International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

Illumbrella 2.0: A Movable Solar Energy Ecosystem for Street Vendors, Electric Mobility, Farmers and Allied Applications

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Abstract: ***Illumbrella 2.0 presents an advanced evolution of the original Illumbrella concept, transforming a simple umbrella-based structure into a portable, flexible-solar clean-energy ecosystem. By integrating high-efficiency (~30%) flexible photovoltaic modules, modular architecture, and frugal engineering principles, the system addresses multiple grassroots energy challenges related to street vending livelihoods, electric mobility, agriculture, and decentralized household power. The proposed framework introduces two primary applications: first, a Movable Illumbrella EVC Station that enables decentralized mobile and e-bike charging for street vendors and delivery workers, and second a Movable Solar Agriculture Pump System capable of operating a 3 HP agricultural water pump while also supplying electricity for household lighting and essential appliances when irrigation is not required. Unlike conventional fixed solar installations, the movable and foldable configuration improves year-round utilization, reduces monsoon-related damage, and allows redeployment of solar assets across locations. Illumbrella 2.0 further enhances vendor livelihoods through integrated lighting, cooling, hygiene protection, and passive income opportunities, while supporting farmers by reducing diesel dependence and grid reliance. The system can also function as a decentralized household and community-level energy source, strengthening resilience during power outages and supporting distributed energy access. By combining flexible solar technology with mobility and multi-sector usability, Illumbrella 2.0 offers a scalable, people-centric solution aligned with India's Net-Zero targets, decentralized renewable energy goals, Atmanirbhar Bharat, and Viksit Bharat 2047.***

Keywords: Flexible Solar Panels, Movable EV Charging Station, Solar Agricultural Pump, Decentralized Renewable Energy, Net-Zero Clean Energy Solutions, Frugal Innovation;

1. Introduction

India's transition toward clean and renewable energy has gained significant momentum over the past decade through large-scale solar parks, grid-connected renewable capacity, and government-supported schemes for agriculture and mobility. However, despite this progress, millions of citizens, particularly street vendors, small farmers, pedestrians, and delivery workers continue to face limited access to reliable and flexible energy at the point of use. Centralized energy infrastructure often fails to address the dynamic, mobile, and livelihood-dependent nature of these communities.

Street vendors, who number over four crores nationwide, depend on daily footfall and operate in outdoor environments with limited access to lighting, cooling, hygiene protection, and charging facilities. Farmers, despite adopting solar irrigation pumps under government schemes, face challenges of seasonal underutilization and weather-related damage to fixed solar arrays. Simultaneously, rapid growth in electric two-wheeler adoption for last-mile delivery has created demand for decentralized micro-charging infrastructure, which remains largely unmet.

The earlier work, "Illumbrella – Umbrella That Shines the Lives," introduced a frugal innovation that combined lighting, cooling, hygiene protection, and small-scale solar charging within a modified umbrella structure for street vendors [15]. While effective at low power levels, the original Illumbrella system was limited in capacity and application scope.

Parallel field research conducted under the Marathi Vidnyan Parishad program, revealed critical inefficiencies in fixed solar agricultural pump systems, including idle operation for 6–7 months annually, surplus solar energy wastage, and vulnerability to monsoon damage [21]. These findings highlighted the need for mobility, flexibility, and multi-use capability in decentralized solar assets.

Illumbrella 2.0 emerges as a direct response to these challenges. Leveraging recent advancements in high-efficiency flexible photovoltaic modules [18] and grounded in frugal innovation principles [16], the system transforms everyday mobile structures into portable clean-energy platforms. By enabling solar generation, storage, and application within a single movable framework, Illumbrella 2.0 bridges the gap between renewable energy deployment and real-world livelihood needs.

This paper presents the design, operation, performance, and impact of Illumbrella 2.0, demonstrating how decentralized, portable solar systems can support street vending, clean mobility, agricultural irrigation, and domestic energy access, while strengthening energy independence and environmental sustainability.

2. Background and Problem Identification

2.1 Street Vendors and Livelihood Vulnerability

India is home to more than four crore street vendors, who form a vital part of the informal urban economy and provide affordable goods and food to millions of citizens daily. However, the livelihood of street vendors remains highly vulnerable due to dependence on daily footfall, weather conditions, and the absence of basic infrastructure support [1],

[2]. Most vendors lack access to reliable lighting during evening hours, forcing early closure or operation under unsafe and poorly visible conditions. This directly limits income potential and increases the risk of accidents and crime [3].

Food contamination caused by dust, flies, rain, and vehicular pollution is a major concern, particularly for vendors selling ready-to-eat food items such as pani-puri, samosa, and snacks. Poor hygiene conditions reduce customer trust and negatively impact sales [4]. Additionally, prolonged exposure to heat during summer months significantly reduces working efficiency and productivity [5]. The lack of mobile charging facilities further restricts vendors' ability to use digital payment systems, which are increasingly essential in India's cashless economy [6]. Importantly, street vendors generally have no passive income sources, making them entirely dependent on daily earnings and highly susceptible to income shocks.

2.2 Delivery Workers and EV Micro-Charging Needs

India's electric vehicle (EV) ecosystem is expanding rapidly, particularly within the gig economy, where electric two-wheelers are increasingly adopted by delivery workers associated with platforms such as food delivery and e-commerce services [7]. Despite this growth, decentralized and affordable EV charging infrastructure remains inadequate. Delivery workers frequently experience range anxiety, limited access to charging points, and time loss due to long charging queues or distant stations [8].

The absence of small-scale, distributed charging solutions adversely affects productivity and discourages wider adoption of electric mobility in last-mile delivery services [9]. A movable micro solar-based EV charging system, especially one integrated into existing street-vendor infrastructure, can significantly reduce downtime, provide localized charging access, and support the transition to clean mobility in dense urban and semi-urban environments.

2.3 Farmers and Underutilization of Solar Agricultural Pumps

In recent years, millions of farmers across Maharashtra and other Indian states have adopted government-subsidized solar agricultural pumps under various renewable energy schemes [10]. While these initiatives have reduced dependence on diesel and grid electricity, field observations and related studies indicate that solar pumps remain underutilized for nearly 6–7 months each year, particularly outside irrigation seasons [11].

Furthermore, the fixed and rigid installation of solar panel arrays exposes them to frequent damage during monsoon seasons due to storms, heavy rainfall, and hailstorms [12]. The lack of portability prevents farmers from utilizing the generated solar power for household electricity or other productive uses when irrigation is not required. As a result, valuable solar infrastructure remains idle for extended periods, reducing the economic efficiency and return on investment of such systems.

2.4 Grid Instability and Energy Access Challenges

Despite improvements in rural electrification, many regions in India continue to face frequent power cuts, voltage fluctuations, and unreliable supply, particularly in agricultural dominated rural and semi-urban areas [13]. Grid instability affects night-time vending, domestic lighting, irrigation scheduling, mobile connectivity, and overall quality of life. In emergency situations or during extreme weather events, dependence on centralized grids further exposes communities to prolonged outages.

There is therefore a pressing need for compact, modular, and mobile energy systems that can operate independently of the grid, provide localized clean power, and enhance resilience for vulnerable populations [14].

3. Conceptual Framework and System Design Methodology

The conceptual framework of Illumbrella 2.0 is derived as a direct continuation and technological expansion of the previously published Illumbrella research paper, which introduced an umbrella-based solar utility system to enhance street-vendor hygiene, lighting, cooling, and mobile charging facilities [15]. The earlier work established that frugal engineering applied to everyday objects can significantly improve livelihood security in the informal sector. Illumbrella 2.0 extends this foundation by evolving the concept from a low-power support device into a high-capacity, portable clean-energy ecosystem capable of serving multiple sectors.

3.1 Design Philosophy

The system design follows three core principles:

- **Frugal Innovation:** Achieving high functionality using minimal material, cost-effective components, and locally serviceable construction [16].
- **Modularity:** Allowing components such as solar panels, batteries, power electronics, and application modules to be added, removed, or reconfigured based on use-case requirements.
- **Decentralized Energy Deployment:** Enabling power generation and consumption at the point of use, reducing reliance on centralized grids [17].

This philosophy ensures that Illumbrella 2.0 remains affordable, scalable, and adaptable to both urban and rural environments.

3.2 Layered System Architecture

Illumbrella 2.0 is architected as a three-layer energy system, which separates generation, control, and application to improve reliability and scalability.

(i) Energy Generation Layer

This layer utilizes high-efficiency flexible photovoltaic modules mounted on umbrellas, handcarts (hatgadis), or trailers. Recent advances in flexible solar technology allow power densities sufficient to support lighting, charging, electric mobility, and agricultural pumping within compact footprints [18]. The foldable nature of the panels improves storm resistance and portability.

(ii) Energy Management and Storage Layer

This layer regulates power flow and stabilizes energy delivery through:

- Maximum Power Point Tracking (MPPT) for optimized solar harvesting,
- Battery buffering to handle intermittency and load surges,
- Variable Frequency Drives (VFDs) or DC motor controllers for smooth motor operation, especially in irrigation pumps [20].

(iii) Application Layer

The application layer represents the end-use domain where the generated solar energy is delivered to practical, field-level operations. This layer enables multi-sector utilization of the Illumbrella 2.0 system and ensures maximum daily and seasonal energy usage. Key applications include:

- Street-vendor support, including LED lighting for evening operations, inbuilt cooling for thermal comfort, hygiene protection through detachable tarpaulin sheets, and mobile charging to support digital payments and communication.
- Decentralized EV micro-charging, particularly for two-wheeler delivery workers, reducing range anxiety and dependence on centralized charging infrastructure.
- Agricultural water pumping up to 3 HP, suitable for small and marginal farms, supporting irrigation requirements during peak agricultural periods.
- Domestic electricity support during non-irrigation periods, enabling household lighting, charging, and operation of essential appliances in off-grid or power-deficit conditions.
- Agriculture and allied rural activities, such as grain threshing, small-scale flour milling (atta chakki), fodder cutting, and post-harvest processing, thereby extending the utility of the solar system beyond irrigation alone. Such diversified usage aligns with field research, which emphasizes surplus solar utilization and DC–AC conversion for productive rural applications [21].

By supporting both primary agriculture and allied activities, the application layer transforms Illumbrella 2.0 into a portable rural energy workstation, improving asset utilization, enhancing farmer income opportunities, and strengthening decentralized energy access.

3.3 Ease of Assembly and Deployment

A defining feature of Illumbrella 2.0 is its ease of assembly. All system components including solar panels, battery units, fans, LED lights, hygiene tarpaulins, and charging circuits are aligned and mounted using simple mechanical fixtures. No specialized tools or skilled labour are required. This design approach, inherited from the original Illumbrella system [15], ensures rapid deployment, ease of maintenance, and suitability for grassroots adoption.

3.4 Conceptual Block Diagram

The overall functional flow of Illumbrella 2.0 can be represented as the following block diagram:

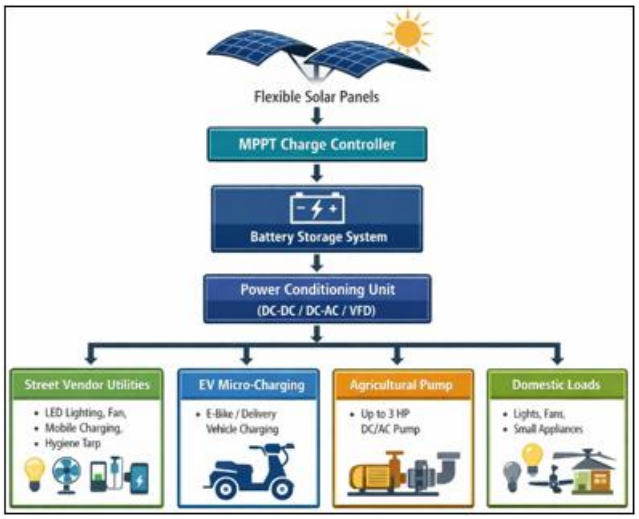

Figure 1: System block diagram / architecture

This architecture allows energy to be dynamically allocated based on demand and availability, ensuring maximum utilization of generated solar power.

3.5 High-Power Operation Capability

For high-load applications such as EV charging and agricultural irrigation, Illumbrella 2.0 integrates battery-assisted power electronics and VFD-based motor control, enabling the operation of up to 3-horsepower water pumps within a portable solar framework. Field experiences in Maharashtra confirm that when flexible solar arrays are combined with battery buffering and soft-start mechanisms, such systems can operate reliably despite solar intermittency [19], [20].

3.6 System Scalability and Multi-Use Capability

Unlike fixed solar installations, Illumbrella 2.0 is designed as a multi-use energy asset. When irrigation is not required, the same solar platform can be redeployed for household electricity, street-vendor support, or community-level energy sharing. This temporal and spatial flexibility significantly improves system utilization and economic returns, aligning with decentralized microgrid models recommended for rural energy resilience [17].

4. System Architecture and Components

Illumbrella 2.0 is designed as a portable, modular clean-energy platform capable of supporting multiple applications through a unified architecture. Unlike conventional fixed solar installations, the system is reconfigurable and mobile, allowing the same solar asset to serve street vending, electric mobility charging, agricultural irrigation, and domestic power needs. This architectural flexibility maximizes system utilization and minimizes idle time of solar infrastructure.

At the core of Illumbrella 2.0 is a flexible high-efficiency photovoltaic generation unit employing approximately 30% efficient foldable solar panels. These lightweight modules can be mounted on umbrellas, handcarts (hatgadis), or tractor-towed trailers, significantly reducing wind loading and structural stress compared to rigid panels. Their foldable

nature enhances storm resilience, addressing monsoon-related damage commonly observed in fixed agricultural solar installations [18], [19].

The generated DC power is processed through a Maximum Power Point Tracking (MPPT) charge controller, which optimizes energy extraction under varying sunlight conditions. Energy storage is provided by a 48 V lithium-ion battery system, which stabilizes power output, supports load surges, and enables operation during low-irradiance periods. Battery capacity is selected according to application requirements, ranging from low-power vending support to higher-capacity agricultural pumping.

Power conditioning is handled through DC–DC converters, DC–AC inverters, or Variable Frequency Drives (VFDs) depending on the connected load. For irrigation applications, VFD-based motor control is employed to reduce starting current and enable efficient operation of pumps up to 3 horsepower within a portable solar framework [20]. For vending and mobility applications, direct DC supply improves overall system efficiency.

The application interface layer distributes conditioned power to end-use modules such as LED lighting, BLDC fans, mobile and EV charging ports, agricultural pumps, and domestic appliances. This multi-mode capability allows temporal and spatial redeployment of the system, ensuring year-round use of the same solar asset.

Mechanically, the system incorporates reinforced frames, fold-lock mechanisms, and low center-of-gravity designs to ensure stability during operation and transport. Electrical components are housed in IP65-rated enclosures to protect against dust and water ingress. Overall, Illumbrella 2.0 integrates advanced solar technology with frugal mechanical design to deliver a scalable, resilient, and people-centric clean-energy solution.

5. Movable Illumbrella EVC Station – Design, Operation and Performance

The Movable Illumbrella Electric Vehicle Charging (EVC) Station represents the urban mobility extension of the Illumbrella 2.0 ecosystem. It is specifically designed to address the absence of decentralized charging infrastructure for electric two-wheelers used by delivery workers and urban commuters. By integrating high-efficiency flexible solar technology into a mobile handcart-based structure, the system enables on-the-go EV micro-charging while simultaneously supporting street-vendor livelihoods.

5.1 System Design

The EVC station is constructed on a hatgadi-based mobile platform, allowing vendors to relocate the system across markets, transport hubs, and high-footfall urban areas. The energy generation unit consists of four foldable flexible solar panels rated at 500 W each, providing a total installed capacity of 2 kW. The flexible nature of the panels reduces overall weight and wind loading, making the structure safe and easy to plan within congested city environments.

Power from the solar array is regulated through an MPPT charge controller and stored in a 48 V lithium-ion battery bank, which acts as an energy buffer to support intermittent solar input and short-term high-current charging demands. The power conditioning stage includes DC–DC converters optimized for EV battery voltages, enabling efficient and safe charging of electric two-wheelers without requiring grid connectivity.

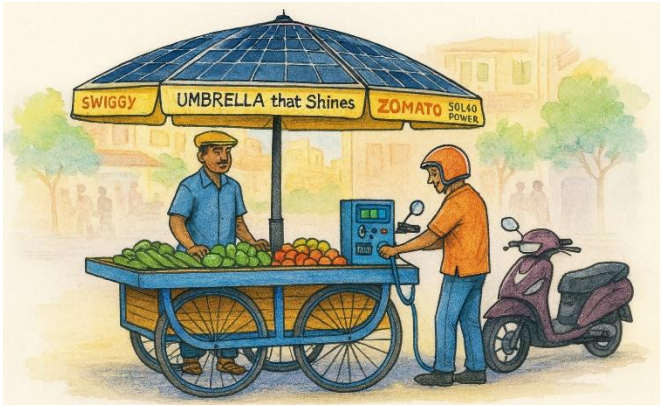

Figure 2: Illustrative deployment of the Movable Illumbrella-2.0 EVC Station, demonstrating decentralized solar-powered mobile and e-bike charging integrated with street vending.

5.2 Operational Modes

During daylight hours, the EVC station primarily operates on direct solar power, with excess energy stored in the battery system. In low-irradiance conditions or after sunset, the stored energy supports continued operation for lighting, mobile charging, and limited EV charging. The system also powers auxiliary loads such as LED lighting and BLDC fans, enabling street vendors to operate safely and comfortably during evening hours.

The charging strategy is designed for micro-charging rather than fast charging, which is better suited to small-capacity two-wheeler batteries commonly used in last-mile delivery. This approach minimizes battery stress, reduces thermal risks, and aligns with the limited but reliable power availability of a portable solar system.

5.3 Performance and Livelihood Impact

Under average Indian solar conditions, the 2 kW flexible solar array can generate approximately 8-10 kWh per day, sufficient to support multiple mobile charges and partial e-bike charging sessions. This energy availability significantly reduces range anxiety for delivery workers and decreases dependence on grid-based charging points.

From a livelihood perspective, the Movable Illumbrella EVC Station introduces a new passive and active income stream for street vendors. Vendors can earn through mobile and EV charging services while simultaneously benefiting from improved lighting, cooling, and hygiene protection offered by the Illumbrella platform. The system thus integrates clean mobility support with economic empowerment, transforming vendors into decentralized energy service providers.

Overall, the Movable Illumbrella EVC Station demonstrates how flexible solar technology and frugal engineering can enable scalable, low-cost EV infrastructure while addressing urban employment and energy-access challenges.

6. Movable Solar Agriculture Pump – Design and 3 HP Pump Integration

The Movable Solar Agriculture Pump represents the agricultural extension of the Illumbrella 2.0 ecosystem, designed to overcome key limitations of fixed solar pump installations deployed under government-supported schemes in Maharashtra and other Indian states. While solar-powered irrigation pumps have significantly reduced diesel dependence, their rigid and stationary configuration often results in seasonal underutilization, vulnerability to monsoon damage, and restricted use of solar energy beyond irrigation.

Field-level findings highlight that many solar pumps operate only 3–5 hours per day and remain idle for nearly 6–7 months annually when irrigation demand is low [21]. During monsoon seasons, fixed solar arrays are exposed to storms, heavy rainfall, hail, and high wind loads, increasing the risk of panel damage and asset loss. Furthermore, conventional systems do not allow farmers to reuse the generated solar power for domestic or alternative agricultural needs, leading to poor overall utilization of high-value solar assets.

6.1 System Design

To address these challenges, Illumbrella 2.0 proposes a portable solar pumping system in which the photovoltaic array is mounted on a movable platform such as a reinforced hatgadi or tractor-towed trailer.

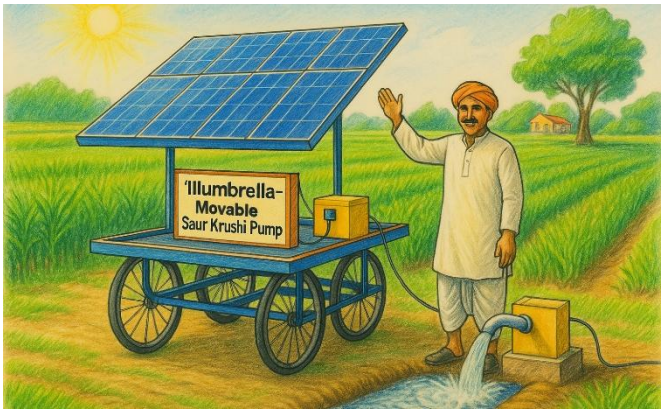

Figure 3: Conceptual illustration of the Illumbrella-2.0 Movable Solar Agriculture Pump system, showing a hatgadi-mounted solar panel array powering agricultural water pumping with portability for field and household use.

Initially, the system employs six flexible and foldable solar panels rated at 500 W each, providing a total installed capacity of 3 kW. The use of high-efficiency (~30%) flexible modules reduces structural stress, improves resistance to environmental exposure, and allows compact storage during adverse weather conditions. Solar power is regulated through an MPPT charge controller and buffered using a 48 V lithium-ion battery system, which supports solar intermittency and high starting current requirements. Power is delivered to the irrigation system through a Variable Frequency Drive (VFD) or DC motor controller, enabling soft-start operation and stable performance.

6.2 3 HP Pump Operation and Energy Reuse

In India, 3 HP, 5 HP and 7.5 HP solar-powered Agriculture pumps are already operational under existing government schemes, demonstrating their feasibility under Indian field conditions. Illumbrella 2.0 integrates this capability into a movable framework, enabling reliable operation of these DC or AC water pump during irrigation periods. Battery buffering ensures consistent water discharge even under partial irradiance.

When irrigation is not required, the same solar platform can be relocated to the farmer's home or farm facility and operated in domestic power mode, supplying clean electricity for lighting, fans, mobile charging, and small appliances. This dual-mode operation significantly increases annual utilization of the solar system.

6.3 Socio-Economic and Energy Impact

By transforming a fixed irrigation asset into a multi-utility portable power system, the Movable Solar Agriculture Pump enhances farmer income stability, reduces diesel and grid electricity expenses, and improves household energy access. The ability to protect panels during monsoons and reuse surplus solar energy strengthens return on public investment in solar pump programs. Overall, the system promotes energy independence, rural resilience, and sustainable agricultural productivity, aligning with India's Net-Zero and Atmanirbhar Bharat objectives.

7. Engineering Safety, Reliability and Environmental Resilience

The deployment of portable solar energy systems requires careful attention to safety, reliability, and environmental robustness. Illumbrella 2.0 is engineered to operate safely and consistently across diverse urban and rural conditions, including street vending zones and agricultural fields.

7.1 Structural and Mechanical Safety

Illumbrella 2.0 uses reinforced frames for umbrellas, hatgadis, and trailers to withstand dynamic loads during movement and operation. The adoption of flexible and foldable solar panels significantly reduces wind loading compared to rigid glass panels, lowering the risk of structural damage during storms. Fold-lock mechanisms allow rapid collapse or secure stowing of the solar array under adverse weather conditions. For agricultural configurations, a low centre-of-gravity design improves stability during transport over uneven terrain, while durable hinges support repeated folding cycles.

7.2 Electrical Safety and Operational Reliability

Electrical safety is ensured through IP65-rated enclosures and integrated protection against over-voltage, over-current, reverse polarity, and short circuits. A 48 V battery architecture provides an effective balance between efficiency

and user safety. In high-power applications such as EV charging and irrigation pumping, soft-start control and Variable Frequency Drives (VFDs) reduce inrush currents, protect motors, and extend system life.

Operational reliability is enhanced through battery buffering and MPPT-based energy management, enabling stable operation under variable solar conditions. The modular system design allows easy maintenance and component replacement, which is particularly important in rural and informal-sector contexts.

7.3 User Safety and Operational Robustness

The foldable and movable architecture minimizes exposure to monsoon-related damage, including heavy rainfall, storms, hail, and flooding, offering a key advantage over fixed solar installations. By replacing diesel pumps and grid-dependent charging, Illumbrella 2.0 contributes to emission reduction, improved air quality, and lower noise levels.

Designed for non-technical users, the system features intuitive operation, insulated connectors, organized cable routing, and hygiene tarpaulins, ensuring safe daily use by street vendors and farmers.

Overall, Illumbrella 2.0 demonstrates that portable renewable energy systems can achieve high safety, reliability, and environmental resilience, making the approach suitable for scalable deployment across India.

8. Economic and Social Impact Assessment

Illumbrella 2.0 delivers significant economic and social benefits by integrating portable clean-energy generation with livelihood-focused applications. The system directly addresses income instability, limited energy access, and productivity constraints faced by street vendors, farmers, and electric mobility users.

8.1 Impact on Street Vendors and Urban Livelihoods

With over 4 crore street vendors forming a major segment of India's informal economy, Illumbrella 2.0 enhances income stability through multiple pathways. Solar lighting extends vending hours, while mobile and EV charging services create additional revenue streams. Advertisement panels on the umbrella canopy enable passive income, and hygiene protection through detachable tarpaulin sheets improves consumer trust and repeat footfall. Together, these features diversify income sources and strengthen vendor resilience.

8.2 Impact on Electric Mobility

The Movable Illumbrella EVC Station provides decentralized micro-charging for delivery workers and urban EV users, reducing range anxiety and operational delays. By offering charging services at high-demand locations without grid dependency, the system complements existing urban infrastructure and supports the adoption of clean two-wheeler mobility.

8.3 Economic Benefits for Farmers

In agriculture, the Movable Solar Agriculture Pump improves utilization of government-supported solar assets by enabling year-round use. When irrigation is not required, the system supplies electricity for domestic needs, reducing dependence on diesel and grid power. The mobility of the solar array also minimizes monsoon-related damage and allows energy sharing across locations, improving economic returns for farmers.

8.4 Social Impact and National Alignment

Illumbrella 2.0 improves safety, comfort, and dignity of work through better lighting, reduced heat stress, and reliable energy access. It promotes energy democratization by enabling decentralized and community-level power generation. These outcomes align with national priorities such as Atmanirbhar Bharat, Net-Zero India, and Viksit Bharat 2047.

8.5 Implementation, Scalability and Field Validation

The system's low-cost, modular design supports local manufacturing through MSMEs and community-level repairability. Scalable deployment can be achieved via street-vendor collectives, farmer cooperatives, CSR partnerships, and municipal adoption. Building on earlier field observations [15], Illumbrella 2.0 enables diverse real-world use cases, including mid-route EV charging, household power during outages, and temporary disaster-relief energy support.

The complete system was presented and demonstrated at a State-Level INSPIRE–MANAK Exhibition, providing stakeholder feedback and practical validation.

9. Environmental Impact and Contribution to India's Net-Zero Goals

Illumbrella 2.0 contributes significantly to environmental sustainability by enabling decentralized, renewable, and fossil-fuel–free energy access across urban and rural settings. By replacing diesel-powered systems and reducing dependence on grid electricity generated from conventional sources, the system directly supports India's long-term Net-Zero emissions target and climate mitigation commitments.

9.1 Reduction in Fossil Fuel Dependence

In the agricultural sector, diesel pumps have traditionally been a major source of greenhouse gas emissions and local air pollution. The Movable Solar Agriculture Pump replaces diesel-based irrigation with solar-powered operation, eliminating fuel consumption, exhaust emissions, and noise pollution. Even in cases where grid-connected electric pumps are used, Illumbrella 2.0 reduces grid load by supplying renewable energy locally, especially during peak daytime demand.

Similarly, the Movable Illumbrella EVC Station supports electric mobility by providing clean solar charging for electric two-wheelers. This reduces indirect emissions associated

with grid-based charging and accelerates the transition away from petrol-powered delivery vehicles.

9.2 Carbon Emission Mitigation Potential

A 3 kW solar system under Indian climatic conditions can generate approximately 12-15 kWh of electricity per day, translating to 4,000–5,000 kWh annually. This generation capacity can offset approximately 3–5 tonnes of CO_2 emissions per year per system, depending on the fuel source displaced. When deployed at scale across street vendors and farming communities, the cumulative emission reduction potential becomes substantial.

By enabling year-round utilization of solar assets—through irrigation, domestic power use, and EV charging—Illumbrella 2.0 maximizes emission avoidance compared to fixed, single-purpose solar installations that remain idle for large portions of the year.

9.3 Environmental Resilience and Resource Efficiency

Illumbrella 2.0 enhances environmental resilience through its foldable and movable solar architecture, which minimizes damage during extreme weather events such as storms, heavy rainfall, and hail. Reduced panel breakage lowers material waste and extends system lifespan, improving overall resource efficiency.

The use of flexible, lightweight photovoltaic modules also reduces material intensity compared to glass-based panels, lowering embodied energy and environmental impact during manufacturing and transportation. Furthermore, modular design enables component-level repair and replacement, reducing electronic waste.

9.4 Support for Sustainable Urban and Rural Ecosystems

In urban environments, Illumbrella 2.0 reduces noise and air pollution by replacing generator-based lighting and charging systems commonly used by vendors. In rural areas, the system supports sustainable irrigation practices while preserving groundwater resources through efficient pump operation enabled by VFD control.

By integrating clean energy into daily economic activities, Illumbrella 2.0 promotes environmentally responsible behavior at the grassroots level, fostering long-term sustainability awareness among users.

9.5 Alignment with National and Global Climate Commitments

Illumbrella 2.0 aligns with India's commitments under the Paris Agreement, national renewable energy targets, and the vision of Net-Zero emissions by 2070. Its decentralized deployment model complements large-scale renewable projects by addressing last-mile energy access challenges and enabling inclusive participation in the clean-energy transition.

Overall, Illumbrella 2.0 demonstrates that small, portable, and people-centric innovations can collectively deliver significant environmental benefits, making them an essential component of India's broader sustainability strategy.

10. Conclusion

Illumbrella 2.0 demonstrates how a simple, everyday object can be transformed into a scalable, high-impact clean-energy ecosystem through frugal engineering, modular design, and advanced flexible solar technology. Building upon the earlier Illumbrella research and MAVIPA field studies, the present work extends the concept from a low-power utility aid into a multi-sector energy platform supporting street vendors, electric mobility users, and farmers.

The study establishes the technical feasibility of portable solar systems operating at 2 kW and 3 kW capacity, enabling practical applications such as EV micro-charging, agricultural irrigation with 3 HP pumps, and domestic electricity supply. By replacing rigid solar installations with movable, foldable, and high-efficiency photovoltaic arrays, Illumbrella 2.0 addresses key challenges of underutilization, monsoon damage, and limited asset flexibility observed in conventional systems. The integration of battery buffering, MPPT control, and VFD-based motor operation ensures reliable performance under variable environmental conditions.

Beyond technical performance, Illumbrella 2.0 delivers measurable economic and social benefits. Street vendors gain improved hygiene, extended working hours, new income streams through charging and advertising, and enhanced work dignity. Farmers benefit from year-round utilization of solar assets, reduced diesel and grid dependence, and improved household energy access. EV users gain decentralized charging access, reducing range anxiety and supporting the transition to clean mobility. Collectively, these impacts contribute to energy democratization and inclusive development.

From an environmental perspective, Illumbrella 2.0 supports India's Net-Zero commitments by reducing fossil fuel consumption, lowering greenhouse gas emissions, and promoting sustainable energy practices at the grassroots level. Its decentralized deployment model complements large-scale renewable energy projects by addressing last-mile energy access challenges in both urban and rural contexts.

11. Future Scope

Future research and development can focus on scaling Illumbrella 2.0 through:

- Integration of next-generation flexible solar materials with higher efficiency and durability,
- Development of smart energy management systems incorporating IoT-based monitoring and predictive control,
- Community-level deployment models enabling shared solar microgrids,
- Policy-level integration with government solar pump, EV, and livelihood schemes,
- Field trials and performance benchmarking across diverse climatic regions.
- Formation of independent rural plug and play grid for the supply of electricity by combining the farmers in group.

Illumbrella 2.0 illustrates that innovation rooted in local needs and practical field experience can evolve into nationally relevant solutions. By combining clean energy, mobility, and livelihood enhancement within a single portable framework, the system offers a replicable model for sustainable development. The work reinforces the idea that India's clean-energy transition can be driven not only by large infrastructure projects, but also by people-centric, frugal innovations capable of empowering millions.

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Author Profile

Arjit Amol More is a student researcher and innovator from Swami Vivekanand High School, Mumbai and a young science communicator, grassroots innovator, and budding physicist. He is the originator of the Illumbrella concept (2019), which has evolved into Illumbrella 2.0 and has been published in *IJSR*. His work focuses on frugal innovation, decentralized renewable energy systems, clean mobility, and livelihood-oriented engineering solutions. Arjit is a recipient of the DST INSPIRE–MANAK Award (2025), along with the Gold Medal in the Dr. Homi Bhabha Balvaidnyanik Competition (2024–25) and multiple Olympiad gold medals. He has also conducted field-based research on solar agricultural pump utilization under the Marathi Vidnyan Parishad (MAVIPA), published in *IJFMR*. Driven by curiosity and social impact, his innovations include bioplastic products from orange peels, an Spinogear, Gutter Guard, Sewage Cage system, automatic shoe shiner, pulley-based physiotherapy device, and rural sanitation solutions developed for national innovation challenges. He is the author of *"Jigyasa: From Curiosity to Clarity"* and actively promotes scientific thinking through his YouTube channel "Littlentist" Arjit aspires to establish a Science and Innovation Centre to empower rural innovators and support India's sustainable development goals.