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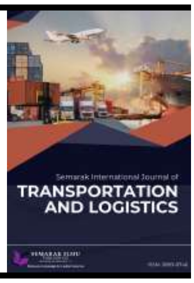

Enhancing Sustainable Street Food Mobility: A Systematic Review of Solar-Powered Electric Bicycle Technologies for Low-Emission Meatball Cart Transportation

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ABSTRACT

The street food sector plays a significant role in supporting urban micro-economies, particularly in developing countries, yet its mobility systems remain largely inefficient and environmentally unsustainable. Mobile meatball vendors commonly rely on human-powered carts or fossil fuel-based vehicles, leading to high physical workload, limited operational range, and increased emissions. This study aims to systematically review the development and applicability of solar-powered electric bicycle technologies for low-emission meatball cart transportation. A Systematic Literature Review (SLR) approach was employed, following PRISMA guidelines, to collect and analyze relevant studies published between 2016 and 2026 from major scientific databases. The review focuses on key aspects including powertrain architecture, photovoltaic (PV) integration, energy management, and auxiliary load requirements. The findings indicate that mid-drive motor configurations are more suitable for heavy-load, low-speed applications due to their superior torque and efficiency. PV systems, while beneficial, function primarily as supplementary energy sources due to limited surface area and environmental constraints such as shading. Additionally, effective energy management is critical, especially in balancing propulsion and auxiliary loads such as heating systems, which significantly impact total energy consumption. The study also identifies major research gaps, including the lack of integrated system design and limited focus on real-world street food applications. In conclusion, solar-powered electric bicycles present a promising solution for sustainable street food mobility, provided that system integration and operational requirements are carefully addressed.

1. Introduction

The street food sector is a crucial element of the urban food system, particularly in developing countries, as it offers affordable, quick, and easily accessible food to everyday consumers. In various

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cities, including in Indonesia, mobile meatball vendors are a tangible reflection of micro enterprises that support household economies while meeting community needs. However, the operations of these mobile food vendors remain heavily reliant on traditional transportation methods that typically rely on human power, fossil fuel powered motorcycles, or modified vehicles not designed with energy efficiency or environmental sustainability in mind. This situation raises new challenges, such as the heavy physical burden on operators, limitations in service coverage, energy inefficiency, and contributions to emissions and urban pollution. Conversely, sustainability issues in the street food sector are now receiving greater attention because they concern not only social and economic aspects but also the environmental impacts of the entire business operation [1,2]. Thus, changes to the mobility system for meatball carts cannot be viewed merely as a transportation issue, but also as a component of the transition plan toward a more environmentally friendly and inclusive urban food system [3,4].

Advances in electric bicycle technology offer significant opportunities to address these issues, particularly by utilizing electric bicycles and electric cargo bikes as small-scale transportation tools in urban areas. Various studies indicate that light electric vehicles have great potential to reduce energy consumption, carbon emissions, noise, and dependence on fossil fuels, especially for short-distance travel and the distribution of light to medium loads. In the context of urban logistics, electric cargo bikes are increasingly viewed as an efficient solution for last-mile delivery because they can operate flexibly on narrow streets, in densely populated areas, and in environments with limited access for motor vehicles. Additionally, the use of electric cargo bikes is considered more suitable for activities requiring high mobility while remaining cost-effective in terms of operational and maintenance expenses. These findings indicate that electric bicycle platforms are not only suitable for current commercial goods transportation but also have the potential to be adapted to the needs of traditional mobile food vendors such as meatball sellers [5-9]. Simply put, the application of electric bicycle technology to food carts can serve as a convergence of transportation innovation, the empowerment of small and medium-sized enterprises, and the goal of decarbonizing the urban mobility sector [10-12].

However, relying solely on electricity does not fully address sustainability concerns if the energy source remains dependent on an electricity grid that is not yet fully clean or if the charging infrastructure is not adequately available. In this context, integrating solar energy into electric bicycle systems becomes particularly appealing, whether through photovoltaic panels mounted directly on the vehicle or through solar powered charging systems. Solar-powered electric bicycles offer an opportunity to enhance energy independence, reduce long-term operational costs, and expand usage flexibility in the informal sector, where mobility is highly variable. Technically, this approach also highlights the importance of design optimization that considers the interplay between solar panel area, battery capacity, motor efficiency, payload weight, additional power requirements, and the operator’s daily travel patterns. Recent studies indicate that the performance of PV battery systems is highly dependent on actual operational conditions; thus, the success of their implementation is determined not only by panel or battery technology but also by energy management strategies and the suitability of the design to its usage context [13-16]. Therefore, the development of a solar-powered electric bicycle for a meatball cart requires a comprehensive analysis, not merely the application of general electric vehicle technology [17-19].

Conversely, the functional characteristics of a meatball cart differ from those of typical urban logistics vehicles. A meatball cart is not merely a mode of transportation but also serves as a mobile service unit that must accommodate food storage, the stability of cooking or serving equipment, operator comfort, hygiene, food safety, and direct interaction with customers. The cargo carried tends to vary and may include food ingredients, cooking equipment, gas cylinders or alternative heating sources, broth containers, cutlery, and business branding elements. Furthermore, the typical workflow of a meatball vendor involves frequent stops, slow speeds, inconsistent routes, and the necessity to operate in densely populated residential areas. This indicates that vehicle design for the street food context must consider various aspects, ranging from the propulsion system, load distribution, safety, energy efficiency, operator comfort, to service hygiene. Unfortunately, current scientific literature tends to focus more on e-cargo bikes in the context of goods distribution or formal urban logistics, while research specifically linking this technology to street food mobility particularly for the environmentally friendly transport of meatball carts remains very limited [20-23]. This gap highlights the urgent need to develop a more systematic knowledge map of the opportunities and limitations of applying this technology in the context of street food businesses [24-26].

Given this context, this study proposes a systematic review focused on solar-powered electric bicycles to support more environmentally friendly and low-emission transportation of meatball carts. The systematic review approach was chosen because it can synthesize, filter, and evaluate the results of various studies in the fields of sustainable transportation, light electric vehicles, solar energy integration, micro logistics, and urban mobility design. In this study, the research focuses on identifying key emerging technologies, the most relevant system elements, design parameters affecting performance, reported environmental and operational benefits, as well as unresolved implementation challenges. Additionally, this study aims to identify research gaps to serve as a conceptual foundation for the development of prototypes or experimental studies more relevant to the situation of meatball vendors in Indonesia. Therefore, this paper not only enriches the literature on low emission mobility but also offers a new perspective on how renewable energy innovations and light electric vehicles can be adapted to support the sustainability of the street food sector and urban SMEs [13,27,28]. Finally, the results of this study are expected to serve as a scientific basis for designing a more efficient, ergonomic, and environmentally friendly mobile food transportation system [10,13,29].

2. Methodology

2.1 Research Approach

This study uses a Systematic Literature Review (SLR) approach to collect, analyze, and synthesize current knowledge of solar-powered electric bicycle technologies for low-emission meatball cart transportation. The SLR approach was chosen because it can provide a comprehensive picture systematically and objectively, and can be replicated while identifying research gaps and recommendations for future development.

2.2 Research Questions (RQ)

As the primary foundation in this systematic literature review approach, the study was designed to answer three research questions (RQ). It was formulated systematically to align with the study's objectives. These questions aim to explore the technical, functional, and implementative aspects of solar-powered electric bicycle technologies for street food mobility. The following are the details of each question:

- RQ1: What are the most effective solar-electric powertrain architectures and motor configurations for heavy-load, low-speed street food carts?
- RQ2: How do existing studies address the optimization of photovoltaic (PV) panel integration, such as tracking mechanisms and structural stability, on light electric vehicles?

- RQ3: What are the technical constraints and power management strategies for balancing traction requirements with auxiliary loads (e.g., food heating elements) in solar e-bikes?

2.3 Search Strategy

To guarantee a thorough and transparent identification of relevant literature, a structured search strategy was formulated. This process was specifically tailored to address the research questions regarding solar-assisted mobility and the electrification of heavy street food carts. The data collection targeted five prominent academic databases recognized for their extensive repositories in engineering, green technology, and environmental sciences.

a. Selected Databases

The systematic retrieval of articles was conducted across a diverse and comprehensive range of digital libraries and indexing platforms to ensure both international breadth and regional specificity. The targeted academic databases included Scopus and Web of Science (WoS) for high-impact multidisciplinary research, alongside engineering and technology-focused repositories such as IEEE Xplore, ScienceDirect, and SpringerLink. To further broaden the scope, Taylor & Francis Online, Wiley Online Library, and SAE Mobilus (Society of Automotive Engineers) were incorporated to capture specialized studies in automotive and electromechanical engineering. Furthermore, to capture localized and context-specific research critical to understanding the unique operational dynamics of the regional street food ecosystem, national indexing platforms such as Garuda (Garba Rujukan Digital) and SINTA (Science and Technology Index) were actively utilized. Google Scholar was also employed as a supplementary tool to guarantee a maximal academic reach and identify any niche publications that might otherwise be overlooked.

To ensure a highly focused and efficient retrieval of relevant literature amidst a vast body of publications, Boolean logic was employed to meticulously combine specific keywords into comprehensive search strings. The primary search query utilized across these databases was explicitly designed to capture the intersection of three core concepts: the power generation technology, the physical application, and the environmental impact. The formulated string was: ("Solar-powered e-bike" OR "photovoltaic integrated LEV" OR "solar electric bicycle") AND ("street food cart" OR "cargo bike" OR "heavy payload") AND ("sustainable mobility" OR "low-emission transport"). This structured approach guaranteed that the search results strictly pertained to mobile solar technologies applied to heavy-duty micro-mobility solutions rather than general electric transportation.

To maintain the utmost quality, relevance, and technical rigor of the synthesized data, articles were required to meet specific and stringent inclusion parameters. Publications had to be written in either English or Indonesian to facilitate a thorough understanding of both global innovations and local implementations. Furthermore, studies had to be published within the specific timeframe of 2016 to 2026. This temporal restriction was deliberately chosen to encompass the most recent and critical technological advancements in high-efficiency solar cells, advanced battery management systems, and modern motor drives. Additionally, the research needed to primarily investigate solar-integrated light electric vehicles (LEVs), cargo tricycles, or e-bikes specifically utilized for commercial transport or mobile vending. Eligible papers also had to present concrete empirical data, detailed system architectures, or technical evaluations of powertrains handling heavy payloads, ensuring that the review is grounded in actionable engineering metrics rather than purely theoretical concepts.

Conversely, records were systematically excluded from this review if they met certain disqualifying conditions that compromised their relevance or reliability. Articles were omitted if they discussed renewable energy or electric mobility broadly but did not explicitly address the physical integration of photovoltaics directly into mobile vehicle applications. Furthermore, research centered on conventional electric vehicles—such as full-sized passenger automobiles, heavy-duty trucks, or transit buses—was strictly excluded, as the aerodynamic profiles, power-to-weight ratios, and energy demands of these vehicles are fundamentally different from those of LEVs and cargo bikes. Finally, to uphold the academic integrity of the systematic review, studies were excluded if the full-text manuscript was inaccessible for detailed extraction, or if the document had not undergone a rigorous peer-review process, thereby filtering out opinion pieces, incomplete drafts, and commercial promotional materials.

2.4 Inclusion and Exclusion Criteria

To ensure the systematic literature review maintains a high degree of academic rigor, relevance, and reproducibility, meticulously defined inclusion and exclusion criteria were established prior to the screening phase. This stringent filtering process is critical for isolating studies that reside exactly at the intersection of renewable energy systems, micro-mobility, and the specific operational demands of the informal street food sector. By applying these parameters, the review guarantees that the synthesized data directly addresses the unique electromechanical challenges of integrating solar power into heavy-load, low-speed transportation frameworks.
Inclusion Criteria:

- Language: Studies published in either English or Indonesian. This ensures the capture of both broad international technological advancements and localized, context-specific research relevant to the regional street food ecosystem.
- Timeframe: Publications released within a ten-year window, specifically from 2016 to 2026. This timeframe was strategically selected to encompass the most relevant and modern technological leaps in high-efficiency photovoltaic (PV) cells, advanced battery management systems (BMS), and compact electric motor efficiency.
- Vehicle Scope: Research primarily investigating light electric vehicles (LEVs), cargo tricycles, utility e-bikes, or pedelecs that are explicitly utilized for commercial logistics, heavy payload transportation, or mobile vending.
- Data Type: Papers that provide concrete empirical data, detailed system architectures, energy management strategies, or technical evaluations. This includes studies reporting on power generation limits, torque requirements for heavy chassis, and the electrical balancing of traction motors alongside auxiliary thermal loads (such as electric heating elements for food).

Exclusion Criteria:

- Thematic Mismatch: Articles that discuss solar energy or electric mobility independently, but do not explicitly address the direct, physical integration of photovoltaics onto mobile vehicle platforms.
- Scale Incompatibility: Research centered on conventional, large-scale electric vehicles (such as full-sized passenger automobiles, transit buses, or heavy-duty trucks). The aerodynamic profiles, power-to-weight ratios, and PV surface area availability of these vehicles are fundamentally incompatible with the micro-mobility focus of this study.

- Quality Control: Studies lacking full-text accessibility, as well as documents not subjected to a rigorous peer-review process. This includes opinion pieces, incomplete preprints, extended abstracts without comprehensive methodologies, and non-technical commercial brochures, thereby safeguarding the integrity of the synthesized engineering data.

2.5 Screening and Selection Process (PRISMA)

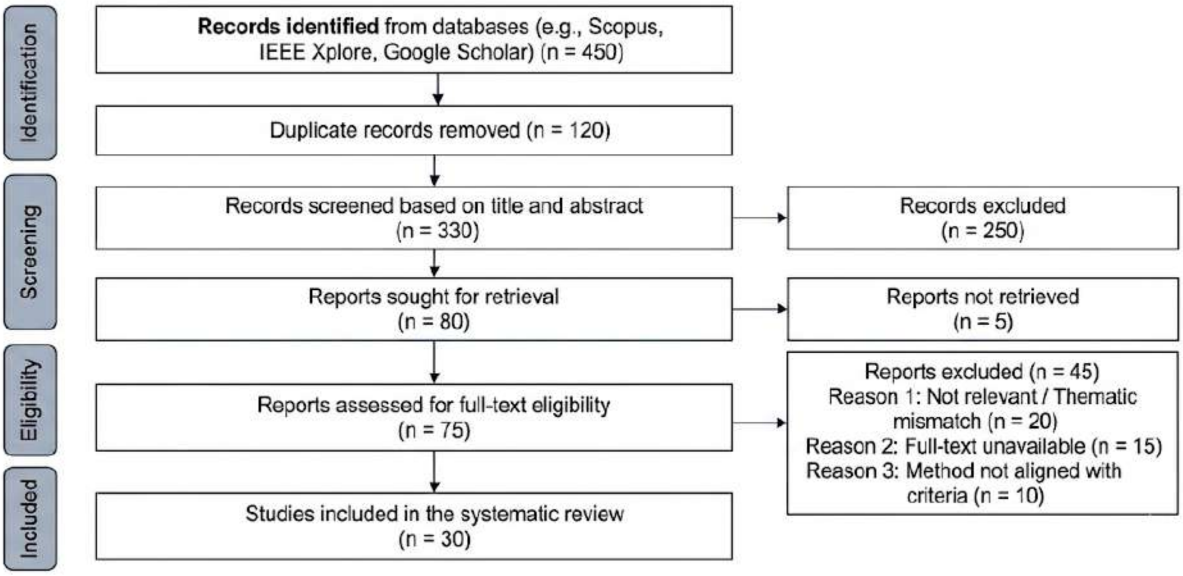


Fig. 1. PRISMA flow diagram for systemathic literature review methodology

To guarantee transparency, replication, and accountability in reporting this systematic review, the literature selection process strictly adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. This structured methodology maps the flow of information through four distinct phases, ensuring that potential biases are minimized and only the most relevant engineering studies are synthesized.

The selection process transitions through the following stages, as illustrated in Figure 1:

Identification: An initial aggregation of records is performed across the designated digital databases. Following the retrieval, duplicate records are systematically identified and removed from the dataset to establish a clean baseline.

Screening: The remaining unique records undergo a preliminary evaluation where the titles and abstracts are screened against the core topic. Reports that pass this phase are then sought for full-text retrieval.

Eligibility: The retrieved reports are subjected to a comprehensive full-text assessment to determine their eligibility. Articles are meticulously evaluated against the predefined inclusion and exclusion criteria. Studies are subsequently excluded at this stage for specific reasons, such as a lack of technical relevance, methodology not aligned with the criteria, or unavailable full-text access.

Included: The final subset of studies that successfully meet all criteria is confirmed and included in the final systematic literature review for thematic synthesis and data extraction.Included: The final subset of studies that successfully meet all criteria is confirmed and included in the final systematic literature review for thematic synthesis and data extraction.

3. Results

3.1 Overview of Selected Studies

Based on a literature search using a Systematic Literature Review (SLR) approach, a number of relevant articles were identified from the IEEE Xplore, ScienceDirect, SpringerLink, Scopus, and Google Scholar databases. After undergoing a selection process based on the PRISMA guidelines, only studies that met the inclusion criteria were analyzed further. The selected studies were generally published between 2016 and 2026 and focused on the development of renewable energy-based light electric vehicles, particularly solar-powered electric bicycles. Overall, research trends indicate growing attention toward low-emission transportation solutions for urban mobility, although specific applications for street food transport remain limited.

3.2 Classification of Reviewed Studies

In order to gain a methodical and organized comprehension of progress in solar-powered electric bicycle technologies, all chosen studies were categorized into four main technical areas: powertrain design, photovoltaic (PV) incorporation, energy regulation, and additional load incorporation. This categorization serves to arrange the literature according to research emphasis while also emphasizing the relationships between system elements and their roles in enhancing overall system performance and practical use.

The classification of the reviewed studies is presented in Table 1.

Table 1
Classification of research domains in solar-powered electric bicycle systems

No	Category	Focus of Study	Description
1	Powertrain Architecture	Motor configuration	Comparison of hub motor and mid-drive motor in terms of efficiency, torque, and performance
2	PV Integration	Solar energy system	Panel placement, conversion efficiency, and shading effects
3	Energy Management	Power distribution	Battery systems, controllers, and hybrid energy integration
4	Auxiliary Load Integration	Additional loads	Heating systems, lighting, and food-related equipment

According to the categorization shown in Table 1, it is clear that a large portion of research is concentrated on the structure of powertrains and the management of energy, since these areas have a direct impact on the primary performance and efficiency of electric vehicles. Additionally, there has been a noticeable rise in studies regarding the integration of photovoltaic systems, particularly aimed at enhancing the collection of renewable energy and the sustainability of systems. Nonetheless, the integration of additional loads is still the least investigated area, even though it holds vital significance for real-world scenarios like mobile food vendors. Auxiliary components, including appliances for cooking, lighting sources, and heating mechanisms, play a substantial role in influencing overall energy requirements and the complexity of system design.

Moreover, a majority of research tends to investigate subsystems in isolation rather than employing a comprehensive system-wide perspective, revealing a gap in studies focused on integrated and application-specific designs, particularly for scenarios such as transporting street food powered by solar energy.

3.3 Solar-Electric Powertrain Architectures

The powertrain architecture is one of the most critical components in electric bicycle systems, as it directly influences vehicle performance, energy efficiency, and load-carrying capability. Based on the literature review, two primary motor configurations are commonly employed: hub motors and mid-drive motors.

3.3.1 Hub motor

A hub motor is conveniently installed within the wheel, located at either the front or back, creating a straightforward mechanical setup that eliminates the necessity for extra transmission components. This configuration of direct drive enhances simplicity in mechanics, allowing for more straightforward installation and upkeep, which makes hub motors a budget-friendly choice for fundamental electric bicycle uses.

In terms of their function, hub motors offer consistent performance when operating at a steady speed. Nonetheless, their ability to generate torque is restricted at lower speeds since they lack gear reduction, which diminishes their efficiency in scenarios that involve heavy items or slopes. Thus, there is often a demand for higher current to sustain performance, resulting in greater energy use when under load.

Moreover, having the motor located within the wheel adds weight that is not supported by the suspension, which can detract from stability and handling, especially on bumpy terrain. These drawbacks render hub motors less ideal for situations that necessitate high torque, capacity to handle varying loads, and effective performance at low speeds.

Consequently, even though hub motors are suitable for applications that prioritize light weight and cost-effectiveness, their performance limitations restrict their effectiveness for rigorous and load-heavy scenarios, as further illustrated in the comparative review presented in Table 2.

3.3.2 Mid-drive motor

In contrast, mid-drive motors are positioned at the crank and deliver power through the bike's drivetrain, enabling the system to take advantage of gear ratios to boost torque. This arrangement allows for significant torque production at lower speeds, which is crucial for tasks that involve heavy weights and changing operating scenarios.

One significant benefit of mid-drive systems is their capacity to function efficiently through gear changes. This leads to enhanced energy efficiency, especially in situations with varying loads and stop-and-start conditions, in comparison to hub motors. Such capabilities are vital for practical uses where energy resources might be scarce.

Additionally, the motor's central location enhances weight distribution and the overall stability of the vehicle, which improves performance on rough surfaces and during slow-speed navigation. These qualities render mid-drive motors highly flexible for challenging operational situations.

Nevertheless, this setup brings about greater complexity within the system due to its connection with the drivetrain, which can lead to increased maintenance needs and possible wear on mechanical parts. Even with these challenges, the advanced torque output, efficiency, and adaptability of mid-drive motors make them preferable for application-specific systems, particularly those related to transporting loads.

3.3.3 Comparative analysis

To provide a clearer evaluation, a comparison between hub motor and mid-drive motor configurations is presented in Table 2.

Table 2
Comparative analysis of hub motor and mid-drive motor configurations

Parameter	Hub Motor	Mid-Drive Motor
Torque Efficiency	Moderate	High
Heavy Load Performance	Limited	Excellent
Energy Consumption	Higher under load	More efficient
Low-Speed Capability	Less optimal	Highly optimal
System Complexity	Low	Medium–High
Maintenance	Easier	More complex
Suitability for Meatball Cart	Low	High

As a result, it can be deduced that mid-drive motor setups serve as the most fitting option for solar-powered electric bicycles designed for transporting meatball carts, owing to their exceptional performance. According to Table 2, mid-drive motors exceed hub motors in most crucial performance factors, especially in terms of torque efficiency, the ability to handle heavy loads, and operation at low speeds. These features are vital for scenarios like solar-powered electric bicycles utilized for street food delivery, wherein the vehicle must function efficiently under significant loading and varying speeds.

Conversely, hub motors offer benefits regarding ease of use and affordability. Nonetheless, their restricted torque and inefficiency when under load render them less appropriate for challenging operational settings. Moreover, this evaluation demonstrates that the choice of motor should not be viewed in isolation. Rather, it should be coordinated with other subsystems such as energy management and additional loads, as these have a substantial effect on the overall performance of the system.

3.3.4 Implications for meatball cart applications

In the realm of solar-operated electric bicycles used for transporting meatball carts, the system must function effectively under heavy load situations and during low-speed movement. This requirement plays a crucial role in determining the appropriate powertrain setup. From the analysis depicted in Table 2, mid-drive motors present distinct benefits related to torque efficiency, adaptability to loads, and energy utilization. These traits are vital for fulfilling the needs of street food vendors, who need to transport cooking tools and ingredients while ensuring consistent operation.

Moreover, the capacity of mid-drive motors to leverage gear ratios facilitates better energy efficiency. This is especially crucial when the system is paired with solar energy sources that provide inconsistent and limited output. This capability guarantees that the available energy is harnessed more productively, increasing operational duration and minimizing reliance on outside charging. Conversely, while hub motors are more straightforward and economical, they struggle to efficiently manage substantial loads and diverse terrain conditions. This drawback makes them less ideal for practical use in mobile food cart settings.

Additionally, this application underscores the necessity of employing an integrated system design strategy. This involves a simultaneous consideration of the powertrain, energy management system, solar integration, and auxiliary loads. Such a strategy is essential for achieving optimal performance and sustainability of the system. As a result, it can be determined that mid-drive motor setups are the best option for electric bicycles powered by solar energy that are used for transporting meatball carts, thanks to their enhanced effectiveness, efficiency, and flexibility in practical use situations.

3.4 Photovoltaic (PV) Integration

The incorporation of solar panel systems into e-bikes offers a beneficial method for enhancing sustainable transportation options for street food sellers, especially concerning low-emission meatball cart delivery. Mobile vendors require energy not only for movement but also for additional functions like lighting and heating, which emphasizes the importance of energy efficiency. Nonetheless, existing research repeatedly shows that solar panel systems on lightweight electric vehicles serve mainly as an additional power source instead of an independent solution. This constraint arises mainly from the limited area available for solar panel placement, which restricts energy production and hinders solar systems from adequately fulfilling traction requirements. Consequently, in applications involving solar-powered meatball carts, integrating solar technology is more advantageous for increasing operational duration and diminishing reliance on electrical grids rather than serving as a replacement for the primary battery.

Alongside the challenges posed by energy constraints, environmental factors and engineering limitations play a vital role in determining how well photovoltaic systems can be applied in practical scenarios. The shading caused by urban structures, trees, and other infrastructures diminishes solar exposure and introduces fluctuations in energy output, a concern that is especially pertinent for street vendors whose locations and movements vary. From the perspective of design, it's essential that the incorporation of photovoltaic systems takes into account factors like structural integrity, load management, and performance in wind conditions, particularly since meatball carts usually have extra weight from cooking tools and storage solutions. If photovoltaic systems are poorly constructed, they can adversely affect the balance and operational efficiency of the vehicle, undermining their intended advantages. Thus, to create an effective solar-driven e-bike framework for transporting meatball carts, a comprehensive strategy is needed that merges energy efficiency, adaptability to environmental conditions, and vehicle design elements, laying the groundwork for identifying suitable photovoltaic integration methods as outlined in this review. Based on the literature synthesis, three general approaches to PV integration can be identified, as shown in Table 3.

Table 3
Common PV integration strategies for light electric vehicles

PV Integration Strategy	Main Advantages	Main Limitations
Fixed Panel	Simple structural design, robust installation, and low mechanical complexity	Limited solar energy capture due to fixed orientation
Foldable Panel	Expanded effective collection area during stationary operation	Increased structural and mechanical complexity
Flexible Panel	Lightweight and adaptable to curved or irregular vehicle surfaces	Generally lower conversion efficiency and potential durability concerns

3.5 Energy Management and Auxiliary Loads

A significant conclusion drawn from the research is that the appropriateness of solar-powered e-bikes for mobile street food vendors hinges not just on their propulsion abilities but also on their capacity to handle additional energy demands. This consideration is especially vital for meatball carts, where electricity is necessary both for moving the vehicle and for essential functions like lighting and heating. According to the analysis of various studies, the overall energy requirements of these systems can be categorized into traction and auxiliary loads, both of which play a crucial role in determining overall efficiency. In this regard, the integration of photovoltaic systems is essential for enhancing energy provision, particularly for auxiliary tasks, thus alleviating stress on the primary battery and prolonging the vehicle's operational time.

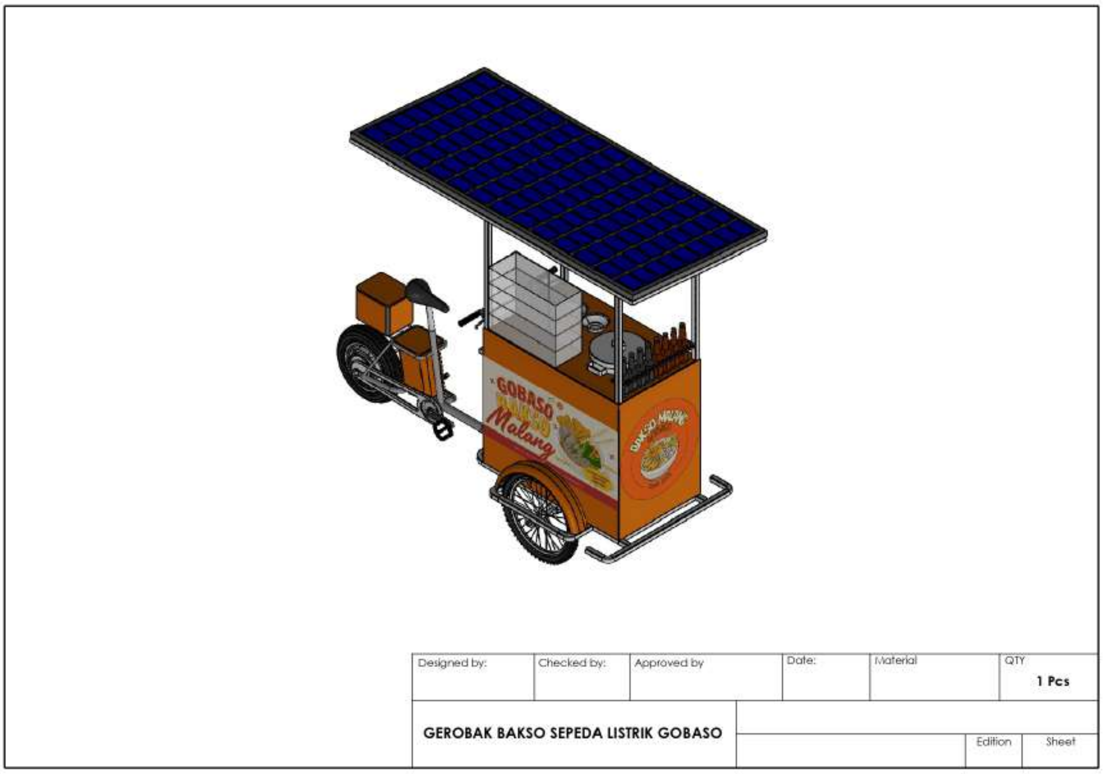
In addition, how effectively energy is used is greatly affected by the weight of the vehicle and the existence of power-hungry auxiliary systems. Research indicates that a heavier load results in increased energy usage and lowers vehicle efficiency, a factor that is particularly significant for meatball carts that transport both the operator and considerable amounts of goods. Among various auxiliary features, heating systems stand out as the most energy-demanding due to their ongoing and relatively substantial power requirements compared to other equipment. Without proper management, this can considerably diminish the vehicle’s range and dependability, especially when it relies solely on one power source. Therefore, an integrated energy management approach that balances traction and auxiliary loads is essential to ensure the feasibility and sustainability of solar-powered electric bicycles for low-emission meatball cart transportation.

Table 4
Estimated system energy demand

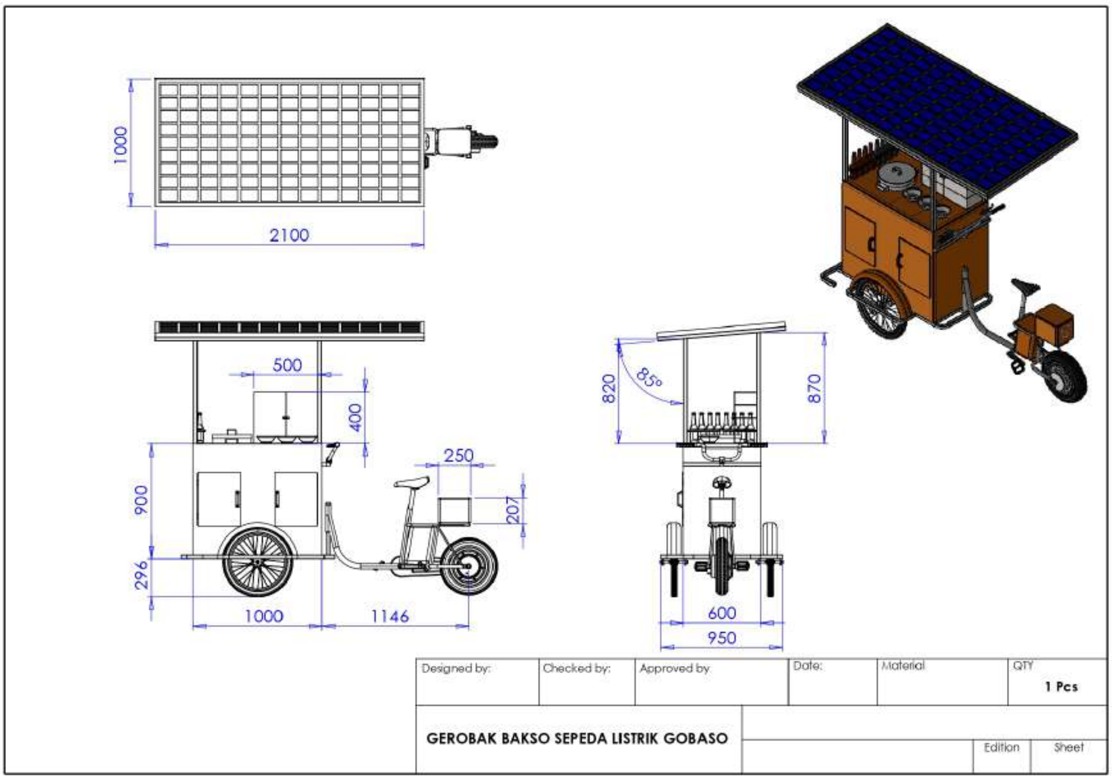
Component	**Estimated Power Consumption**
Electric Motor	250–500 W
Heating System	100–300 W
Lighting	5–20 W

3.6 Proposed Solar-Powered Meatball Cart Design

To address the research gaps identified in the reviewed literature, this study proposes a solar-powered electric bicycle integrated with a mobile meatball cart, as illustrated in Fig. 2. The proposed system is designed as a comprehensive platform that combines mechanical stability, photovoltaic energy utilization, and real operational requirements of street food vendors. This integrated approach ensures that both energy efficiency and operational practicality are simultaneously achieved. As a result, the system offers a more realistic and applicable solution for sustainable mobile street food operations.



(a)



(b)

Fig. 2. Structural design and orthographic representation of a solar-powered electric bicycle integrated with a meatball cart: (a) Proposed system configuration and (b) Orthographic projection

a. Mechanical Configuration and Structural Design

The mechanical configuration of the system utilizes a three-wheel layout that integrates a front electric bicycle unit with a rear cargo module. This design is intentionally chosen to enhance stability, particularly when operating under heavy load conditions commonly encountered in mobile food vending. In comparison to conventional two-wheel systems, the tricycle configuration offers improved balance, better load distribution, and greater structural support. It also minimizes the likelihood of tipping during movement, especially when navigating uneven surfaces or making turns. Furthermore, the additional wheel provides a more stable contact base with the ground, which contributes to improved maneuverability at low speeds—an important factor in crowded street environments. As a result, the system becomes more reliable, safer, and more suitable for continuous operation in real-world conditions where operational variability is high.

The structural design of the cargo module incorporates a reinforced frame capable of supporting cooking equipment, food storage, and a functional workspace. The placement of each component is carefully arranged to achieve an optimal distribution of weight across the chassis. By maintaining a low center of gravity, the system ensures better stability in both stationary and dynamic conditions, including during acceleration, deceleration, and braking. In addition, the frame is designed to withstand vibrations and mechanical stresses generated during daily operation, including those caused by uneven road surfaces and repeated loading cycles. Consideration is also given to ease of maintenance and modularity, allowing components to be accessed, repaired, or replaced with minimal disruption to the overall system. This design approach enhances durability, extends service life, and supports practical usability in long-term applications. Further details regarding the mechanical characteristics, material selection, and structural specifications of the system are summarized in Table 5.

Table 5
Mechanical design characteristics of the proposed system

Parameter	Description
Configuration	Three-wheel system (front bicycle + rear cart) for better balance and load distribution.
Frame Type	Reinforced steel or aluminum frame for strength and durability.
Load Capacity	Designed to carry cooking equipment, food materials, and storage loads.
Stability	Improved with low center of gravity to reduce tipping risk.
Operational Mode	Supports both mobility and stationary food service.

b. Photovoltaic System Integration

The photovoltaic (PV) system is integrated through a roof-mounted panel installed above the cart, serving a dual function as both an energy generator and a protective canopy for the vendor workspace. This design approach allows efficient utilization of the available structure without requiring additional space or complex modifications. The elevated positioning of the panel is intended to maximize solar radiation exposure during daily operation, particularly in open environments. Furthermore, the canopy function enhances user comfort by providing protection against direct sunlight and light rain, thereby improving the practicality of the system in real operating conditions.

Despite these advantages, the PV system is subject to several technical and environmental limitations that can affect its overall performance. The tilt angle of the panel is not always optimized according to the geographical location and sun path, leading to suboptimal energy absorption throughout the day. In addition, the limited surface area available on the cart restricts the total capacity of the installed PV system. Urban operational environments also introduce shading effects from surrounding buildings, trees, or moving objects, which can significantly reduce power output. The main characteristics and performance considerations of the PV integration are summarized in Table 6.

Table 6
Photovoltaic integration characteristics

Aspect	Description
Placement	Installed on the roof above the cart to maximize exposure to sunlight during operation.
Function	Serves as both an energy generation unit and a protective canopy for the vendor workspace.
Power Range	Typically generates 50–150 W depending on panel size, solar irradiance, and environmental conditions.
Advantages	Enables continuous energy harvesting during operation and reduces reliance on external charging sources.
Limitations	Performance is affected by shading, limited installation area, and fixed panel orientation which reduces efficiency.

c. Design Contribution and Practical Relevance

The proposed design provides a practical framework for implementing solar-powered electric mobility in street food applications. By integrating mechanical, electrical, and operational aspects into a unified system, the design presents a comprehensive representation of real-world operating conditions. The mechanical subsystem ensures structural stability and efficient load distribution, while the electrical subsystem manages energy generation, storage, and utilization in a coordinated manner. At the same time, operational considerations such as working duration, mobility patterns, and varying load demands are incorporated to reflect realistic usage. This holistic approach enables better system coordination and ensures that each component functions effectively within the overall configuration. As a result, the system is not only technically feasible but also adaptable to the dynamic and varied needs of mobile vendors in urban environments, where flexibility and reliability are essential.

Furthermore, the explicit consideration of auxiliary loads distinguishes this work from previous studies that primarily focus on propulsion systems alone. The inclusion of cooking equipment, lighting, and other supporting devices reflects the actual operational demands faced by street vendors in daily activities. This approach enhances the realism of the design and ensures that energy consumption is evaluated more accurately and comprehensively. In addition, it allows for better estimation of total energy requirements and supports more appropriate sizing of system components such as batteries and solar panels. Consequently, the proposed system significantly improves the applicability and practicality of solar-powered electric bicycles for real-world street vendor scenarios, while also contributing to the development of more sustainable and energy-efficient urban mobility solutions.

3.7 System Architecture

To support the proposed design, a system architecture is developed to clearly describe the interaction between energy generation, storage, and utilization components, as illustrated in Fig. 3. This architecture provides a structured representation of how energy flows from the photovoltaic system to the battery and subsequently to various electrical loads. It also highlights the coordination between major subsystems, including power management and distribution. By presenting this integrated framework, the system operation can be better understood and evaluated under realistic working conditions.

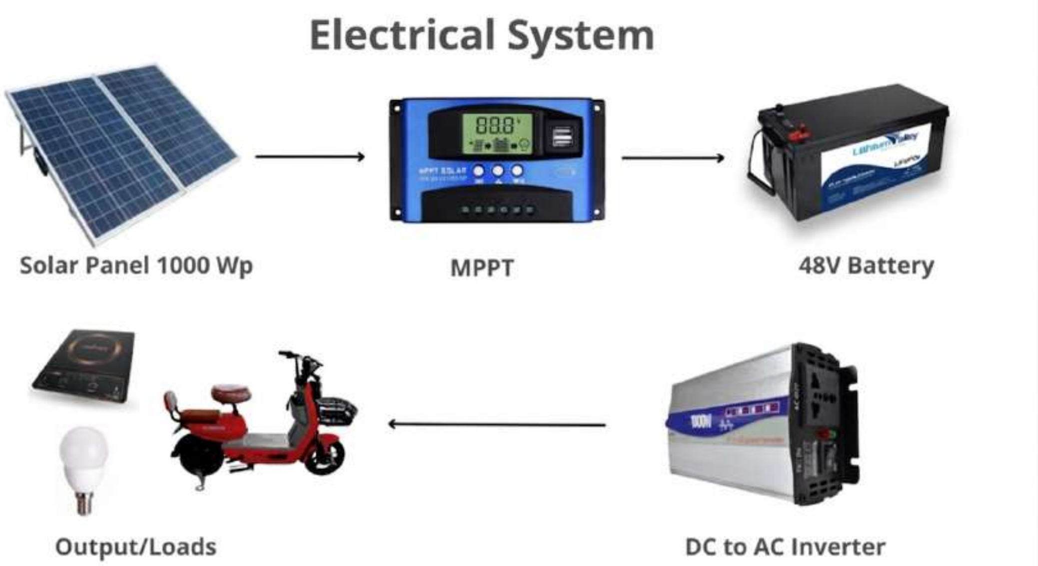


Fig. 3. System architecture of the proposed solar-powered electric meatball cart

a. Energy Generation Layer

The energy generation layer consists of a photovoltaic panel that converts solar energy into electrical energy to support the overall system operation. The output power produced by this layer is inherently variable, as it is strongly influenced by environmental conditions such as solar irradiance, temperature, panel orientation, and shading effects. This variability leads to fluctuations in energy generation throughout the day, making the output inconsistent for direct usage. Consequently, the generated energy cannot be directly utilized as a stable power source for both propulsion and auxiliary loads. Therefore, additional components such as energy storage and regulation systems are required to ensure a continuous and reliable power supply.

b. Energy Storage and Management Layer

To address the variability of solar energy, a battery storage system is incorporated along with a charge controller as part of the energy management layer. The battery functions to store excess energy generated during peak solar conditions and supply power when solar input is insufficient, thereby ensuring continuous and stable operation. Meanwhile, the charge controller plays a crucial role in regulating energy flow, protecting the battery from overcharging and deep discharge, and maintaining overall system safety. In addition, the coordination between these components improves the efficiency and reliability of the system under fluctuating conditions. The key components and specifications of this layer are summarized in Table 7.

Table 7
Energy storage and management components

Component	Primary Function	Technical Description	Role in System
Battery	Energy storage and supply	Stores energy from PV and supplies power when solar input is low, typically using rechargeable batteries (e.g., lithium-ion).	Maintains continuous operation and stabilizes power availability.
Charge Controller	Regulates charging/discharging	Controls energy flow from PV to battery, preventing overcharging and deep discharge, and improving charging efficiency.	Protects battery and enhances system efficiency.
Energy Management System	Load prioritization and control	Distributes energy between propulsion and auxiliary loads based on demand and battery condition.	Ensures critical loads operate and optimizes energy usage.

c. Load Distribution and Utilization Layer

The load layer consists of propulsion and auxiliary systems that operate with different power characteristics and operational patterns. The propulsion system requires a continuous and stable power supply to ensure consistent mobility, particularly under varying load and road conditions. In contrast, auxiliary systems such as heating equipment and lighting operate intermittently but can demand relatively high power during active use. This dual-load configuration creates a significant challenge in energy allocation, especially when the available energy from the battery and photovoltaic system is limited. Therefore, an effective prioritization strategy is necessary to ensure that critical functions, particularly propulsion, remain operational while auxiliary loads are managed adaptively based on available energy resources.

d. Energy Flow and System Interaction

The system operates through a structured energy flow that begins at the photovoltaic panel, passes through the charge controller, and is stored in the battery before being distributed to the load subsystems. This sequential configuration ensures efficient energy management and optimal utilization under varying environmental conditions. As a result, the system can maintain continuous operation despite fluctuations in solar input. The detailed interaction between subsystems and the overall energy flow structure are presented in Table 8.

Table 8
System energy flow structure

Stage	Component	Function
Generation	PV Panel	Converts solar energy into electrical energy based on available irradiance conditions.
Regulation	Charge Controller	Regulates and stabilizes energy flow from the PV panel to the battery, preventing overcharging and voltage fluctuations.
Storage	Battery	Stores electrical energy and supplies power when solar generation is insufficient or unavailable.
Utilization	Motor & Auxiliary Loads	Consumes stored energy to support propulsion and operate auxiliary systems such as heating and lighting.

e. Architectural Significance

The proposed system architecture provides a comprehensive framework for integrating renewable energy into mobile street food systems. By combining energy generation, storage, and utilization within a unified structure, the system is able to manage energy flow more efficiently and systematically. The interaction between photovoltaic modules, battery storage, and electrical loads is designed to ensure stable energy distribution under varying conditions. This approach effectively addresses key challenges related to energy variability, intermittent solar input, and multi-load operation that includes both propulsion and auxiliary demands. In addition, the architecture incorporates basic energy management strategies to balance supply and demand in real time. As a result, the system enhances overall reliability, efficiency, and performance under dynamic operating conditions. Furthermore, the integrated design allows for better coordination between system components, minimizing energy losses and optimizing overall energy usage.

In addition, the architecture emphasizes practical implementation by incorporating real operational requirements of street vendors. This consideration ensures that the system is not only theoretically sound but also applicable in real-world conditions where uncertainty and variability are common. The design accounts for usability, flexibility, and operational constraints such as limited space, varying workloads, and different business hours. It also supports ease of maintenance through modular component arrangement and straightforward system configuration. Moreover, the architecture is adaptable to different operational scenarios, allowing customization based on vendor needs, types of food preparation, and energy consumption patterns. Consequently, the proposed architecture helps bridge the gap between conceptual research and practical deployment, making it a viable solution for real applications while supporting the broader adoption of sustainable energy technologies in small-scale urban businesses.

3.8 Research Gaps

Drawing from the review of existing literature, various gaps in research highlight that the creation of solar-powered e-bikes tailored for the transportation of meatball carts has not been deeply investigated in a context-specific way. The majority of current studies concentrate on general electric bicycles, urban transportation systems, or the integration of photovoltaic technology separately, overlooking the distinct operational demands faced by street food vendors. Consequently, the particular requirements of mobile food enterprises, such as frequent stops, varied operating environments, and the need for both propulsion and service energy, are not adequately represented in existing research.

Additionally, the literature often examines technical aspects like photovoltaic performance, battery efficiency, and motor functions independently instead of as a cohesive system. In real-world situations involving meatball carts, system efficiency is greatly affected by the interplay of propulsion load, additional loads like heating and lighting, the weight carried, and actual environmental conditions. Moreover, insufficient focus has been placed on verifying findings in real-world settings, where variations in the environment, such as urban shading and user habits, have a significant impact on system effectiveness. Therefore, upcoming research needs to embrace a more comprehensive and application-focused strategy that blends technical, operational, and socio-economic elements to ensure the viability of solar-powered e-bikes for sustainable street food transportation.

Table 9
Summary of identified research gaps

Research Gap	Brief Description	Relevance to This Study	Supporting Reference
Limited application-specific studies	Research mostly focuses on general e-bikes or solar EVs, not street food mobility.	Meatball carts require specific design based on operational patterns.	[1]
Lack of integrated system design	PV, battery, and motor are often studied separately.	Integrated systems are needed for efficient energy use.	[2]
Insufficient focus on auxiliary loads	Heating and service loads are rarely analyzed.	Heating significantly affects energy consumption.	[3]
Limited real-world validation	Studies rely on simulations rather than real conditions.	Street vendor environments are dynamic and variable.	[4]

4. Conclusion

This study demonstrates that solar-powered electric bicycles have strong potential to enhance the sustainability of street food mobility, particularly for meatball cart transportation. The findings show that conventional mobility systems used by street vendors are inefficient, physically demanding, and environmentally harmful. By integrating electric bicycle technology, vendors can reduce emissions, improve operational efficiency, and expand their service range. Among the available technologies, mid-drive motor systems are identified as the most suitable due to their superior torque, efficiency, and adaptability to heavy-load and low-speed conditions.

The study also reveals that photovoltaic (PV) integration provides additional benefits in improving energy sustainability, although it cannot serve as a primary energy source. Limitations such as restricted panel area, shading, and environmental variability significantly affect solar energy generation. Therefore, PV systems function mainly as supplementary energy sources that support battery performance and extend operational time. In this context, effective energy management becomes essential to balance the energy demand between propulsion systems and auxiliary loads such as heating and lighting.

Furthermore, this research highlights several important gaps in existing literature, particularly the lack of integrated and application-specific system designs for street food mobility. Most previous studies focus on individual subsystems rather than considering the interaction between mechanical structure, energy systems, and real operational conditions. The proposed integrated design in this study addresses these challenges by combining powertrain optimization, PV integration, and practical usability considerations. Ultimately, a holistic and context-based approach is necessary to ensure the successful implementation of solar-powered electric bicycles for sustainable and low-emission street food transportation.

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