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Solar-Integrated Electric Vehicles: A Systematic Review of Photovoltaic Technologies, MPPT Systems, and Adoption Barriers

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Abstract

The global transition toward sustainable transportation has accelerated interest in Vehicle-Integrated Photovoltaics (VIPV) as a supplementary energy source for Electric Vehicles (EVs). This paper presents a systematic literature review following the PRISMA 2020 framework, synthesizing 72 peer-reviewed studies published between 2015 and 2025, sourced from Scopus, Web of Science, IEEE Xplore, and ScienceDirect. The review is structured around five principal themes: photovoltaic cell and module technologies, energy yield performance and driving range extension, Maximum Power Point Tracking (MPPT) algorithm effectiveness under dynamic vehicular conditions, barriers to EV manufacturer adoption, and safety risks with proposed engineering solutions. Findings indicate that monocrystalline silicon cells dominate commercial VIPV at 20-24% efficiency, while perovskite-silicon tandem cells have achieved certified laboratory efficiencies exceeding 34%. AI-enhanced MPPT algorithms demonstrate 16-25% superior energy extraction over conventional Perturb and Observe methods under shaded conditions. Key adoption barriers include high integration costs, limited roof surface area (~1.7-2 m2), immature supply chains, and absent standardized testing protocols. Safety risks encompass arc faults, thermal runaway, high-voltage exposure, and structural vulnerability, addressable through smart disconnect circuits, advanced Battery Management Systems, and automotive-grade encapsulation. Tropical regions such as Indonesia, with average Global Horizontal Irradiance (GHI) of 4.8 kWh/m2/day, represent an exceptional and critically under-researched VIPV opportunity for Southeast Asian automotive industries.

Keywords: *Vehicle_integrated_photovoltaics (VIPV); Electric_vehicles; Solar_energy; Maximum_power_point_tracking (MPPT); Adoption_barriers.*

INTRODUCTION

The transportation sector accounts for roughly 25% of global CO_2 emissions, and Electric Vehicles (EVs) have emerged as one of the most practical responses to this challenge [1]. Yet even as EV adoption grows, range anxiety remains a persistent concern among potential buyers [2]. Vehicle-Integrated Photovoltaics (VIPV) offers a partial answer to this problem by embedding solar cells directly into vehicle surfaces such as the roof, hood, trunk, and side panels, allowing the car to generate energy continuously while driving or parked. As manufacturing costs have declined and cell efficiencies have improved, VIPV has gradually moved beyond its origins in solar racing competitions toward genuine commercial relevance [3, 4]. Early examples include the Toyota Prius PHV solar roof and the Hyundai Sonata hybrid, and prototype solar EVs from Lightyear and Sono Motors showed that fully solar-assisted vehicles were at least commercially imaginable [4].

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Despite this progress, VIPV has not been widely adopted by mainstream EV manufacturers. The reasons are practical: the surface area available on a car roof is small, typically around 1.7 to 2 m², which limits how much power the panels can realistically generate. This is enough to extend range modestly or support auxiliary systems, but not enough to replace conventional charging. Added to this are high integration costs, reduced panel performance under cloud cover or urban shading, and the reality that most automakers have prioritized battery and charging infrastructure improvements over solar integration. Safety considerations specific to VIPV, including arc faults, high-voltage exposure during crashes, and increased thermal risks for the battery, have also received limited attention in the literature [3, 4].

What makes this gap particularly striking is the geographic context. Indonesia receives an average daily Global Horizontal Irradiance (GHI) of 4.8 kWh/m²/day [6], which exceeds the solar resource available in Germany, Japan, and Singapore, the countries where most existing VIPV research has been conducted. For a country with a large vehicle market, growing EV policy support, and abundant year-round sunshine, the absence of VIPV-focused research is a significant oversight. This review was motivated by that gap. It addresses five research questions: (RQ1) which PV cell technologies are best suited for vehicle integration; (RQ2) what energy yields and driving range extensions are achievable across different geographies and climates; (RQ3) how MPPT algorithms perform under the shading conditions typical of vehicular use; (RQ4) what barriers are preventing widespread VIPV adoption by EV manufacturers; and (RQ5) what safety risks exist and which engineering solutions have been validated.

METHOD

This study follows the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework [7], which is the standard approach for systematic literature reviews in engineering research. The database search covered Scopus, Web of Science, IEEE Xplore, and ScienceDirect, and was restricted to publications from January 2015 to March 2025. The year 2015 was chosen as the starting point because it broadly marks the period when VIPV research began engaging seriously with modern EV technology. Studies published before this tend to focus on earlier solar and battery configurations that do not reflect the current state of either photovoltaic or electric vehicle development, and including them would have introduced findings that are difficult to compare with more recent work.

The primary search string used was: ("vehicle integrated photovoltaics" OR "VIPV" OR "solar electric vehicle" OR "photovoltaic electric vehicle") AND ("efficiency" OR "MPPT" OR "energy yield" OR "range extension" OR "solar cell" OR "perovskite" OR "safety" OR "adoption" OR "barrier"). Additional searches were run separately to capture literature on safety risks, adoption barriers, and tropical climate performance, areas that did not always surface consistently through the primary string. Inclusion and exclusion criteria are summarized in Table 1.

Table 1. Inclusion and exclusion criteria for the systematic literature review.

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Criterion	Inclusion	Exclusion
Publication type	Peer-reviewed journal articles, indexed conference papers	Book chapters, theses, grey literature
Language	English only	Non-English publications
Date range	January 2015 - March 2025	Publications before 2015
Topic relevance	PV integration in EVs or hybrid vehicles	Non-EV solar systems; general EV topics unrelated to solar
Technology focus	VIPV hardware, MPPT algorithms, safety, adoption studies	Purely theoretical modeling without empirical validation
Data quality	Quantitative performance metrics or validated findings	Opinion pieces without primary data synthesis

Source: *Author (2026)*

The initial search returned 1,847 records. After removing duplicates, 1,203 unique records remained for screening. At the title and abstract stage, 1,031 records were excluded. The most common reason for rejection was topic mismatch: a large proportion of results covered solar energy systems or electric vehicles in a general sense, without actually addressing photovoltaic integration into vehicle bodies. Papers that were purely theoretical, lacked empirical testing, or presented no performance data relevant to VIPV were also excluded at this stage.

The remaining 172 articles were assessed in full text. Quality appraisal used a modified Critical Appraisal Skills Programme (CASP) checklist, applied as a guide rather than a rigid scoring system. In practice, inclusion required that a study had clearly described methods, reported actual performance data or validated findings, and maintained direct relevance to vehicle-integrated photovoltaics. Studies that made broad claims without adequate validation, or whose findings felt too speculative to be useful for synthesis, were not included. This process yielded a final corpus of 72 studies. The full PRISMA flow is summarized in Table 2.

Table 2. PRISMA 2020 flow summary of study selection process.

PRISMA Stage	Action	Records
Identification	Database search (Scopus, WoS, IEEE Xplore, ScienceDirect)	1,847
Identification	Duplicates removed	644
Screening	Records screened (title + abstract)	1,203
Screening	Records excluded (out of scope)	1,031
Eligibility	Full-text articles assessed	172
Eligibility	Full-text excluded (low quality, topic mismatch)	100
Included	Studies included in final synthesis	72

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RESULTS AND DISCUSSION

1. Photovoltaic Technologies for Vehicle Integration

Solar panels designed for vehicle integration cannot simply be taken from a rooftop installation and attached to a car. VIPV modules must meet a different set of requirements entirely: they need to be lightweight, able to conform to curved body surfaces, resistant to physical impact and vibration, and visually acceptable as part of the vehicle design [4]. Five main cell technology categories came up consistently across the reviewed literature.

1.1 Monocrystalline Silicon

Monocrystalline silicon remains the most commercially established option for VIPV. Module efficiencies sit between 20 and 24%, and the technology has a demonstrated service life of around 25 years, which matters for a component that needs to survive the full operational life of a vehicle [3]. Heinrich et al. found that a c-Si roof panel covering 1.7 to 2 m² could add between 1,900 and 3,400 km of solar-assisted driving per year under Central European conditions [11]. The main drawback is physical: standard glass-glass modules weigh more than 11 kg/m² and do not bend, which limits where they can realistically be installed on a vehicle body [4]. Shingling technology, which eliminates the gaps between cells using conductive adhesive, helps improve both surface coverage and visual integration [55].

1.2 CIGS and Thin-Film Technologies

CIGS and other thin-film technologies trade some efficiency for physical flexibility and lighter weight, both of which are genuinely useful properties for vehicle integration. Commercial efficiencies range from 14 to 18%, with laboratory CIGS reaching close to 23%. IMEC demonstrated prototype VIPV modules below 6 kg/m² using glass-fiber reinforced encapsulants, cutting weight by roughly half compared to conventional modules [55]. The U.S. Department of Energy's 2022 VIPV Request for Information flagged domestic thin-film manufacturing as a strategically important supply chain gap [41].

1.3 Perovskite and Tandem Cells

Perovskite cells have developed faster than almost any other solar technology in recent history. Starting from a certified efficiency of 3.8% in 2009, single-junction perovskite cells had reached 26.1% by the time of this review [23], and LONGi reported a certified perovskite-silicon tandem efficiency of 34.58% in 2024 [24]. They can be manufactured through low-temperature solution processing onto flexible substrates, which makes them potentially cheaper to produce than silicon at scale [25]. Semi-transparent variants with efficiencies around 17.95% are also being evaluated for window integration in vehicles [22]. The problem that has not been solved yet is outdoor durability: performance loss rates of 7 to 8% per month have been reported in outdoor testing, with the best-performing specimens retaining around 78% efficiency after one year [24]. A comparison of all five technologies is provided in Table 3.

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Table 3. Comparative overview of PV cell technologies evaluated for VIPV application

Technology	Efficiency (Commercial)	Lab Record	Key VIPV Advantage	Primary Limitation	Authors
Monocrystalline Si (c-Si)	20-24%	~27%	Proven reliability, mature supply chain	Heavy and rigid; poor curvature conformance	Heinrich et al., 2020; Commault et al., 2021
CIGS Thin-Film	14-18%	~23%	Flexible, lightweight, diffuse-light performance	Lower efficiency than c-Si	Commault et al., 2021; Tous, 2021
Multi-junction / III-V	28-32%	~47%	Highest efficiency available	Extremely high cost, limited scalability	Rezaei et al., 2023
Perovskite (single-junction)	~20-22%	26.1%	Low-cost fabrication potential, high efficiency	Stability concerns outdoors	Cao et al., 2024
Perovskite-Si Tandem	~24-27%	34.58%	Breakthrough efficiency, future cost parity	Early commercialization; durability unproven	Kim et al., 2026

Source: *Author (2026)*

2. Energy Yield Performance and Driving Range Extension

How much range a VIPV system actually adds depends on several interacting factors: available irradiance, the surface area covered by panels, cell efficiency, module angle, shading patterns, and local climate conditions. Research shows that the solar radiation hitting a vehicle roof can be anywhere from 1.09 to 3.85 times greater than what reaches the side panels, depending on the season and weather [9]. Heinrich et al. established that a 1.7 to 2 m² c-Si roof installation adds between 1,900 and 3,400 km of solar range per year in Central Europe [11]. A Dutch study using a Vehicle Irradiance Test System found that under favorable conditions VIPV could meet up to 40% of total vehicle energy demand, translating to over 5,000 km per year [4]. A spatial analysis of 48,827 parking locations in Berlin found daily range extensions of 7 to 14 km, with median annual savings of EUR 164 from reduced grid charging [8].

Indonesia sits in a meaningfully different position compared to all of these study locations. With an average daily GHI of 4.8 kWh/m²/day, Indonesia receives more solar energy than Germany, Japan, China, and Singapore [36]. That advantage is real, but it comes with a complication. High ambient temperatures reduce silicon PV efficiency by roughly 0.4 to 0.5% for every degree Celsius above 25°C [31], and panels on vehicles in tropical climates routinely reach 60 to 70°C, which can offset 15 to 25% of the irradiance gain [33]. For equatorial deployment specifically, thermally robust cell materials and active cooling systems are not optional extras but practical necessities. Comparative energy yield data across locations are provided in Table 4.

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Table 4. Comparative VIPV energy yield data by geographic location.

Location	Climate	GHI (kWh/m2/day)	Annual Solar Range Added	Authors
Freiburg, Germany	Temperate	~3.0	1,900-3,400 km/year	Heinrich et al., 2020
Netherlands	Maritime	~2.8	Up to 5,000 km/year (40% energy)	Commault et al., 2021
Berlin, Germany	Continental	~3.1	2,527 km/year (median)	Urban et al., 2024
Multiple EU cities	Mixed temperate	~2.9-3.4	2-7 km/day (185W module)	Özden et al., 2025
Indonesia (projected)	Tropical	4.5-6.0	Projected >5,000 km/year	Mangkuto et al., 2024; DSNEG, 2024

Source: *Author (2026)*

3. Maximum Power Point Tracking (MPPT) Systems in Solar EVs

A MPPT controller continuously adjusts the electrical operating point of a PV array to extract the maximum power available at any given moment [12]. In a stationary rooftop installation this is relatively straightforward, but in a moving vehicle the conditions change constantly. Rapid transitions between shade and sunlight, changes in driving direction, varying angles of incidence, and high-frequency road vibration all cause sudden shifts in PV output that standard algorithms may not respond to quickly enough [14].

The Perturb and Observe (P&O) algorithm is the most commonly used method because of its simplicity, but under rapidly changing irradiance it tends to oscillate around the maximum power point rather than locking onto it, which means energy is lost [12, 16]. Incremental Conductance (IC) is more accurate under stable conditions but can behave erratically when irradiation changes quickly [12]. A modified 0.8VOC-based method showed 15 to 25% higher energy generation compared to both IC and variable-step P&O across three simulated EV models [18]. Particle Swarm Optimization (PSO) handles partial shading better than IC by navigating the multiple local maxima that appear in the power-voltage curve when parts of a panel are shaded [18]. The most sophisticated approach reviewed was Artificial Neural Network (ANN)-based MPPT, which uses irradiance, temperature, and load data to predict the optimal converter duty cycle in advance rather than reacting after the fact, achieving tracking efficiencies close to 99% [21]. A full comparison of algorithm performance is provided in Table 5.

What Table 5 makes clear is that algorithm choice has a direct and measurable effect on how much energy a VIPV system actually recovers. The gap between conventional P&O and AI-based methods exceeds 15% under urban shading conditions. This is particularly relevant for Indonesian cities: Jakarta, Surabaya, and Denpasar all involve dense traffic environments where shading from buildings, overpasses, and other vehicles is constant. In those conditions, the difference between a basic charge controller and an ANN-based system is not trivial. That said, the higher cost of PSO and

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ANN implementations means they are not practical everywhere. A more sensible approach is to match the algorithm to the deployment context, using simpler adaptive controllers in rural or suburban settings and reserving advanced MPPT for urban environments where partial shading losses are most severe.

Table 5. Comparative performance of MPPT algorithms for VIPV applications.

MPPT Algorithm	Tracking Accuracy	Partial Shading	Cost	Best Suited For	Authors
Fixed-step P&O	~85-92%	Poor; oscillates at MPP	Very Low	Not recommended for VIPV	Hassan et al., 2024
Variable-step P&O	~90-95%	Moderate	Low	Mild shading; basic VIPV	Hassan et al., 2024
Incremental Conductance (IC)	~92-95%	Moderate; can oscillate	Low-Med	Semi-urban VIPV	Khatib et al., 2013
Modified 0.8VOC	~93-96%	Good; 15-25% over IC	Medium	Urban VIPV with shading	Özden et al., 2025
Particle Swarm Opt. (PSO)	~96-98%	Very Good; escapes local maxima	Med-High	Dense urban VIPV	Ullah et al., 2025
Artificial Neural Network (ANN)	~98-99%	Excellent; predictive	High	High-performance tropical VIPV	Ullah et al., 2025
Fuzzy Logic Control (FLC)	~95-97%	Good; robust to rapid changes	Medium	Variable cloud cover conditions	Gul et al., 2025

4. Barriers to VIPV Adoption by EV Manufacturers

As of 2025, VIPV has not moved far beyond the edges of the commercial market. Toyota and Hyundai offer optional solar roof packages, but major manufacturers including Tesla, BYD, Volkswagen, and General Motors have not adopted the technology. The IEA-PVPS 2025 report characterizes VIPV as stuck at the innovator and early adopter stages of the Diffusion of Innovation curve, unable to cross into mainstream uptake [48].

Cost is the barrier that comes up most consistently. The U.S. Department of Energy's 2022 VIPV Request for Information identified it as the primary obstacle [41]. Payback periods can exceed the operational lifetime of the vehicle itself, and because the available roof area is limited to roughly 1.7 to 2 m², maximum installed capacity tops out at around 400 to 600 Wp. The daily energy output from that capacity is modest and difficult to justify against the premium charged for integration, especially when compared to simply adding equivalent battery capacity [3, 11]. Beyond cost, integrating PV modules into vehicle bodies requires significant changes to manufacturing processes, and the supply chain for conformal VIPV modules has not scaled to automotive production volumes [41]. The modules themselves also need to survive conditions that standard PV equipment is not designed for: stone chips, hailstorms,

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high-pressure washing, temperature cycling between -40°C and +85°C, and vibration frequencies up to 2,000 Hz [49].

The regulatory picture adds another layer of difficulty. There is currently no internationally agreed standard for VIPV performance testing. Stationary solar panels are governed by mature IEC 61215 and IEC 61730 frameworks, but no equivalent exists for vehicle-integrated systems that must account for dynamic irradiance, curved surfaces, and automotive mechanical loads [49]. Without standardized testing, manufacturers have no common basis for certifying performance or safety. Consumer perception compounds the problem: research shows that buyers tend to underestimate how much range solar panels can realistically add, or assume that VIPV means the vehicle runs entirely on solar power [48]. A summary of adoption barriers is provided in Table 6.

Table 6. Summary of barriers to VIPV adoption by EV manufacturers.

Barrier Category	Specific Barrier	Severity	Authors
Economic	Payback period exceeds vehicle lifetime at current costs	High	Muntwyler & Schüpbach, 2025; U.S. DOE, 2022
Economic	Small roof area limits installed capacity and ROI	High	Heinrich et al., 2020; Commault et al., 2021
Manufacturing	Immature VIPV-specific supply chain	High	U.S. DOE, 2022; Muntwyler & Schüpbach, 2025
Manufacturing	Automotive-grade durability requirements unmet	Med-High	Araki et al., 2024; Muntwyler & Schüpbach, 2025
Technical	Vibration-induced resonance in module substrates	Medium	Araki et al., 2024
Regulatory	No international VIPV performance testing standard	High	Araki et al., 2024
Market	Consumer misunderstanding of VIPV capability	Medium	Muntwyler & Schüpbach, 2025; Lee et al., 2025

Source: *Author (2026)*

5. Safety Risks and Engineering Solutions

Combining photovoltaic systems with high-voltage EV architecture creates a safety profile that is different from either technology in isolation. A standalone EV can be de-energized. A stationary solar panel can be disconnected. A VIPV system does neither cleanly: the solar modules remain live whenever sunlight reaches them, including after a crash, during maintenance, and in situations where emergency responders need to work on the vehicle [57].

5.1 Electrical Safety Risks

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Arc faults can develop at wiring connections between PV modules and the DC power bus, caused by crash damage, vibration fatigue over time, or moisture getting into connections. The temperatures generated by electrical arcs can exceed 19,500°C, producing toxic smoke and acoustic shock waves [57]. The inability to de-energize VIPV modules without physically blocking all sunlight makes high-voltage exposure during crashes and maintenance a persistent hazard. Emergency responders who cut wiring on a crashed VIPV vehicle without knowing the system layout face a real electrocution risk [57]. There is also a subtler issue: to enable solar charging while the vehicle is parked, the Battery Management System must stay active. If standby power consumption exceeds what the panels are generating, the system has to shut down entirely to avoid draining the auxiliary battery [51].

5.2 Thermal and Mechanical Risks

Of all the safety risks reviewed, thermal runaway stood out as the most serious concern. EV battery fires driven by thermal runaway are already difficult to extinguish once they start [60], and VIPV adds a new pathway to trigger them. A fault in the solar charge controller or MPPT circuit can push unregulated current into the battery pack, which is a known thermal runaway initiation condition. The connection between solar charging and battery safety means that power regulation failures in the VIPV system are not just an efficiency problem but a fire risk. Beyond this, PV modules in tropical vehicle integration contexts regularly reach temperatures of 60 to 80°C, which accelerates encapsulation delamination and risks insulation failure over time [9]. Vibration is another underappreciated problem: rooftop frequencies can reach 2,000 Hz, which is two to three orders of magnitude above the 0.1 to 10 Hz range that conventional PV encapsulation materials are engineered for, creating conditions for resonance and microcracking in solar cell substrates [49].

5.3 Proposed Engineering Solutions

Several engineering responses to these risks have been developed or proposed. Module-level rapid shutdown systems using MOSFET switches can cut solar current within milliseconds of crash detection through the airbag deployment signal, significantly reducing post-crash electrical hazard [57]. For encapsulation, automotive-grade polyvinyl butyral (PVB) outperforms standard EVA on both impact resistance and acoustic properties, and a hybrid strategy combining a PVB impact layer with a hydrophobic polymer moisture barrier has been proposed to meet both PV and automotive requirements at once [55]. An enhanced BMS architecture with dedicated overcurrent protection on the solar input channel, using dynamic limits that adjust in real time based on state-of-charge and temperature, can prevent thermal runaway from unregulated solar charging while also reducing battery calendar ageing by 9% and grid charging frequency by 23% [51]. Active micro-channel cooling beneath module substrates has been validated computationally to recover 10 to 20% of efficiency losses from thermal degradation, with larger gains expected in tropical deployment contexts [9]. Safety risks, proposed solutions, and current development status are summarized in Table 7.

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Table 7. VIPV safety risks, proposed engineering solutions, and development status.

Safety Risk	Severity	Proposed Solution	Status	Authors
Arc fault at solar wiring	High	Rapid shutdown/smart disconnect	Prototype/Standards dev.	Ismail et al., 2024; Araki et al., 2024
High-voltage post-crash exposure	High	Crash-triggered solar circuit isolation	Proposed/Partial deploy.	Ismail et al., 2024
BMS standby losses	Medium	Intelligent standby management in BMS	Validated in simulation	Bhatt et al., 2025
Thermal runaway from solar input	High	Solar-specific BMS overcurrent protection	Proposed	Wang et al., 2021; Bhatt et al., 2025
PV module thermal degradation	Medium	Active micro-channel cooling	Computationally validated	Samadi et al., 2023; Rezaei et al., 2023
Vibration-induced microcracking	Medium	High-frequency vibration-rated encapsulants	Prototype stage	Araki et al., 2024; Muntwyler & Schüpbach, 2025
Moisture ingress/encapsulant failure	Medium	Hybrid PVB + hydrophobic barrier	Research stage	Muntwyler & Schüpbach, 2025

Source: *Author (2026)*

6. Discussion

Going through 72 studies on VIPV produced a few findings that were genuinely unexpected. The technology itself is further along than its market presence suggests. The energy contribution numbers are solid: 1,900 to 3,400 km of added range per year in temperate climates, with conservative projections pushing past 5,000 km per year for Indonesia's irradiance conditions. That represents roughly 10 to 30% of typical annual vehicle mileage in Indonesia, which is a meaningful number, not a marginal one [36]. What was more surprising was how consistently the barriers holding VIPV back turned out to be non-technical. Supply chain immaturity, absent testing standards, cost structures tied to low production volumes, and consumer misunderstanding are all problems that do not require scientific breakthroughs to solve. They require investment, policy coordination, and time.

The MPPT findings reinforced something that is easy to overlook when focusing on panel efficiency: how the energy is managed matters as much as how it is generated. The 16 to 25% performance gap between conventional P&O and AI-based algorithms is not a minor optimization. In a city like Jakarta or Denpasar, where dense traffic means frequent shading transitions throughout the day, that gap translates into a meaningful difference in actual range added. VIPV deployments in Indonesian urban environments should treat advanced MPPT hardware as a core component rather than an optional upgrade.

On safety, the reviewed literature does not support the conclusion that VIPV makes vehicles inherently more dangerous. What it does show is that the risks are real and specific, and that they require engineering responses that go beyond what either standard EV or stationary PV design currently provides. Thermal runaway risk from

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unregulated solar input is the concern that stands out most, precisely because battery fires in EVs are already difficult to manage once initiated. The good news is that the proposed solutions, rapid shutdown systems, enhanced BMS architectures, improved encapsulation, are all technically feasible. The gap is standardization and regulatory clarity, which IEC TC82 PT600 is beginning to address.

The finding that stayed with me most from this entire review is how few of the 72 studies had anything to say about tropical climates. Only four included empirical or simulation data from Southeast Asia or equatorial regions [34, 39, 40, 33]. No published study has measured actual VIPV performance on Indonesian roads. Indonesia has some of the highest GHI of any major economy, a growing EV market, supportive policy under Presidential Regulation No. 55/2019, and 2024 regulatory reforms expanding rooftop solar adoption [36]. The conditions for VIPV development here are better than in any of the markets currently leading VIPV research. The research simply has not followed. Critical gaps that need filling include empirical VIPV performance data from tropical climates, standardized testing protocols for automotive-grade mechanical and environmental loads in high-temperature conditions, long-term outdoor stability data for perovskite modules under tropical humidity and UV exposure, life-cycle assessment data for tropical VIPV deployment, and consumer acceptance research in emerging market contexts.

CONCLUSION

This review covered 72 peer-reviewed studies under the PRISMA 2020 framework and examined VIPV from five angles: photovoltaic technology options, energy yield and range performance, MPPT algorithm effectiveness, manufacturer adoption barriers, and safety risk. The overall picture that emerges is of a technology that works, that is becoming more economically justifiable, and that is being held back by barriers that are solvable rather than fundamental.

On the technology side, monocrystalline silicon delivers reliable VIPV performance with proven commercial infrastructure behind it. Perovskite-silicon tandem cells, now reaching 34.58% efficiency in certified testing, represent what the next generation of VIPV could look like if outdoor stability issues are resolved. ANN and PSO-based MPPT algorithms can recover up to 99% of available solar energy even under complex urban shading, which matters most in exactly the kind of dense city environments where EVs are most commonly used. Safety risks from arc faults, thermal runaway, and crash exposure are genuine but addressable through rapid shutdown systems, better BMS design, and automotive-grade encapsulation, none of which depend on technology that does not yet exist.

The conclusion that feels most important, particularly from an Indonesian perspective, is that the tropical region is the most underresearched and simultaneously the most promising geographic context for VIPV. Indonesia's GHI of 4.8 kWh/m²/day exceeds Germany, Japan, and Singapore. The domestic vehicle market is large. EV policy support is growing. And yet the research base for VIPV in this context is almost nonexistent. Future work should focus on real-world VIPV performance measurement on Indonesian roads, cooling system design optimized for high-temperature high-irradiance conditions, perovskite stability under tropical humidity and UV, and

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consumer willingness-to-pay research in the Indonesian EV market. This review is meant to be a starting point for that work, not an endpoint.

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