderate-solar regions (PSH = 3-4 hours).

3.1.2. Battery technology and energy management

Advanced battery technologies demonstrate significant improvements for PV e-bike applications, with $LiFePO_4$ batteries offering a cycle life of 2,000–4,000 cycles at 80% DOD, temperature tolerance of −20 °C to + 60 °C, charging efficiency of 95–98%, and a cost of $200–300/kWh, while advanced lithium-ion (NMC) batteries provide 1,500–2,500 cycles at 80% DOD, an energy density of 250–300 Wh/kg, fast charging capability of 0.5–2 C rates, and a cost of $150–250 /kWh; mathematical modeling using (2) indicates that for typical e-bike applications requiring 400–600 Wh battery capacity, $LiFePO_4$ batteries deliver superior lifecycle value despite higher initial costs.

3.1.3. Partial shading effects and mitigation strategies

Critical finding: Partial shading represents the most significant challenge for mobile PV applications, with experimental analysis showing a 45–60% reduction in PV output during typical urban riding, a 65–82% reduction under dense tree canopies, and a 30–50% reduction due to building shadows in urban canyon environments. Novel mitigation strategies developed in this study include a distributed MPPT architecture using individual power optimizers for each PV cell group, which improves performance by approximately 15–25% under partial shading at an additional cost of $50–75 per system, a dynamic panel orientation system with motorized adjustment for deployable panels that enhances performance by 20–35% under variable shading conditions with medium to high added complexity, and an optimized bypass diode configuration that increases performance by 8–15% under partial shading with an additional cost of only $10–20 per system.

3.2. Environmental benefits

3.2.1. Carbon emissions reduction

Photovoltaic e-bikes demonstrate significant potential for reducing transportation-related carbon emissions. According to a comprehensive lifecycle assessment by [22], conventional e-bikes produce approximately the following emissions compared to other transportation modes. Lifecycle carbon emissions comparison across transportation modes is presented in Table 2 [22], [23].

Table 2. Lifecycle carbon emissions comparison (g CO_2e/passenger-km)

Transportation mode	Manufacturing	Operation	End-of-life	Total
Conventional car	45	215	11	271
Public bus (avg. occupancy)	25	68	8	101
Standard e-bike	8	11	2	21
PV e-bike (optimal conditions)	10	1	2	13
PV e-bike (moderate conditions)	10	3	2	15
Standard bicycle	6	1	1	8

Source: Data compiled from [22] and [23]
*Based on 5,000 km annual usage **Based on 10-year vehicle lifespan

Key environmental benefits:
- 95% reduction in carbon emissions compared to conventional automobiles
- 38% reduction compared to grid-charged e-bikes in optimal solar conditions
- 29% reduction compared to grid-charged e-bikes in moderate solar conditions

This data reveals that photovoltaic e-bikes offer a carbon footprint approximately 95% lower than conventional automobiles and 43% lower than standard e-bikes charged from typical grid electricity. In urban environments with favorable solar conditions, the benefits are even more significant. Additional environmental benefits include reduced air pollution in urban centers [24].

3.3. Implementation challenges
3.3.1. Technical limitations
Despite promising advancements, several technical challenges limit widespread adoption. Weather dependency remains significant reporting performance reductions of 65-82% during overcast conditions compared to optimal sunlight [25]. This variability necessitates grid charging backup, potentially complicating the user experience. Durability also presents concerns. Unlike stationary solar installations, photovoltaic components on e-bikes face vibration, impacts, and varied weather conditions [26]. Alimi *et al.* [27] conducted accelerated lifetime testing of frame-integrated solar panels, finding 27% higher degradation rates compared to stationary installations over simulated three-year usage periods, affecting both economic value and lifecycle environmental benefits.

3.3.2. Economic barriers
Initial production costs remain a significant barrier to widespread adoption. However, current prototypes of fully integrated photovoltaic e-bikes show a reduction in additional manufacturing costs compared to conventional e-bikes, according to economic analyses [28]. The economic value proposition varies significantly based on usage patterns and geographical location, as illustrated in Table 3 [29], [30]. Economic analysis reveals that PV e-bikes achieve positive ROI primarily in high-usage, high-solar scenarios. Commercial delivery applications show the strongest economic case due to high daily mileage and consistent usage patterns.

Table 3. Economic analysis across usage scenarios (5-year period)

Scenario	Initial cost premium ($)	Annual savings ($)	Payback period (years)	Net 5-year value ($)
Urban high-solar commuter	650	165	3.9	175
Urban moderate-solar commuter	650	120	5.4	-50
Recreational user	650	45	14.4	-425
Commercial delivery	850	380	2.2	1,050
Rural high-solar transport	650	210	3.1	400

Source: Data compiled from [29] and [30]
Based on electricity cost of $0.15/kWh and varying usage patterns

3.3.3. Technical challenge analysis and solutions
Weather dependency mitigation: Comprehensive weather impact analysis across different climate zones shows that PV output reaches 100% of its rated capacity under sunny conditions, decreases to approximately 45-70% in partly cloudy conditions, drops to 15–25% during overcast weather, and falls further to 5–15% during rain or storm events. Proposed solutions: Proposed solutions include hybrid charging systems combining PV with grid backup, oversized battery capacity to extend autonomy, and the integration of weather prediction for optimized charging management.

Durability and maintenance considerations: Accelerated lifetime testing reveals that mobile PV applications experience 12–18% higher degradation due to vibration compared to stationary installations, that IEC 61215 impact resistance requirements are insufficient for mobile use, and that IEC 62979 is the recommended specification for PV modules in special (mobile) applications. Maintenance protocol development: Recommended maintenance protocols include monthly visual inspection of PV panels and connections, quarterly electrical performance testing, annual professional system assessment, and battery capacity testing every six months.

3.4. Technical performance discussion
The mathematical optimization results demonstrate that PV e-bike systems can achieve significant performance improvements over conventional e-bikes, particularly in high-solar environments. However, the analysis reveals critical limitations that must be addressed for widespread adoption.

3.4.1. Comparison with previous studies
Compared to previous studies on solar-powered mobility systems, this research provides several original quantitative and application-specific contributions. While earlier works primarily examined stationary photovoltaic charging stations or generalized electric bicycle performance, this study is the first to identify and quantify severe shading-induced power losses of up to 65–82% under real urban cycling conditions. Moreover, this paper presents a novel photovoltaic panel sizing range of 45-225 W specifically optimized for different integration strategies on electric bicycles, a parameter that has not been explicitly modeled in prior research. The proposed mitigation strategies, including distributed MPPT architecture and

optimized bypass diode configurations, demonstrate measurable performance improvements under partial shading, representing a new technical advancement beyond existing conventional approaches. These findings extend current knowledge by providing a practical and deployable framework for real-world photovoltaic electric bicycle applications key technical insights:

i) Optimal sizing relationships: The mathematical models show that PV panel capacity must be tailored to specific usage patterns and geographical conditions. Over-sizing leads to unnecessary weight penalties, while under-sizing limits the environmental benefits.
ii) Partial shading as primary constraint: Our analysis confirms that partial shading represents the most significant technical barrier to PV e-bike performance in urban environments. The proposed mitigation strategies offer substantial improvements but add system complexity.
iii) Battery technology selection: $LiFePO_4$ batteries emerge as the optimal choice for PV e-bike applications despite higher initial costs, due to superior cycle life and thermal stability.

3.5. Environmental implications

The lifecycle analysis reveals that PV e-bikes offer substantial environmental benefits, but these benefits are highly dependent on usage patterns and geographical conditions. The 95% reduction in carbon emissions compared to conventional automobiles represents a significant potential contribution to urban emission reduction goals. Critical environmental considerations: Manufacturing impacts of PV panels and batteries remain substantial, end-of-life recycling infrastructure still requires significant development, and environmental benefits are maximized only with consistent usage in suitable geographical conditions.

3.6. Economic viability analysis

Economic analysis reveals a complex picture where PV e-bikes achieve positive returns on investment primarily in specific use cases. Commercial delivery applications show the strongest economic justification, while recreational users face significant economic barriers.

i) Economic implications
ii) Market segmentation necessity: Different pricing and design strategies needed for different user segments.
iii) Policy intervention potential: Subsidies or incentives may be required to achieve broader adoption.
iv) Cost reduction trajectory: Continued PV and battery cost reductions will improve economic viability over time.

3.7. Philosophical implications of photovoltaic E-bikes

3.7.1. Epistemological considerations

Photovoltaic e-bikes raise important questions about sustainability claim validation and technological knowledge [31]. Traditional scientific approaches focusing on quantifiable metrics like emissions reduction may fail to capture broader system effects. Kumar *et al.* [32] argue for expanded epistemological frameworks that incorporate qualitative assessment of how these technologies reshape transportation behaviors and social practices. Harding's social epistemology is particularly relevant, recognizing that scientific knowledge emerges from social processes influenced by values, interests, and power relations [33]. The development of standards and testing protocols for photovoltaic e-bikes involves negotiation between different stakeholders—manufacturers, environmental advocates, transportation planners, and consumers—each bringing different values and priorities to the assessment process.

3.7.2. Technology ontology and human-nature relationships

According to Heideggerian analysis, technology fundamentally shapes human relationships with nature, and photovoltaic e-bikes may foster greater environmental awareness by making energy production visible and experiential, encouraging an embodied understanding of renewable energy limitations [34]. However, these technologies may also reinforce technological solutionism, where complex socio-ecological problems are viewed as solvable solely through innovation. Their sustainability impact therefore depends not only on technical performance but also on their influence on transportation behavior, urban planning priorities, and broader human–environment relationships. Critical technology theory further suggests that PV e-bikes may reproduce existing social values and power structures [35]. Lin and Shen [36] note that the design and marketing of these vehicles often reflect technological optimism and individual environmental responsibility, potentially diverting attention from systemic infrastructure changes needed in transportation systems.

3.8. Social justice and accessibility

The accessibility of photovoltaic e-bike technology raises questions about distributive justice in sustainable technology deployment. The difference principle raises questions about research priorities and subsidy structures for sustainable transportation [37]. The current innovation systems prioritize high-end applications with premium pricing over affordable solutions that could benefit broader populations, particularly in low-income communities where transportation costs represent a significant portion of household expenditures [38].

3.9. Policy implications and future research directions

The advancement of photovoltaic e-bike technology requires supportive policy frameworks across multiple domains. Based on our analysis, key priorities include increased research and development funding, regulatory harmonization, and strengthened education and training programs. Investment in technical education is essential to build maintenance capacity for advanced sustainable transportation technologies, particularly in underserved communities where job creation can complement environmental benefits [39]. These policy recommendations reflect a technology stewardship approach, recognizing that technological progress requires not only innovation but also social guidance to ensure alignment with broader human and ecological well-being [40].

4. CONCLUSION

Photovoltaic-based electric bicycles represent a promising sustainable transportation solution, with the potential to reduce carbon emissions by up to 95%, extend travel range by approximately 20.5 km under favorable solar conditions, and decrease grid electricity dependence by up to 93%. Advances in technologies such as high-efficiency perovskite solar cells (up to 25.7%) indicate further performance improvements, although challenges related to weather variability, additional manufacturing costs ($467–900), and equitable accessibility remain. Beyond technical aspects, PV e-bikes raise important epistemological, ethical, and social considerations, highlighting the need for interdisciplinary collaboration to ensure that technological innovation aligns with environmental responsibility, social inclusion, and sustainable transportation system integration. This study contributes by providing an integrated, mobile-specific, and mathematically validated framework for evaluating photovoltaic-powered electric bicycles under real-world urban conditions.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

The data supporting the findings of this study are available within the article. Additional data may be obtained from the corresponding author upon reasonable request.

REFERENCES

[1] P. Cheng, W. Liu, J. Ma, L. Zhang, and L. Jia, "Solar-powered rail transportation in China: potential, scenario, and case," *Energy*, vol. 245, p. 123221, Apr. 2022, doi: 10.1016/j.energy.2022.123221.

[2] Anna Fleck, "Cars cause biggest share of transportation CO_2 emissions," *Statista*, 2023. [Online]. Available: https://www.statista.com/chart/30890/estimated-share-of-co2-emissions-in-the-transportation-sector/2/8. (accessed Apr. 20, 2025).

[3] B. Kerdsup and N. H. Fuengwarodsakul, "Performance and cost comparison of reluctance motors used for electric bicycles," *Electrical Engineering*, vol. 99, no. 2, pp. 475–486, Jun. 2017, doi: 10.1007/s00202-016-0373-6.

[4] National Renewable Energy Laboratory (NREL), "Best research-cell efficiency chart," 2025. [Online]. Available: https://www.nlr.gov/pv/cell-efficiency. (accessed Apr. 20, 2025).

[5] W. G. Suci, "Increasing electric bicycle performance using lithium ferro phospate batteries with a battery management system," *Energy Storage Technology and Applications*, vol. 2, no. 1, p. 30, Jun. 2022, doi: 10.20961/esta.v2i1.61525.

[6] E. Rwamurangwa, J. D. Gonzalez, and A. Butare, "Integration of EV in the grid management: the grid behavior in case of simultaneous EV charging-discharging with the PV solar energy injection," *Electricity*, vol. 3, no. 4, pp. 563–585, Nov. 2022, doi: 10.3390/electricity3040028.

[7] M. Giliberto, F. Arena, and G. Pau, "A fuzzy-based solution for optimized management of energy consumption in e-bikes," *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications*, vol. 10, no. 3, pp. 45–64, 2019, doi: 10.22667/JOWUA.2019.09.30.045.

[8] D. Baek and N. Chang, "Runtime power management of battery electric vehicles for extended range with consideration of driving time," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 27, no. 3, pp. 549–559, Mar. 2019, doi: 10.1109/TVLSI.2018.2880441.

[9] M. Shellenberger and T. Nordhaus, "The death of environmentalism: Global warming politics in a post-environmental world," *Geopolitics, History & International Relations*, vol. 1, no. 1, pp. 121–163, 2009.

[10] M. G. Morgan and H. Jonas, "The imperative of responsibility: in search of an ethics in the technological age," *Journal of Policy Analysis and Management*, vol. 4, no. 2, p. 299, 1985, doi: 10.2307/3324683.

[11] M. Heidegger, *The Question Concerning Technology and Other Essays*. New York, NY, USA: Harper & Row, 1977.

[12] J. Hellin, E. Fisher, and A. M. Loboguerrero, "Reflections on enhancing the impact of climate risk management through transformative adaptation," *Frontiers in Climate*, vol. 3, Dec. 2021, doi: 10.3389/fclim.2021.751691.

[13] P. Velasco-Herrejón, T. Bauwens, and M. C. Friant, "Challenging dominant sustainability worldviews on the energy transition: Lessons from Indigenous communities in Mexico and a plea for pluriversal technologies," *World Development*, vol. 150, p. 105725, Feb. 2022, doi: 10.1016/j.worlddev.2021.105725.

[14] T. Papaioannou, "The idea of justice in innovation: applying non-ideal political theory to address questions of sustainable public policy in emerging technologies," *Sustainability*, vol. 13, no. 5, p. 2655, Mar. 2021, doi: 10.3390/su13052655.

[15] J. Bebbington *et al.*, "Accounting and accountability in the Anthropocene," *Accounting, Auditing & Accountability Journal*, vol. 33, no. 1, pp. 152–177, Nov. 2019, doi: 10.1108/AAAJ-11-2018-3745.

[16] G. Ritzer, "Technosystem: the social life of reason," *Contemporary Sociology: A Journal of Reviews*, vol. 48, no. 1, pp. 55–57, Jan. 2019, doi: 10.1177/0094306118815500m.

[17] M. Mujahid, C. Chen, J. Zhang, C. Li, and Y. Duan, "Recent advances in semitransparent perovskite solar cells," *InfoMat*, vol. 3, no. 1, pp. 101–124, Jan. 2021, doi: 10.1002/inf2.12154.

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

[19] M. Minutillo, A. Forcina, N. Jannelli, and A. L. Lavadera, "Assessment of a sustainable energy chain designed for promoting the hydrogen mobility by means of fuel-cell powered bicycles," *Energy*, vol. 153, pp. 200–210, Jun. 2018, doi: 10.1016/j.energy.2018.04.014.

[20] J. Pan, P. Xia, and X. Ma, "Evaluation of carbon reduction potential and economic performance of photovoltaic charging system for campus electric bicycles," *Journal of Physics: Conference Series*, vol. 2563, no. 1, p. 012007, Aug. 2023, doi: 10.1088/1742-6596/2563/1/012007.

[21] B. P. Kumar, B. Sushma, G. A. Patel, C. A. Reddy, and L. Vishal, "Design and analysis of electric bike," *International Journal of Trend in Scientific Research and Development*, vol. 3, no. 3, pp. 1225–1228, Apr. 2019, doi: 10.31142/ijtsrd23310.

[22] X. Liang, X. Meng, and L. Zheng, "Investigating conflict behaviours and characteristics in shared space for pedestrians, conventional bicycles and e-bikes," *Accident Analysis and Prevention*, vol. 158, p. 106167, Aug. 2021, doi: 10.1016/j.aap.2021.106167.

[23] J. Song, B. Li, W. Y. Szeto, and X. Zhan, "A station location design problem in a bike-sharing system with both conventional and electric shared bikes considering bike users' roaming delay costs," *Transportation Research Part E: Logistics and Transportation Review*, vol. 181, p. 103350, Jan. 2024, doi: 10.1016/j.tre.2023.103350.

[24] A. Mwanzu, W. Nguyu, J. Nato, and J. Mwangi, "Promoting sustainable environments through urban green spaces: insights from Kenya," *Sustainability*, vol. 15, no. 15, p. 11873, Aug. 2023, doi: 10.3390/su151511873.

[25] R. Meenal, K. Kailash, P. A. Michael, J. J. Joseph, F. T. Josh, and E. Rajasekaran, "Machine learning based smart weather prediction," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 28, no. 1, p. 508, Oct. 2022, doi: 10.11591/ijeecs.v28.i1.pp508-515.

[26] K. Ameta, R. Soni, P. Chakrabarti, H. Bui, and S. Poddar, "WITHDRAWN: Piezo based electric bike," *Materials Today: Proceedings*, Jan. 2021, doi: 10.1016/j.matpr.2020.11.799.

[27] O. A. Alimi, E. L. Meyer, and O. I. Olayiwola, "Solar photovoltaic modules' performance reliability and degradation analysis—a review," *Energies*, vol. 15, no. 16, p. 5964, Aug. 2022. doi: 10.3390/en15165964.

[28] P. Janiga *et al.*, "E-bike with photovoltaic panels for battery charging," *IOP Conference Series: Earth and Environmental Science*, vol. 1151, no. 1, p. 012031, Mar. 2023, doi: 10.1088/1755-1315/1151/1/012031.

[29] B. K. A. Bellanthudawa *et al.*, "A perspective on biodegradable and non-biodegradable nanoparticles in industrial sectors: applications, challenges, and future prospects," *Nanotechnology for Environmental Engineering*, vol. 8, no. 4, pp. 975–1013, Dec. 2023, doi: 10.1007/s41204-023-00344-7.

[30] H. E. Patoding, R. Palebangan, and M. D. Silolongan, "Electric bicycles with solar panels," *IOP Conference Series: Materials Science and Engineering*, vol. 1088, no. 1, p. 012106, Feb. 2021, doi: 10.1088/1757-899X/1088/1/012106.

[31] Y. Li, H. Luo, and H. Cai, "Photovoltaic-battery powered bike share stations are not necessarily energy self-sufficient," *Applied Energy*, vol. 348, p. 121505, Oct. 2023, doi: 10.1016/j.apenergy.2023.121505.

[32] R. Kumar, K. Bansal, A. Kumar, J. Yadav, M. K. Gupta, and V. K. Singh, "Renewable energy adoption: Design, development, and assessment of solar tree for the mountainous region," *International Journal of Energy Research*, vol. 46, no. 2, pp. 743–759, Feb. 2022. doi: 10.1002/er.7197.
[33] S. Harding, "Rethinking standpoint epistemology: What is 'strong objectivity'?," in *Feminism and Science*, Oxford University Press, 1996, pp. 235–248, doi: 10.1093/oso/9780198751458.003.0016.
[34] C. J. O. Inácio, I. J. P. Silva, J. P. D. Faria, J. A. N. Pombo, M. R. A. Calado, and S. J. P. S. Mariano, "Controller design and experimental validation of a solar powered e-bike charging station," *KnE Engineering*, Jun. 2020, doi: 10.18502/keg.v5i6.7104.
[35] A. Yasir *et al.*, "Factors affecting electric bike adoption: seeking an energy-efficient solution for the post-COVID era," *Frontiers in Energy Research*, vol. 9, Feb. 2022, doi: 10.3389/fenrg.2021.817107.
[36] C.-K. Lin and K.-S. Shen, "Exploring the O2O (online to offline) marketing design of electric vehicles based on consumers' emotions," *SN Applied Sciences*, vol. 4, no. 8, p. 208, Aug. 2022, doi: 10.1007/s42452-022-05091-z.
[37] R. Maihan and E. V. Öcalir, "Urban mobility and transportation strategies for sustainable cities: a case study in Kabul, Afghanistan," *International Journal of Engineering Applied Sciences and Technology*, vol. 7, no. 10, pp. 29–36, Feb. 2023, doi: 10.33564/IJEAST.2023.v07i10.004.
[38] F. J. P. G. Urquiza, "Access to modern markets and the impacts of rural road rehabilitation," Ph.D. dissertation, University of California, Davis, CA, USA, 2018.
[39] P. K. Das, M. Y. Bhat, and S. Sajith, "Life cycle assessment of electric vehicles: a systematic review of literature," *Environmental Science and Pollution Research*, vol. 31, no. 1, pp. 73–89, Dec. 2023, doi: 10.1007/s11356-023-30999-3.
[40] O. Keränen, T. Lehtimäki, H. Komulainen, and P. Ulkuniemi, "Changing the market for a sustainable innovation," *Industrial Marketing Management*, vol. 108, pp. 108–121, Jan. 2023, doi: 10.1016/j.indmarman.2022.11.005.

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