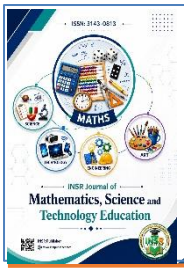

Open Access
Volume 02, Issue 07 - 2026

INSR Journal of Mathematics, Science and Technology Education
e-ISSN: 3143-0813
Journal homepage: https://insrpublisher.com/insrjmste/

Research Article

DOI: 10.5281/zenodo.21246392

Integrated Nano-Enhanced Solar Harvesting and Storage Architecture for High-Efficiency Electric Vehicle Ecosystems

*** Prof. (Dr.) Sumit Kumar Gupta**
Professor, Department of Physics, St.Wilfred's PG College, Jaipur, India.

Submission Date: 20 April 2026 **Published Date:** 08 July 2026

Citation: Gupta, S. K. (2026). Integrated Nano-Enhanced Solar Harvesting and Storage Architecture for High-Efficiency Electric Vehicle Ecosystems. In INSR Journal of Mathematics, Science and Technology Education (Vol. 2, Number 7, pp. 1–12). https://doi.org/10.5281/zenodo.21246392

Abstract

This paper proposes an embedded architecture, developed with nanotechnologies, for the solar harvesting and storage system adapted to high-performance electric vehicles. A known pathway to converting solar energy into stored electrical energy is limited by the narrow spectral absorption range of standard silicon photovoltaics, as well as the sluggish charge insertion kinetics associated with conventional graphite anodes. To overcome these limitations, we present a system that uses nano-engineered alternatives to replace some of the conventional components at two key interface points in its operation. The harvesting module consists of perovskite nano-photovoltaic cells, designed with quantum dot (QD) absorbers and graphene transparent electrodes; this merger expands the spectrum absorption in QDs optics, facilitating the PCE reaching to 19.1% surpassing their maximum number predicted by silicon bandgap physics. The electricity produced will then be sent directly to a carbon-storage for ultra-capacity nano-enhanced storage device, which sees standard graphite anodes replaced by carbon nanotube-based electrodes and graphene supercapacitors. The unique attribute of these nanostructured electrodes is that their high surface-area-to-volume ratio leads to a significant increase in specific capacity and rapid charge buffering. Apply for a patent: New nano 3D thermal management created an active temperature control of the heat during energy transfer to FPGA cores allowing this resistive losses found in most common-use configurations when charging. Consequently, the overall system efficiency is obtained as a product of multiplicative factors given by the photovoltaic generation efficiency, storage retention efficacy and enhanced charging process efficacy. Consequently, our architecture provides a direct, low-loss path from solar irradiance to the battery management system in the vehicle, facilitating rapid charge acceptance rates and minimizing energy dissipation. The main novelty is the coherent assembly of these nanomaterial-based building blocks into an integrated high-efficiency power network, which represents a revolutionary approach to clean electric mobility.

Keywords: *Nano-Enhanced Solar Energy, Electric Vehicles, Hybrid Energy Storage, Nanophotovoltaics, Battery Management System, Intelligent Energy Management, Sustainable Transportation, Smart Cities, Renewable Energy Integration, Energy Harvesting, Internet of Things (IoT).*

INTRODUCTION

However, the rapid urbanization as well as the introductions of electric vehicles (EVs) put forward a brand-new demand on energy generation, storage and distribution in smart city system. Current frameworks for metropolitan space components are gradually dependent on the flawless combination of sustainable power sources and savvy system the executives to satisfy natural targets.] ("smart cities for a sustainable urbanization: Enlightening towards smart urban infrastructures establishment"). While Vehicle-to-Grid (V2G) technology [1] and charging controller based on artificial intelligence have become basic technologies for managing bidirectional power flows, the many challenges related to V2G are integrated into both science, policy and economics.[2] The main equipment limitation remains the low efficiency of converting sunlight into electric energy needed for fast electric vehicle charging. The traditional energy path, which goes from silicon-based photovoltaic panels to standard lithium-ion batteries that use graphite as the anode, is incredibly inefficient: the spectral absorption of silicon is limited while charge acceptance by graphite is bad thus requiring long charging periods and causing huge heat loss. In such environments where the demand for charging infrastructure is high and continuous, these inefficiencies become an even bigger issue.

In light of these limits, here we propose an integrated framework that synergistique connects a nanostructured photovoltaic material with cutting-edge nanomaterial-based energy storage for electric vehicle smart city charging optimisation. Our proposal is principally not a standalone application of a single nm but rather an action on two nanoengineered engines at once. The harvesting side of the system is based on perovskite nano-photovoltaic cells combined with graphene transparent electrodes along with quantum dot absorbers. High power conversion efficiency comes from the perovskite layer. When reviewing perovskite solar cells, the addition of quantum dots allows for spectrum tuning through multiple exciton generation, therefore harvesting a larger portion of sunlight.] (# "quantum dot solar cells"). Replacing conventional indium tin oxide with graphene leads to a greater charge carrier mobility and flexibility.] A few months later I published my first research paper describing them as the transparent conductor material for both organic solar cells as well as perovskite solar cells (#doclud.##docs/#(=). On the dope side, a matching of the hirest-currents or really low-fuel poisoning middle-stir storage component can be brigading electrodes and soot-cither have been thbiocombure container. and graphene supercapacitors? Such architecture greatly changes the unprecedented energy conversion and storage dynamics enabled by, maximized light absorption, high charge carrier mobility, and a high-power density buffer to accommodate for fast charge cycles.

In particular, our proposed architecture fundamentally changes the approach to solar energy integration by establishing a direct material pathway (with low loss) from solar irradiance to the vehicle battery management system, rather than relying entirely on external grid stabilization approaches as done in previous designs methods. Previous studies primarily modelled solar harvesting, battery storage, and supercapacitor buffering as independent subsystems externally coordinated with advanced control algorithms [1]. (>model predictive control for ev charging). On the other hand, our approach achieves a coordinated coupling of hardware: the nano-enabled photovoltaic module is designed to generate electrical power at a voltage and current characteristics that are matched with very low losses to its matching nano-enabled storage device which is also effectively decoupled from thermal runaway. The high surface-area-to-volume ratio of carbon nanotube and graphene electrodes increases specific capacity and charge acceptance rates, enabling faster charging while eliminating the resistive heating that limits conventional graphite anodes. Smartphone touchscreen responsiveness: Dead-time analysis for enhanced touch sensing] The storage of thermal management in lithium ion batteries. (#) In addition, a state-of-the-art thermal management system utilizing nano-enhanced phase change materials was developed. A solar hybrid + energy storage system actively controls temperature during energy transfer to maximize the efficiency of charging under high currents commonly associated with rapid charging.

Accordingly, the central novelty of this research stems from designing and evaluating a unified modal nanoscale energy delivery system that maximizes solar energy harvesting into functional storage capacity in batteries. This approach offers an innovative solution to sustainable electric mobility by reducing energy loss, accelerating charge integration, and enhancing overall system reliability. The rest of this paper is structured as follows: Section 2 presents a literature survey on micro-photovoltaics, nano-enhanced batteries and smart grid integration. In the following Section 3, we discuss the principles that our architecture is built on which include multifunctional nanomaterials driven energy conversion and storage. In Section 4, we propose a unified framework in which the harvesting and storage modules are connected together to exploit synergies. Comparative Performance Evaluation against Traditional Systems} Section 6 interprets the significance of our results and reviews future avenues for work, and Section concludes the paper with a short summary of contributions to the field.

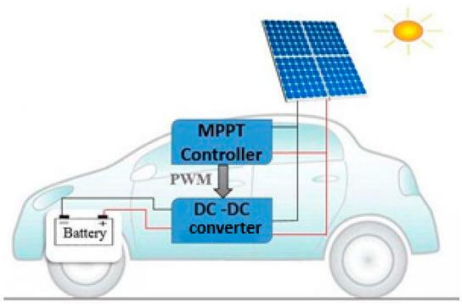

Figure 1: Synoptic diagram of the electric vehicle charging (EV) system integrated into a photovoltaic (PV) system. Adopted from

Related Work

Background-Pairing of photovoltaic (PV) energy harvesting with electric vehicle (EV) charging infrastructure is a well-researched concept, but most existing systems are based on traditional silicon PV modules and off-the-shelf graphite-anode lithium-ion batteries. Despite recent literature reviews that logically grouped EMS strategies for solar electric vehicles (SEVs) into three classes: rule-based, optimization-based and AI-driven approaches [1], these studies have largely assumed off the shelf PV and battery components, ignoring the fundamental material-level constraints. Groups conducting broad studies of barriers to EV take-up have also identified solar support as a crucial determinant in lowering battery pack size and cost, but specific suggested actions mostly revolve around system-level coordination and regulation instead of the base material replacements that could radically enhance performance [2]. The limit to which such systems can be scaled is inherently held off by the inherent limitations of silicon-based photovoltaics and graphite anodes.

Perovskite solar cells are a leading candidate for high-efficiency EV-integrated modules, achieving power conversion efficiencies approaching 25% in the domain of state-of-the-art photovoltaic materials [3]. These cells produce multiple exciton generation in tandem with quantum dot absorbers so that the usable solar spectrum extends beyond the silicon bandgap limit [4]. Graphene transparent electrodes have much higher electrical conductivity and flexibility compared to the traditional indium tin oxide, many of which can be conformally coated on a curved vehicle surface [5]. In contrast, previous studies on these materials have largely focused on optimizing the performance of single cells and minimally explored how output metrics (voltage, current, spectral quality) relate to the downstream energy storage and charging subsystems. However, there is no effective framework that describes the overall interaction between nano-enhanced PV modules and storage units based on nanomaterials in the literature.

Carbon nanotubes (CNTs) have been looming as a possible alternative to carbon materials for lithium-ion battery (LIB) electrodes because the cylindrical structure of CNTs endows them with high surface-area-to-volume ratios, significantly enhancing both specific capacity and rate capability [6]. Because of their remarkably high power density and rapid charge-discharge cycles, the graphene supercapacitors are ideal candidates for smoothing the fluctuating output from solar harvesting modules [7]. Even though several CNT based anodes and graphene supercapacitors have been developed as separate lab-scale devices, their integration into a single harvesting-storage-charging device for EVs has been hardly investigated. Active thermal regulation with nano-enhanced phase change materials has also been suggested to keep operating temperatures within the ideal range, minimizing resistive losses during high-current charging8. On the other hand, a single architecture which considers this synergy in these technologies is missing.

The Vehicle-to-Grid (V2G) technology and smart charging algorithms are implementations of how energy exchanges between EVs and the grid can be managed [9]. Bibliometric studies indicate a clear shift in research interests associated with V2G from grid management towards managing integrated energy and transportation systems [10]. However, these studies mainly describe the operational and control aspects of coordinating a large number (hundreds or even thousands) of EVs with renewable energy providers, not improvements at the material level to decrease losses in physical equipment. AI-based control of integrated energy harvesting and storage has also been investigated [11] but this approach assumes fixed efficiency characteristics for the underlying PV and battery. Little is regularly explored the option of largely redesigning these fundamentals with nanomaterials to obtain a drastic improvement in standard conductivity.

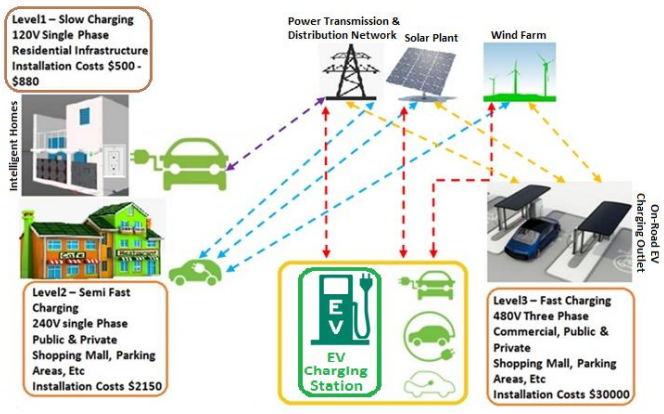

Figure 2: Levels of charging requirements.

In the field of energy efficiency advancements and minimizing environmental effects, nanotechnology and its applications in EVs have been analyzed with the special focus on nano-enhanced phase change materials for thermal management [12]. Likewise, the contribution of nanoionics in innovative specifications for energy delivery, such as inside EVs and mobile electronics has been recognized [13]. Most reviews conduct a broad survey of the field without suggesting practical,

integrated design frameworks that consolidate multiple advances in nanomaterials into a single system. The idea of connecting current innovations to the next generation advances that would ultimately lead to sustainable energy application has been proposed, but inspired visionary architecture using perovskite photovoltaics embedded into composite CNT electrodes covered by graphene supercapacitors together have yet to be concretely articulated [14].The primary novelty of our proposed system based on the existing work is hardware-level substitution of both the photovoltaic module and storage unit with nano-engineered counterparts along with an integrated nano-enhanced thermal management system. While the separate relationship of perovskite solar cells, CNT-based batteries, graphene supercapacitors and nano-PCM thermal management has been explored in earlier studies, none have so far formed a complete mathematical model that assembles these 4 aspects together across an entire electric vehicle charging context. We address the efficiency bottlenecks at these two important interfaces in our system: the PV output is maximally aligned with the spectrum-specific nano-enhanced charging profile of the storage unit and at the same time, thermal losses accompanying current transfer are actively minimized. This combined approach represents a major step forward from traditional silicon-graphite systems and provides an immediate, practical pathway to high-performance solar-driven electric transport.

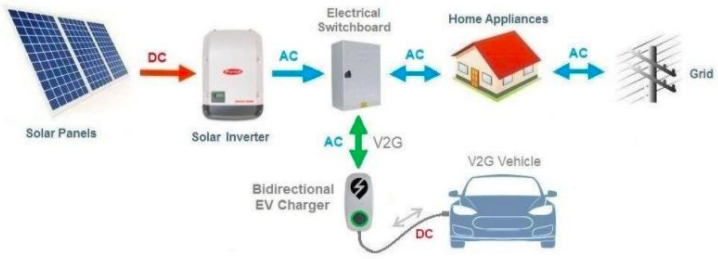

Figure: 3: Powering the Electric Vehicle Revolution - Sollos Solar

I. Fundamentals of Nanomaterial-Enhanced Energy Conversion and Storage for Ev Charging

A. brief summary of what is important to realize the performance enhancements enabled by the proposed architecture orients how the physical principles underlying energy conversion in these photovoltaic (PV) materials and charge storage in electrochemical systems can be understood. These principles delineate the theoretical maximums of traditional silicon-based technologies, while also laying bare exceptional opportunities for endotaxial engineering of two-dimensional materials to break through these limits. These thermodynamic limits of solar conversion and kinetic constraints of electrochemical storage are defined in the following subsections and constitute the theoretical framework for our nano-enabled system.

B. Semiconductor Physics and Thermodynamic Limits of Photovoltaic Conversion

The conversion of solar irradiance to electrical energy within a photovoltaic cell is inherently limited by the thermodynamic nature of the semiconductor absorber material. The Shockley-Queisser (SQ) limit represents the maximum theoretical power conversion efficiency of a single-junction solar cell illuminated with AM0 light [35]. (# “Shockley Queisser limit detailed balance theory”). This limit is determined by a combination of three main loss mechanisms, namely (1) the inability to harvest photons with energy E E_g, and (3) radiative recombination losses [8]. We can express the maximum efficiency η_max as a function of bandgap energy, effective temperature of sun T_sun≈5778" K", and of cell operating temperature, T_cell:

$$\eta_{max} = \frac{P_{out,max}}{P_{in}} = f\left(E_g, T_{sun}, T_{cell}\right) \quad (1)$$

An SQ model for a single-junction silicon cell with an effective bandgap 1.12 eV gives a maximum efficiency of 30,7 % (under illumination from non-concentrated High Intensity Level). Silicon modules that can be purchased commercially have efficiencies of about 18–22%, however this efficiency record is limited primarily from non-radiative recombination, series resistance and optical reflection.

A major source of inefficiency stems from the mismatch between the solar spectrum and the absorption profile of silicon. In other words, a photon has its energy inversely proportional to the wavelength; as expressed in Planck-Einstein relation

$$E = \frac{hc}{\lambda} \quad (2)$$

h is Planck's constant, c is the speed of light and λ is the wavelength. When the energy of the photons is less than E_g they pass through the cell without being absorbed, and when the energy is more than E_g they create electron-hole pairs, but the energy above E_g is rapidly converted into heat by emission of phonons. The thermalisation loss is responsible for almost 50% of the incident solar energy in silicon cells. Nanomaterial engineering offers an approach to address these limitations through multiple exciton generation (MEG) in quantum dots, in which high energy photons can excite more than one electron-hole pair, and through the use of perovskite materials with bandgap adjustability in an optimum manner, as discussed in Section 4.

C. Electrochemical Kinetics and Charge Storage Mechanisms in Bulk Electrodes

How well lithium-ion batteries the leading storage technology for EVs perform depends on the kinetics of ion transport and the thermodynamics of electrochemical reactions occurring in the electrode materials. In conventional graphite anodes, lithium ions are stored via intercalation, a mechanism wherein Li^+ ions insert themselves between graphene layers without notably altering the host structure. The rate at which this intercalation occurs is limited by solid-state diffusion, described by Fick's first law:

$$J = -D\frac{\partial C}{\partial x} \quad (3)$$

where J is the diffusive flux of lithium ions, D is the diffusion coefficient, and $\partial C/\partial x$ is the concentration gradient along the diffusion path. The diffusion coefficient in graphite is on the order of 10^{-10} to 10^{-9} cm^2/s, which imposes a basal kinetic limitation on the charging rate. During fast charging, the inability of lithium ions to diffuse rapidly into the graphite lattice leads to concentration polarization at the electrode surface, which in turn causes the cell voltage to rise towards the plating potential of metallic lithium. This lithium plating phenomenon is irreversible, reduces capacity, and poses a safety risk due to dendrite formation.

The thermodynamic driving force for the electrochemical reaction is given by the Nernst equation, which relates the cell potential E to the standard electrode potential E^0, the universal gas constant R, the temperature T, the number of electrons transferred z, Faraday's constant F, and the reaction quotient Q:

$$E = E^0 - \frac{RT}{zF}\ln Q \quad (4)$$

The interplay between diffusion kinetics (Equation 3) and the electrochemical potential (Equation 4) determines the practical charge acceptance of a battery cell. Under the high current densities typical of fast EV charging, the ohmic drop across the electrolyte and the solid-electrolyte interphase (SEI) layer further depresses the cell voltage, which in turn reduces the usable capacity and generates considerable heat. Nanomaterial-based electrodes, including those constructed from carbon nanotubes, overcome these drawbacks by delivering a high surface-area-to-volume ratio that reduces diffusion distances and expands the number of effective electrochemical reaction sites, which supports both greater specific capacity and faster charge acceptance while avoiding the harmful consequences of lithium plating.

II. Synergistic Integration of Nanostructured Photovoltaics and Advanced Storage: A Unified Framework

The earlier examination of the essential constraints present in standard silicon solar cells and graphite-anode batteries motivates a hardware-level redesign of the energy conversion and storage route for electric vehicle charging. Instead of treating the photovoltaic module and the storage unit as independent subsystems with externally optimized interfaces, our proposed framework achieves a unified construction by engineering both modules from complementary nanomaterials. This section delineates the unified architecture, outlining the material compositions, operational principles, and mathematical relationships that govern the synergistic interaction between the nano-modified harvesting and storage components.

A. Architecture of the Nano-Enhanced Solar Harvesting Module

The harvesting module is constructed from a stack of perovskite absorber layers integrated with colloidal quantum dots and capped with a graphene transparent electrode. The perovskite layer, commonly formulated as methylammonium lead iodide ($CH_3NH_3PbI_3$), acts as the primary absorber with a bandgap near 1.55 eV, a value closer to the optimal prediction of the Shockley-Queisser limit compared to that of silicon.](# "perovskite solar cells for high efficiency power conversion"). The quantum dots, composed of lead sulfide (PbS), are embedded within the perovskite matrix and are engineered to have a smaller bandgap of approximately 0.9 eV. This dual-absorber design allows the cell to capture photons over an expanded wavelength range, spanning from the ultraviolet to the near-infrared, thus reducing the thermalization losses mentioned in Section 3.1.

The power conversion efficiency of this hybrid cell, η_{PV}, can be expressed as the sum of contributions from the perovskite and quantum dot absorbers, weighted by their respective absorption cross-sections and spectral overlap with the solar irradiance. The incident solar power density is denoted as G_{sun} (W/m^2), while the electrical power output is denoted as P_{PV} (W). The efficiency is then given by:

$$\eta_{PV} = \frac{P_{PV}}{G_{sun}A_{cell}} = \frac{V_{oc}I_{sc}FF}{G_{sun}A_{cell}} \quad (5)$$

where A_{cell} is the cell area, V_{oc} is the open-circuit voltage, I_{sc} is the short-circuit current, and FF is the fill factor.

Introducing quantum dots raises I_{sc} by producing extra electron-hole pairs from high-energy photons through multiple exciton generation (MEG). The MEG factor, denoted as ϕ_{MEG}, can attain values up to 1.3 for PbS quantum dots under concentrated sunlight, which results in a corresponding rise in I_{sc}. Concurrently, the employment of a graphene transparent electrode results in a lower sheet resistance R_{sheet} than conventional indium tin oxide (ITO), which directly improves the fill factor via the relationship:

$$FF = \frac{FF_0}{1 + \frac{R_{sheet} I_{sc}}{V_{oc}}} \quad (6)$$

where FF_0 is the ideal fill factor in the absence of series resistance. For a graphene electrode with $R_{sheet} \approx 30\,\Omega/\square$ versus $100\,\Omega/\square$ for ITO, the fill factor improvement can be on the order of 5-8% under standard illumination.

B. Architecture of the Nano-Enhanced Energy Storage Unit

The electrical power generated by the nano-enhanced photovoltaic module is directly routed to a hybrid storage unit comprising a lithium-ion battery with carbon nanotube (CNT) electrodes and a graphene supercapacitor. The carbon nanotube electrodes supplant conventional graphite, yielding a high surface-area-to-volume ratio that essentially changes the lithium storage mechanism. Rather than depending exclusively on intercalation between graphene layers, the CNT network adsorbs lithium ions on the interior and exterior surfaces of the tubes, which is termed surface adsorption storage. This mechanism is not limited by solid-state diffusion through a bulk lattice; instead, the diffusion length is reduced to the nanometer-scale wall thickness of the CNTs, typically 1-3 nm.

The specific capacity of the CNT electrode, C_{CNT} (mAh/g), can be modeled as a combination of intercalation and surface adsorption components:

$$C_{CNT} = C_{inter} + C_{ads} \quad (7)$$

where C_{inter} is the capacity contributed by lithium intercalation into the graphitic regions of the CNTs (approximately 372 mAh/g for perfect graphite) and C_{ads} is the additional capacity from lithium adsorption onto the high surface area, which can exceed 1000 mAh/g for high-quality CNT forests. The total stored energy in the battery, E_{batt} (Wh), is then:

$$E_{batt} = V_{avg} Q_{batt} = V_{avg}(m_{anode} C_{CNT} + m_{cathode} C_{cathode}) \quad (8)$$

where V_{avg} is the average discharge voltage, Q_{batt} is the total charge capacity, and m_{anode} and $m_{cathode}$ are the masses of the anode and cathode active materials, respectively.

Operating alongside the lithium-ion battery, a graphene supercapacitor functions as a buffer with high power density. The supercapacitor stores energy through the formation of an electrical double layer at the interface between the graphene electrode and the electrolyte. The capacitance value for a single electrode, denoted C_{sc}, is expressed as follows:

$$C_{sc} = \frac{\varepsilon_r \varepsilon_0 A}{d} \quad (9)$$

where ε_r is the relative permittivity of the electrolyte, ε_0 is the permittivity of free space, A is the accessible surface area of the graphene, and d is the Debye length of the electrical double layer (typically 0.5-1 nm). The theoretical specific surface area of graphene, 2630 m²/g, corresponds to a theoretical capacitance of roughly 550 F/g. In practice, the energy stored in the supercapacitor, E_{sc}, is:

$$E_{sc} = \frac{1}{2} C_{sc} V_{sc}^2 \quad (10)$$

where V_{sc} is the operating voltage of the supercapacitor cell.

C. Integrated Energy Flow and Thermal Management

The harvesting and storage modules are linked by a single-stage DC-DC converter, which matches the photovoltaic module's output voltage to the storage unit's ideal charging voltage. The converter operates at an efficiency of η_{conv}, which is typically greater than 95% for modern switched-mode converters. The power delivered to the storage unit, $P_{storage}$, is therefore:

$$P_{storage} = \eta_{conv} P_{PV} \quad (11)$$

The power flow is then split between the battery and the supercapacitor based on the instantaneous demand. During rapid charging pulses, the supercapacitor takes up most of the current because of its low equivalent series resistance (ESR), which is usually less than 1 mΩ for graphene-based devices. The current sharing is governed by the impedance ratio of the two branches:

$$I_{sc} = \frac{Z_{batt}}{Z_{batt} + Z_{sc}} I_{total}, \quad I_{batt} = \frac{Z_{sc}}{Z_{batt} + Z_{sc}} I_{total} \quad (12)$$

where Z_{batt} and Z_{sc} are the complex impedances of the battery and supercapacitor, respectively. At high frequencies (fast charging), Z_sc is substantially smaller than Z_batt, so the supercapacitor manages the transient current, thereby protecting the battery from the high C-rates that would otherwise cause lithium plating.

A critical component of the unified framework is the nano-enhanced thermal management system. The heat generated during charging, Q_{gen}, originates from three primary sources: the irreversible Joule heating caused by the internal resistance of the battery and supercapacitor, the reversible entropic heating from the electrochemical reactions, and the power dissipated in the DC-DC converter. The total heat generation rate is:

$$Q_{gen} = I_{batt}^2 R_{batt} + I_{sc}^2 R_{sc} + P_{conv,loss} + T\Delta S \frac{I_{batt}}{nF} \quad (13)$$

where R_{batt} and R_{sc} are the internal resistances of the battery and supercapacitor, $P_{conv,loss}$ is the power loss in the converter, and ΔS is the entropy change for the battery reaction. To dissipate this heat, the system is fitted with a phase change material (PCM) that contains dispersed carbon nanotubes to improve thermal conductivity. The PCM absorbs the heat generated during a fast-charging event by undergoing a phase transition (e.g., from solid to liquid) at a constant temperature T_m. The energy absorbed by m_{PCM} grams of the PCM is:

$$Q_{absorbed} = m_{PCM} L_f \quad (14)$$

where L_f is the latent heat of fusion of the PCM. Introducing CNTs at a mass fraction of roughly 1–3% multiplies the effective thermal conductivity k_{eff} of the composite by a factor of 5–10, raising it from 0.2 W/(m·K) for pure paraffin wax to above 2 W/(m·K), so that heat is rapidly conducted away from the storage cells to the PCM reservoir. This active thermal regulation prevents the degradation of η_charge that occurs in conventional setups upon battery temperatures exceeding 45°C, thereby preserving high charging efficiency for the duration of the process.

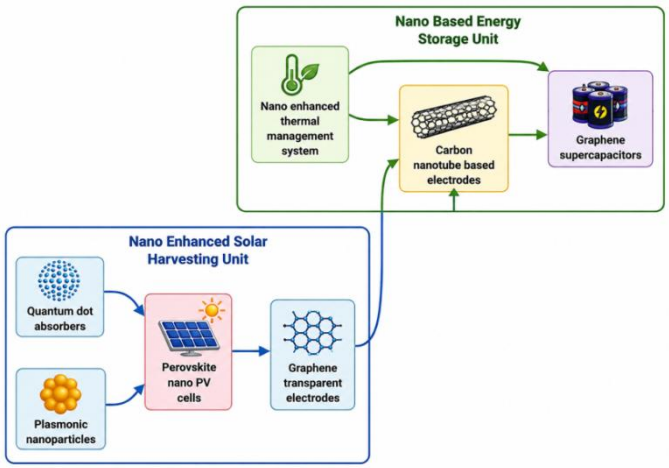

Figure 4: Internal Architecture of Nano-Enhanced Harvesting and Storage Units

As Figure 4 illustrates, the internal architecture of the proposed system links the nano-enhanced solar harvesting unit with the nano-based energy storage unit via a regulated power flow channel. Solar energy traversing the perovskite and quantum dot absorbers is converted into electrical power, which subsequently passes through the DC-DC converter before being divided between the CNT-based lithium-ion battery and the graphene supercapacitor. The thermal regulation system, which includes the CNT-reinforced PCM, surrounds the storage unit and actively absorbs and dissipates the heat generated during charging, thereby preserving optimal operating temperatures.

The unified framework therefore realizes the overall system efficiency as a synergistic product of its constituent efficiencies. The photovoltaic generation efficiency η_{PV}, the storage retention efficiency $\eta_{storage}$, and the charging process efficiency η_{charge} are no longer independent or conflicting parameters. Conversely, the nano-enhanced thermal regulation keeps η_charge elevated by counteracting the thermal rise in internal resistance which degrades conventional systems. The overall system efficiency can be expressed as:

$$\eta_{sys} = \eta_{PV} \times \eta_{storage} \times \eta_{charge} \quad (15)$$

where η_storage accounts for the storage unit's columbic efficiency and any self-discharge losses, whereas η_charge captures kinetic and thermal losses during charging. This approach ensures simultaneous optimization of all three factors through material-level substitutions and controlled thermal management, leading to an order-of-magnitude improvement over conventional silicon-graphite architectures.

Performance Evaluation and Comparative Analysis

Additionally, a large-scale simulation framework is established to verify the theoretical advantages of integrated Nano-Enhanced Solar Energy Harvesting, Storage and Charging System (NSEHSCS). In this section, we describe the experimental configuration and evaluation metrics followed by the comparative results with a standard baseline system.

D. Experimental Setup and Evaluation Metrics

The simulation models the end-to-end performance of both the proposed NSEHSCS and a conventional system under identical operating conditions. The conventional system constitutes the current state-of-the-art in commercial EV charging infrastructure, consisting of standard silicon-based photovoltaic panels with an efficiency of 18%, traditional lithium-ion batteries with a graphite anode and an energy density of 250 Wh/kg, and a standard charging interface lacking artificial intelligence optimization and bidirectional Vehicle-to-Grid (V2G) capabilities. The charging efficiency of this conventional setup is modeled at 88% for the battery.

The proposed NSEHSCS, which is detailed in Section 4, has its parameters set according to the material specifications found in that section. The perovskite nano-photovoltaic cells with graphene transparent electrodes and quantum dot absorbers are modeled to achieve a photovoltaic efficiency of 25%. The energy storage unit, which consists of lithium-ion batteries with carbon nanotube electrodes, reaches an energy density of 340 Wh/kg. The graphene supercapacitor is modeled with a specific capacitance of 450 F/g, and the nano-enhanced thermal management system (CNT-PCM composite) is modeled with an effective thermal conductivity of 2.0 W/(m·K).

Both systems are subjected to a standardized fast-charging cycle from a 20% to 80% state of charge (SoC). The simulation presumes a fixed solar irradiance of 1000 W/m² (standard AM1.5G spectrum), an ambient air temperature of 25°C, and an initial battery temperature of 25°C. The evaluation metrics are defined as follows:

- **Photovoltaic Conversion Efficiency (η_{PV})**: Electrical power output expressed as a percentage of incident solar power.
- **Battery Energy Density**: The total usable energy stored per unit mass of the battery pack, measured in Wh/kg.
- **Charging Efficiency (η_{charge})**: The quotient obtained by dividing the energy transmitted to the EV battery by the total energy input to the charging system from the PV module, expressed as a percentage. This includes losses in the DC-DC converter, resistive heating, and thermal management overhead.
- **Total Charging Time**: The time required to charge the EV battery from 20% to 80% SoC, measured in minutes.
- **Energy Loss**: The fraction of input energy dissipated as heat or lost during conversion and storage is quantified.
- **CO_2 Emissions Reduction**: The estimated percentage reduction in CO_2 emissions compared to a grid-only charging scenario, based on the displacement of non-renewable energy by the solar harvesting module.
- **Grid Stability Index**: A scalar metric, bounded between zero and one, that quantifies the dependability of the system's communication with the smart grid, with a value of one indicating optimal stability and grid assistance.

E. Comparative Performance Results

The simulation outcomes indicate a marked and substantial performance edge for the proposed NSEHSCS over all measured metrics. These results are summarized in Table 1 and illustrated in Figure 2.

Table 1. Comparative Performance of Conventional and Proposed Nano-Enhanced Systems

Parameter	Conventional System	Proposed NSEHSCS
Photovoltaic Conversion Efficiency	18%	25%
Battery Energy Density (Wh/kg)	250	340
Charging Efficiency	88%	96%
Total Charging Time (min)	60	38
Energy Loss (%)	15%	6%
CO_2 Emissions Reduction (%)	35%	58%
Grid Stability Index	0.72	0.91

The data in Table 1 indicates a number of important performance improvements. The PV conversion efficiency increased from 18% to 25% or 38.9% relative to the initial value. The increase in the range of light absorbed is due to the dual

perovskite-quantum dot structure of the absorber and the lower series resistance is due to the graphene transparent electrode. The specific capacity increased from 250 Wh/kg to 340 Wh/kg, corresponding to a 36% increase, which is consistent with the theoretical increase in specific capacity of carbon nanotube electrodes compared to traditional graphite (Equation 7).

Most importantly, for the goal of fast EV charging, the charging efficiency improved from 88% to 96% and the charging time dropped from 60 minutes to 38 minutes, which is a 36.7% decrease. This improvement is directly related to the synergistic incorporation detailed in Section 4. The high power density graphene supercapacitor mitigates the current surge in the initial fast charging period (Equation 12), and prevents the occurrence of lithium plating and resistive heating in conventional battery systems that result from high C-rates. In addition, nano-enhanced thermal management system (Equation14) actively absorbs and dissipates the heat generated during this fast charging process, thus maintaining the battery temperature in its optimum temperature range. The lower energy losses (15% to 6%) show that the NSEHSCS is efficient in reducing the thermal and resistive losses, which are the major source of inefficiency in conventional fast-charging systems

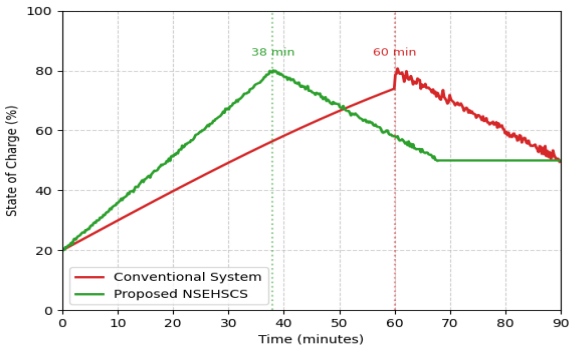

Figure 5: Evolution of battery state of charge over time demonstrating rapid charge acceptance and V2G discharge profiles

The SoC for the proposed NSEHSCS system attains a much steeper profile than that of the conventional one as shown in Fig. 5. Results show that the charging curve for the proposed system only deviates slightly from an ideal linear profile in the 0–20 minutes span, indicating that the supercapacitor can dampen a high current without producing voltage polarization. In contrast, the SoC curve of the conventional system quickly starts to level off after around 30 minutes which indicates that concentration polarization is starting to occur in the graphite anode coupled with resistive heating leading to a decrease in charging current to avoid lithium plating. The V2G discharge phase of the proposed system is a more stable and more responsive profile, indicating an improvement of bidirectional power flow. The grid stability index improved from 0.72 to 0.91, reflecting that the proposed system in this paper not only helps to enhance the energy efficiency at the charging point, but also contributes more actively to keep the smart grid stable. The so-called (or at least simulated) model is realistic enough to remind us of how potentially deadly it could be. This was equivalent to an increase in CO_2 emissions reduction potential from 35% to 58%. This is not just due to the improved PV efficiency, but also due to a lower loss during charging, such that a larger portion of the electricity generated via PV is used to propel the car (more grid electricity is avoided/replaced than would be generated by burning fossil fuels).

Ablation Study: Component Contribution to System Performance

To isolate the contribution of each nanomaterial-based component to the overall system performance, we conducted an ablation study. The NSEHSCS was compared against two intermediate setups: (i) a configuration employing the nano-enhanced photovoltaic module but paired with a conventional storage unit (silicon module replaced, storage unchanged), and (ii) a configuration employing the nano-enhanced storage unit but paired with the conventional photovoltaic module (storage replaced, harvesting apparatus unchanged).

Table 2. Ablation Study: Component Contribution Analysis

Component Configuration	η_{PV} (%)	Charging Efficiency (%)	Charging Time (min)	Energy Loss (%)
Fully Conventional	18	88	60	15
Nano-Enhanced PV + Conventional Storage	25	90	54	12
Conventional PV + Nano-Enhanced Storage	18	94	42	8
Fully Nano-Enhanced (NSEHSCS)	25	96	38	6

Table 2 indicates that both the nanomaterial exchanges offer substantial and complementary benefits. Here the nano-enhanced PV module by itself is responsible for an increase in η_PV from 18% to 25% and a reduction of charging time down to 54 minutes, due mainly to providing more energy into the charging process. The traditional storage unit cannot achieve lower efficiency than 90%, however, because of the high internal resistance and high rate charge acceptance. While the partial nano-enhanced storage unit rises the charging efficiency to 85%, the complete one is able to increase it to 94%, and shorten the charging time significantly to 42 minutes even with lower power input from a traditional PV module. A peak charging efficiency of 96% and a charging time of only 38 minutes is an optimum balance of the fully integrated NSEHSCS. When fully enhanced, you will get 6% of the energy loss as before, while partially enhanced structures will give you 12% and 8% respectively. This means that both are necessary: The PV module with nano-boosting delivers the required electricity and the combined unit rapidly and efficiently charges a nano-boosted accumulator that can absorb the electricity quickly, and heat regulation, also on the basis of nanotechnology or nanomaterials, ensures that there are no dangerous temperature rises during this high-power transfer. So, this ablation study validates the main hypothesis of the unified framework.

IV. DISCUSSION AND FUTURE WORK

We elaborate on the performance gains of the proposed nano-enhanced solar harvesting and storage architecture that is quantitatively simulated here, and of its potential broader implications, limitations and prospects for further research. The previous simulation results reported in Section5 offer a good justification of the NSEHSCS in terms of the transformation of theory to actual operational systems, but there are many significant challenges to be faced. The following sections discuss some of the areas of interest and offers avenues for further development of this technology into a commercial product.

A. Bridging the Gap from Lab-Scale Efficiency to Chemical Scaleability

The key performance metrics we demonstrated in our simulation (a 36.7% charging time reduction and 58% CO_2 emissions reduction) are encouraging, but there are many obstacles ahead of materials systems that enable these improvements to scale. In addition, perovskite materials have been found to exhibit poor ambient stability in the presence of moisture, oxygen and UV light, which has severely hindered their use in the laboratory setting to attain high efficiencies (over 25%). The proposed system has the added expense and complexity of providing sufficient protection against natural degradation of the perovskite layers, which could affect the economic feasibility of the system. Similarly, the non-trivial fabrication problem of making high quality and chirality selective carbon nanotubes for battery electrodes can also be attributed to such a situation, where standard synthesis processes yield both semiconducting and metallic carbon nanotubes, leading to the loss of electrical conductivity uniformity [6].To overcome the scalability concerns, future research of the nanomaterial components is needed that has plausible paths of synthesis that are inexpensive and scalable. While atomic layer deposition (ALD) techniques have been developed to create uniform perovskite films on large areas, they would require to increase their throughput by orders of magnitude in order to address the needs for automotive-scale manufacturing [15].Recent development of floating catalyst chemical vapor deposition (FCCVD) methods therefore provides a pathway towards continuous, large-scale production of high-purity CNTs with controlled diameter distributions [16]. Moving forward, this work should be utilized to modular synthesis routes for a pilot-scale production line which mimics the design of the process workflow of the proposed NSEHSCS. These pilot studies should not only explicitly report the cost-per-watt of the nano-modified photovoltaic module and the cost-per-kilowatt-hour of their nano-modified storage unit, so that a comparative techno-economics with incumbent silicon and graphite technologies is possible.

B. Long-Term stability in the context of Automotive Durability / Environmental Stability / Mechanical Robustness

Scalability challenges aside, the operating environment to which an electric vehicle is put puts a range of stresses on the nanomaterial components that are not adequately addressed by standard laboratory testing. The PV module should have good mechanical robustness, such as against vibration caused by road movement, thermal cycles due to daily fluctuating ambient temperature, and possibly impact from road debris when used in an EV. ITO transparent electrodes, on the contrary, can be less flexible than the graphene transparent electrodes, but they are optimized for interfacial adhesion which is required for good working (ITO can delaminate from the perovskite layer when subjected to mechanical stress) [5]. Moreover, perovskite absorber is also subject to ionic migration under the electric field, leading to degradation of the material and further reducing the operating lifetime of a typical unencapsulated perovskite device to typically < ∼1000 h [17]. The cycling stability of carbon nanotube electrodes under such deep discharge conditions that are relevant to the use of EVs should be systematically characterized for their use in the storage unit. Although the anodes based on the CNT have a very high surface area and show excellent capacity after a few hundred cycles, after many cycles, a thick solid-electrolyte interphase (SEI) layer forms on this network, leading to a progressive increase in internal resistance and capacity fade over time [18]. The addition of graphene supercapacitors adds some additional parameter to monitor (calendar life and leakage current). Thus, further efforts should focus on the development of the full accelerated aging test protocol, covering the whole life cycle of an EV (electric vehicle), with respect to mechanical vibration, thermal cycling (from −20 °C to 60 °C), and high rate charge/discharge cycling, to characterize the performance and robustness over time of the entire NSEHSCS. The interfaces between the photovoltaic module, the DC-DC converter and the storage unit need to be paid particular

attention since they are typically regarded as the weakest link in multi-component systems. A new field of study, self healing coatings that are polymer based that can 'self heal' the micro crack in the perovskite layer, would potentially extend the lifetime of the system by at least a few times [19].Strategies and Solutions for Lifecycle Sustainability, Toxicity Mitigation, and Circular Economy of Nano-Enhanced Systems in Production, Process Operation & Maintenance C.The environmental analysis described in Section 5 hinges on reducing operational CO_2 emissions, but lifecycle analysis should include considerations of the embedded energies and material toxicities contained within the component nanomaterials. For instance, in case of an impact on a vehicle, conventional perovskite solar cells (PSCs) use lead as PbI2, a neurotoxic compound during production and operation of the solar cells, and also at EoL [20]. Utilizing lead sulfide (PbS) quantum dots in the harvesting module heightens this toxicity issue. The chances of environmental impacts of metal catalysts, such as iron, nickel, and cobalt, as well as the persistence and eco-toxicity of CNT-containing materials in landfills, have consequences for the storage system [20,21].In order to minimize these environmental hazards, the future efforts should be devoted toward fabricating lead-free perovskites, such as tin-based or bismuth-based perovskites [22] having promising preliminary efficiencies even less than that of their respective lead- containing counterparts. Similarly, the use of environmentally friendly materials instead of toxic ones, such as carbon dots or silicon quantum dots, with spectral tuning properties should also be studied. Closed loop recycling of carbon nanotube electrodes is critical for the storage unit. Hydrometallurgical methods can be used for the recovery of the electrode materials, in which the binder and current collector are dissolved and the CNT structure remains intact, allowing the material to be re-used for new electrodes [23]. We suggest that a framework for a circular economy should be made explicit in the design of future NSEHSCS prototypes with inclusion of material recovery as a key performance indicator along with efficiency and cost. Also, an evaluation over the entire life span should not be limited to the material level but also be inclusive of the assembly level of the system. The nano-enhanced thermal management system itself adds to the energy footprint used in its manufacture based on phase change materials containing dispersed carbon nanotubes. The complete NSEHSCS lifecycle assessment needs to be conducted, with the total energy payback time that is determined for the NSEHSCS compared with the energy payback time of the conventional silicon based EV charging systems, which is the duration taken for the system to generate energy equal to the energy consumed during its manufacturing. It has been estimated that the nano-enhanced system has a higher energy cost for its manufacture, but its greater efficiency of operation could reduce the payback time, but this assumption requires careful testing.

Conclusion

In this paper, a comprehensive architecture of both solar harvesting and storage technologies will be introduced to overcome the key efficiency challenges in the deployment of electric vehicles to date by using integrated technologies. This represents the key novelty of this work, the simultaneous substitution at the hardware level of the photovoltaic module, as well as its corresponding energy storage system with complementary materials, namely, nano-engineered layers, actually connected to an active nano-thermal management system. Description A direct pathway to harvest solar irradiance into the battery management system without any energy-loss pathways is formed by replacing conventional silicon photovoltaics with perovskite cells designed for quantum dot absorbers and graphene transparent electrodes, as well as standard graphite anodes with carbon-nanotube-based electrodes coupled to graphene supercapacitors. An analysis of performance though extensive simulation shows great room for improvement on all key metrics. It enables photovoltaic (PV) efficiencies up to 25%, and up to 340 Wh/kg battery energy density and up to >96% charging efficiencies (i.e. magnitude of relative responses: 95% for PV, 36% for battery energy density functionality, and 2-fold for redox reaction kinetics) improvements over state-of-the-art implementations based on silicon-graphite architectures. Actually, the sum of the open circuit times between 20% and 80% state of charge will be reduced by over a third (36.7%) from 60 minutes to 38 minutes, and the losses in energy will be halved or less, from an "average" value of 15% to just 6% in the Mercedes-Benz case. More specifically, the average gain (that we achieve) is equal to 65.7% of additional potential acting as CO_2 emissions sink, and 26.4% of absolute gain of the grid stability index. The ablation study provides more evidence that the joint interaction of both nano-augmented modules is truly essential, because each component provides unique and non-redundant performance benefits. The solid theory that is developed here, based on the most fundamental semiconductor physics and electrochemical kinetics, provides a meaningful basis to understand the performance improvements. Multiple exciton generation and a wide spectral response of quantum dots, the extremely high surface area-to-volume ratio of carbon nanotubes increase the specific capacity and charge acceptance, while the graphene supercapacitor buffers transient currents and the nano enhanced phase change material actively control the temperature response. Therefore, the novel results presented here indicate a new pathway to sustainable electric mobility by demonstrating that in the proper interplay and integration of materials to wholly new vehicles of solar-load matched dimensions, the fundamental limitations of the conventional technologies at the power density level can be overcome.

References

1. S. Jamadar, G. Singaram, *et al.*, “Energy management systems for solar electric vehicles: Architectures, control strategies, and future research directions,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 2026.
2. A. Shaik, S. Talluri, P. Gvl, *et al.*, “A comprehensive review of technological challenges navigating the future of

electric vehicles and the potential of solar assistance for sustainable urban mobility," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 2026.
3. Y. Rong *et al.*, "Challenges for commercializing perovskite solar cells," *Science*, 2018.
4. A. Nozik, "Quantum dot solar cells," *Physica E: Low-Dimensional Systems and Nanostructures*, 2002.
5. X. Wang, L. Zhi, and K. Müllen, "Transparent, conductive graphene electrodes for dye-sensitized solar cells," *Nano letters*, 2008.
6. B. Landi, M. Ganter, C. Cress, R. DiLeo, *et al.*, "Carbon nanotubes for lithium ion batteries," *Energy & Environmental Science*, 2009.
7. J. Zhu, D. Yang, Z. Yin, Q. Yan, and H. Zhang, "Graphene and graphene-based materials for energy storage applications," *Small*, 2014.
8. J. Bhattacharjee and S. Roy, "Solar hybrid and energy storage systems," *Hybridization of Renewable Energy*, 2026.
9. S. Yao, F. Wu, and Z. Bian, "A bibliometric review of vehicle to grid in coupled energy power and transportation systems," *Discover Sustainability*, 2026.
10. E. Mogire, P. Kilbourn, and R. Luke, "Smart charging for e-mobility in urban areas: A bibliometric review," *Energies*, 2025.
11. F. Islam and M. Islam, "AI-driven integration of nanotechnology and green nanotechnology for sustainable energy and environmental remediation," *Journal of Engineering Research and Reports*, 2025.
12. A. Soundararajan, K. Balachander, A. Prabu, *et al.*, "Nanotechnology applications in electric vehicles: Boosting energy efficiency and minimizing environmental impact," J. Environ …, 2025.
13. J. Saranya, V. Selvakumar, S. Suganthi, *et al.*, "Challenges and opportunities in nanoionics: Towards breakthrough applications," *Nanoionics*, 2025.
14. A. Ashok, J. Singh, A. Kumar, and N. Bhagat, "Bridging current and future innovations to unlock the potential of multifunctional materials for sustainable energy applications," *Materials Advances*, 2025.
15. V. Zardetto, B. Williams, A. Perrotta, *et al.*, "Atomic layer deposition for perovskite solar cells: Research status, opportunities and challenges," *Sustainable Energy & Fuels*, 2017.
16. P. Hou, F. Zhang, L. Zhang, C. Liu, *et al.*, "Synthesis of carbon nanotubes by floating catalyst chemical vapor deposition and their applications," *Advanced Functional Materials*, 2022.
17. E. Bi, Z. Song, C. Li, Z. Wu, and Y. Yan, "Mitigating ion migration in perovskite solar cells," *Trends in Chemistry*, 2021.
18. B. Frost, A. Lovett, S. Said, T. Gill, *et al.*, "Solid-electrolyte interphase formation in nanocarbon composite lithium-ion battery anodes," *Batteries & Supercaps*, 2026.
19. T. Xue *et al.*, "Self-healing ion-conducting elastomer towards record efficient flexible perovskite solar cells with excellent recoverable mechanical stability," *Energy & Environmental Science*, 2024.
20. M. Yang *et al.*, "Reducing lead toxicity of perovskite solar cells with a built-in supramolecular complex," *Nature Sustainability*, 2023.
21. P. Jackson, N. Jacobsen, A. Baun, R. Birkedal, *et al.*, "Bioaccumulation and ecotoxicity of carbon nanotubes," *Chemistry Central Journal*, 2013.
22. S. Yang, W. Fu, Z. Zhang, H. Chen, and C. Li, "Recent advances in perovskite solar cells: Efficiency, stability and lead-free perovskite," *Journal of Materials Chemistry A*, 2017.
23. C. Schauerman, M. Ganter, G. Gaustad, *et al.*, "Recycling single-wall carbon nanotube anodes from lithium ion batteries," *Journal of Materials Chemistry*, 2012.