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Application of Gauss's Law in High Energy Capacitor Design for Electric Vehicles: A Systematic Literature Review

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ABSTRACT

This article uses a PRISMA flowchart-based Systematic Literature Review (SLR) approach to analyze the role of Gauss's Law in the design of high-energy dielectric capacitors for electric vehicles. Through a synthesis of 17 recent studies (2019–2025), this article identifies three main themes: (1) the application of Gauss's Law in electric field distribution analysis, (2) optimization of dielectric geometry and materials, and (3) the potential application of high-energy capacitors in electric vehicle power systems, especially as high-power components in inverters and regenerative braking. The results show that understanding the field distribution based on Gauss's Law is key to improving the energy density (>18 J/cm^3) and operational reliability of capacitors. This study confirms that Gauss's Law serves not merely as a theoretical principle of electrostatics, but as a foundational analytical framework guiding electric field modeling, geometry optimization, and material design for electrostatic dielectric capacitors—a framework that applies specifically to dielectric capacitors and does not extend to electrochemical supercapacitors.

KEYWORDS: Gauss's law; high energy dielectric capacitor; electric field distribution; geometry optimization; dielectric materials; electric vehicles.

INTRODUCTION

The development of electric vehicles (EVs) has become a key pillar of the global transition to sustainable, low-emission transportation. In Indonesia, this commitment is reinforced through Presidential Regulation No. 55 of 2019 concerning the Acceleration of the Battery-Based Electric Motor Vehicle Program, which encourages local innovation in energy storage technology to support national energy security. Although lithium-ion batteries dominate the EV market, their limitations (particularly in terms of charging rate, cycle life, and instantaneous power delivery) have prompted the exploration of high-performance supporting components.

One promising solution is high-energy dielectric capacitors, which are fundamentally different from electrochemical-based supercapacitors (Hasan & Hudaya, 2023). According to Meyland et al. (2023), Indonesia is positioning itself to become an electric vehicle manufacturing nation, even as it continues to collaborate with countries that possess advanced technological capabilities. Unlike supercapacitors, which store energy through an electrochemical electric double-layer, dielectric capacitors store energy through the polarization of an insulating material (dielectric) located between two conductive electrodes. Their performance is determined by the distribution of the electric field within the capacitor structure, which directly affects the capacitance, energy density, and risk of electrical breakdown. This electric field distribution can be rigorously analyzed using Gauss's Law, one of the fundamental pillars of electrostatics (Griffiths, 2013). This law relates the electric field flux through a closed surface to the free and bound charges in a dielectric

material, providing a rigorous basis for electric field analysis in dielectric capacitor design, complemented by Poisson's equation, boundary conditions, constitutive relations, and numerical methods such as finite element analysis (FEM) for complex geometries. Within the broader framework of Maxwell's equations, Gauss's Law provides the foundational electrostatic basis for electric field analysis in dielectric capacitor design, complemented by Poisson's equation, boundary conditions, constitutive relations, and numerical methods such as finite element analysis (FEM) for complex geometries.

$$\left(U = \frac{1}{2}\varepsilon E^2\right) \quad (1)$$

Gauss's law allows optimization of capacitor geometry (such as parallel-plate, cylindrical, or multilayer) based on the symmetry of the system and the resulting field distribution. For example, a cylindrical configuration produces a more uniform radial field, thereby reducing the fringing field concentration and increasing the operational voltage limit (Du et al., 2022). In addition to geometry, the choice of dielectric material is also crucial; materials with high permittivity and high breakdown strength can significantly increase energy density (Burke, 2021). Recent innovations include lead-free ceramics, polymer nanocomposites, and high-temperature stable polyimide-based films (Zubairi et al., 2024; Ding et al., 2024).

Currently, high-energy dielectric capacitors have achieved energy densities exceeding 18 J/cm³, with advanced multilayer polymer architectures reaching up to 30 J/cm³, as reported by Ghosh & Lin (2025). This makes them highly suitable for high-power applications in EV motor inverters and regenerative braking systems Ren et al. (2022); Wang et al. (2021). These components are frequently combined in practice with batteries in Hybrid Energy Storage Systems (HESS). This combination is driven by the complementary nature of both devices: batteries provide high energy capacity for long-distance driving, whereas dielectric capacitors offer instantaneous high-power delivery during rapid acceleration and regenerative braking—capabilities that batteries alone cannot efficiently sustain without accelerated degradation. Long-term energy storage is handled by the battery while the capacitor supplies immediate peak power (ElGhanam et al., 2023; Urooj & Nasir, 2024). It is crucial to recognize that even within HESS architectures, the fundamental operating principle of dielectric capacitors remains rooted in electrostatics—not electrochemistry. This integration enhances overall system effectiveness while preserving conceptual clarity between different capacitor types. Therefore, Gauss's Law-based analysis remains directly applicable and essential even in the context of hybrid energy storage systems.

Although numerous studies have been conducted, most are fragmentary: some focus on material simulation, others on geometry optimization or HESS integration. There has been no systematic literature review that explicitly addresses Gauss's Law as a unified theoretical foundation in high-energy capacitor design for EVs. The review by Burke (2021), for example, most studies focus on materials or system applications, but have not explicitly linked high-energy capacitor design to the principles of Gauss's Law as a unified electrostatic foundation. Therefore, this article addresses this gap through a Systematic Literature Review (SLR) that, for the first time, explicitly maps Gauss's Law as a unified electrostatic foundation connecting electric field theory, geometry optimization, and material engineering in high-energy capacitor design for EVs. The novelty of this work lies in its integrative perspective: rather than examining materials, geometry, or system integration in isolation, it demonstrates how Gauss's Law—within the broader Maxwell's equations framework—serves as the common theoretical thread linking all three domains of high-energy dielectric capacitor development.

RESEARCH METHOD

The method used in writing this article is a

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Systematic Literature Review (SLR) with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) design. SLR or Systematic Literature Review is a structured and methodological approach to conducting research with the aim of collecting, identifying, evaluating, and critically synthesizing all research studies relevant to a specific topic or research question (Febrianti, 2024). In this study, SLR is implemented across three major stages: the planning stage, the implementation stage, and the reporting stage. The planning stage involves formulating research questions that examine how Gauss's Law is applied to analyze electric field distributions and capacitance in various geometric configurations of high-energy capacitors including parallel-plate, cylindrical, and spherical geometries optimized using electrostatic principles—and how electric flux analysis informs the development of capacitor technology for electric vehicle energy storage systems.

The search approach was created to find current and pertinent scientific publications. from four academic databases: IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. IEEE Xplore and ScienceDirect were selected for their extensive peer-reviewed coverage of engineering and applied physics. SpringerLink was included for high-impact materials science publications. Google Scholar served as a supplementary source to capture additional relevant studies indexed in Scopus and Web of Science that may not appear in the other three databases. Boolean operators were used to combine keywords as follows: (Electric vehicle or EV) and (High-energy capacitor or Dielectric Capacitor or Electrostatic Capacitor or High-energy-density Dielectric Capacitor or Hybrid Energy Storage System or HESS) and (Gauss's law or Electrostatics or Electric Field Analysis) and Design or Optimization or Modelling). This search strategy was designed to ensure that results are both wide-ranging—covering diverse aspects of capacitor technology including materials, geometry, and system integration and still pertinent to the core focus of the study: the role of Gauss's Law in high-energy capacitor design for electric vehicles (EVs). The breadth of the strategy prevents omission of relevant studies, while keyword specificity keeps results aligned with the theoretical and applied scope of the review.

Table 1. Inclusion and Exclusion Criteria for Article Selection (Febrianti, 2024)

Article Criteria	Inclusion	Exclusion
Publication Type	Peer-reviewed articles (journals, conferences, preprints)	Non-peer reviewed articles (e.g., blogs, news reports)
Publication Year	2019-2025	Articles before 2019
Language	English and Indonesian	Languages other than English and Indonesian
Relevance	Discusses Gauss's Law, high capacitor design and battery-capacitor dielectric hybrid energy storage systems in electric vehicles.	It is irrelevant to Gauss's Law, high capacitor design or battery-capacitor dielectric hybrid energy storage systems in electric vehicles.
Data	Provide empirical data, simulations, or practical implementations	Doesn't provide empirical data, simulations, or practical implementations
Access	Full text available	Full text not available

Article selection was carried out in several stages according to the PRISMA process. First, the identification stage: a total of 187 records were identified through database searches (IEEE Xplore: 35, ScienceDirect: 60, SpringerLink: 25, Google Scholar: 70). Second, the screening stage: after removing 28 duplicates, 162 records were screened by title and abstract, and 96 were excluded for irrelevance, yielding 66 records for further review. Third, the eligibility stage: full texts of all 66 articles were assessed against the inclusion and exclusion criteria; 44 were excluded due to insufficient relevance to Gauss's Law, lack of empirical data, or

unavailability of full text. Finally, the inclusion stage: 17 articles meeting all criteria were included in the final thematic analysis.

The inclusion criteria for acceptance include publications that have undergone peer-review and are indexed in reputable international databases (Scopus or Web of Science) or, for Indonesian-context supporting references, indexed at minimum Sinta 3. All selected articles were published between 2019–2025, written in English or Indonesian, directly relevant to high-energy capacitor design, Gauss's Law, or battery-dielectric hybrid energy storage systems in electric vehicles, and must present empirical data, simulations, or practical implementations. Articles indexed only at Sinta 3 were limited to contextual background references; the primary analytical corpus draws exclusively from internationally reputable sources. Meanwhile, publications that have not been peer-reviewed or have no relevance were excluded. Article selection was

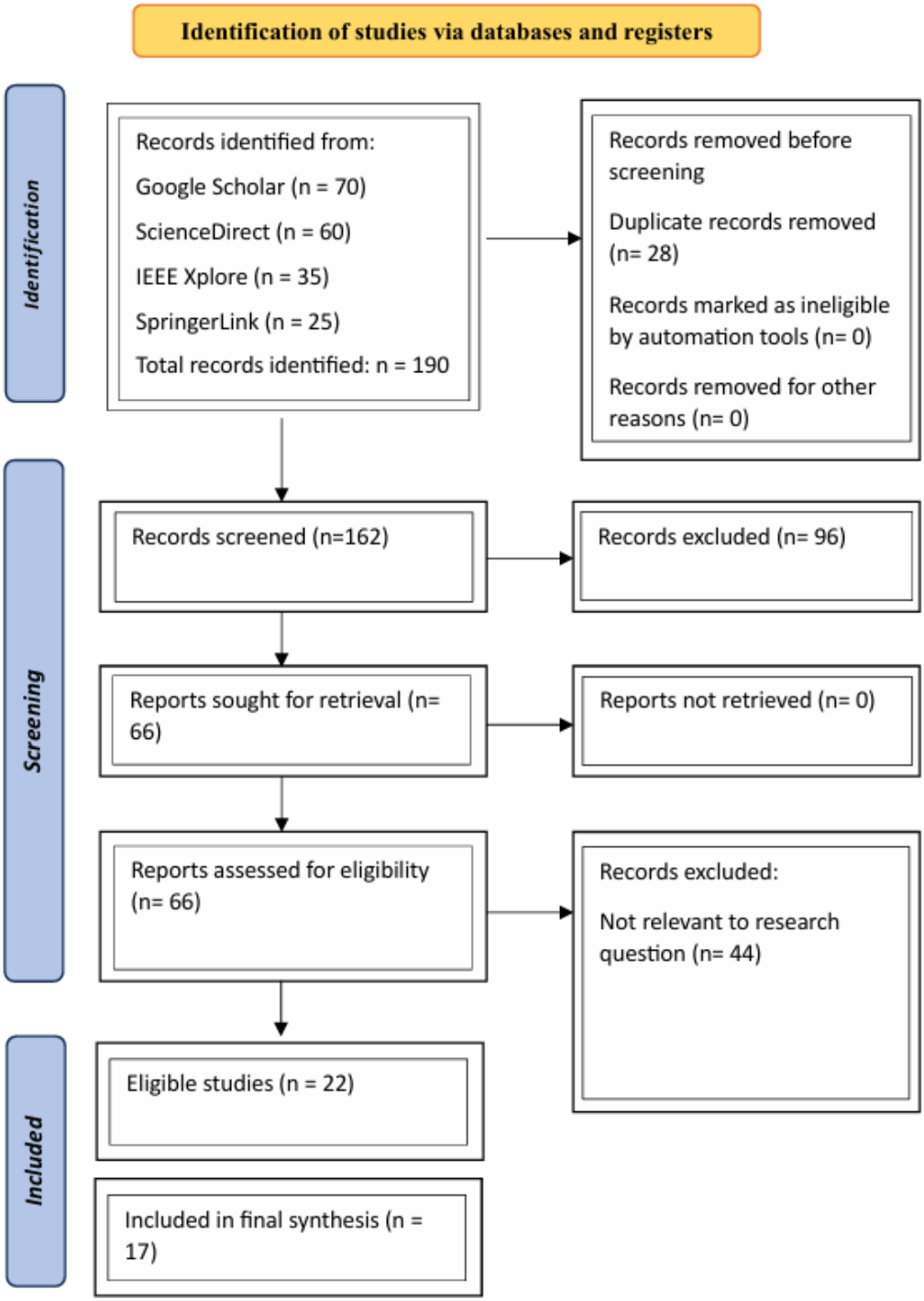

Figure 1. PRISMA Diagram of the Literature Selection Process

guided by the PRISMA diagram, with the support of reference management tools such as Mendeley. Data were subsequently synthesized using a narrative approach to address the research questions, with dual-researcher cross-verification conducted to minimize interpretational bias. The inclusion and exclusion criteria applied in this study are presented in Table 1.

For each selected article, the following data were extracted using a standardized form: author name, year of publication, research objectives, methodology, sample characteristics, and key findings relevant to Gauss's Law. The extraction process was conducted independently by two researchers, with discussions held to resolve interpretational disagreements. Articles with related topics were subsequently categorized and subjected to thematic analysis based on each study's focus area. The PRISMA flowchart illustrating the complete article selection process is presented in Figure 1.

RESULTS AND DISCUSSION

Data extracted from the 17 selected articles were grouped thematically according to three main themes: (1) application of Gauss's Law in electric field distribution analysis, (2) dielectric material and geometry optimization, and (3) integration of capacitors into EV hybrid energy storage systems. A summary of the selected articles is presented in Table 2.

Literature results using the PRISMA method show a significant increase in research related to high-energy dielectric capacitors in the context of electric vehicles since 2019. Publications discussing energy storage technologies based on electrostatic principles (especially those linking capacitor design to Gauss's Law) are growing in line with the need for reliable and efficient high-power systems in modern EVs. Urooj & Nasir (2024) reported that research on hybrid energy storage systems (HESS) that combine batteries and high-power components has received widespread attention because they are able to overcome the limitations of batteries in short-term charge-discharge cycles. However, as emphasized by Liu et al. (2024), dielectric film capacitors are prime candidates for such roles in high-power EV applications, given their thermal stability, high voltage reliability, and fully electrostatic energy storage mechanism. Thus, the role of dielectric capacitors in supporting acceleration, regenerative braking systems, and battery life extension remains relevant without blurring the conceptual boundaries with electrochemically based supercapacitors (ElGhanam et al., 2023; Liu et al., 2024). It is crucial to distinguish between high-energy dielectric capacitors and electrochemical supercapacitors. While both offer high power capability, dielectric capacitors store energy purely through electrostatic polarization of an insulating material, governed by Gauss's Law within the broader framework of Maxwell's equations. This distinction is reinforced by Liu et al. (2024), who explicitly categorize dielectric film capacitors as prime candidates for high-power EV applications precisely because of their purely electrostatic storage mechanism, as opposed to electrochemical supercapacitors that rely on ionic charge separation at electrode–electrolyte interfaces. It is important to clarify that Gauss's Law, as a universal law of electromagnetism, remains physically valid for all electromagnetic systems, including supercapacitors. However, in supercapacitors, energy storage is dominated by electrochemical processes—such as electric double-layer formation and Faradaic reactions—that are governed by electrochemical thermodynamics and kinetics rather than classical electrostatics. Consequently, while Gauss's Law is not inapplicable, it has limited practical utility as the primary design framework for supercapacitors. In contrast, dielectric capacitors—whose capacitance, energy density, and breakdown behavior are all directly determined by electric field distribution—are uniquely amenable to Gauss's Law-based analysis. This makes dielectric capacitors uniquely suited for high-

voltage, high-frequency, and thermally demanding applications in electric vehicles.

Table 2. Summary of Previous Research

No.	Article Title	Writer	Year	Focus of Study	Key Findings/ Relevance
1	Electroceramics for High-Energy Density Capacitors: Current Status and Future Perspectives	Wang G., et al.	2021	Electroceramic materials for high energy capacitors	A comprehensive review of strategies for increasing energy density through microstructural and compositional engineering of ceramics. Relevant because it links dielectric properties (permittivity, breakdown strength) with the fundamental principles of Gauss's Law in field distribution
2	Current Development, Optimization Strategies and Future Perspectives for Lead-Free Dielectric Ceramics in High Field and High Energy Density Capacitors	Zubairi, H., et al.	2024	Lead-free ceramics	Environmentally friendly ceramic optimization strategies for high-energy capacitors. Relevant to the green materials trend.
3	Analysis and Design of a High Power Density Full-Ceramic 900V DC-Link Capacitor for a 550kVA Electric Vehicle Drive Inverter	Cittanti, D., et al.	2022	Design and validation of high-power full ceramic (dielectric) capacitors for ultra-high-power (550 kVA) electric vehicle inverters.	Real implementation in electric vehicles, emphasizing the design of uniform electric field distribution, geometry optimization, and dielectric material selection.
4	Ultrahigh energy storage density in lead-free relaxor antiferroelectric ceramics via domain engineering	Jiang, J., et al.	2021	Lead-free antiferroelectric ceramics based on $NaNbO_3 - BiFeO_3$	Achieving an energy density of 18.5 J/cm³ and an efficiency of 78.7% through domain engineering that improves electric field homogeneity and breakdown strength. This approach aligns with the principles of Gauss's Law in heterogeneous materials and is particularly relevant for high-power capacitors in electric vehicle inverters.
5	On Capacitance and Energy Storage of Supercapacitors with Dielectric Constant Discontinuity	Zhou, S.	2022	Theoretical study of the effect of discontinuity in dielectric constant on electric field and stored energy.	The concept of inhomogeneous electric field and energy density changes can be explained by Gauss's Law, which is important for modeling charge distribution in composite capacitors. Relevant for EV optimization.

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No.	Article Title	Writer	Year	Focus of Study	Key Findings/ Relevance
6	A Gauss's Law Analysis of Redox Active Adsorbates on Semiconductor Electrodes: The charging and faradic currents are not independent	Vasquez, R., et al.	2022	Theoretical analysis (Gauss's Law)	Gauss's law is used to analyze charge distribution and electric fields. It is relevant as a foundation for capacitor design.
7	High-energy-density polymer dielectrics via compositional and structural tailoring for electrical energy storage	Cheng, R., et al.	2022	Review of high energy dielectric polymer materials with composition and structure design.	discussing the increase in permittivity, breakdown strength, and energy storage capacity as a basis for understanding the optimization of dielectric materials in capacitor design.
8	Design strategy of barium titanate / polyvinylidene fluoride-based nanocomposite films for high energy storage	Wang, Y., et al.	2020	Nanocomposite design$BaTiO_3$/ PVDFfor high energy dielectric films.	describes the relationship between microstructure, permittivity, and internal electric fields. Strong is associated with the application of Gauss's Law in the analysis of field distributions.
9	Modification of Charge Distribution Based on Fermi-Dirac Distribution and Its Application to Gauss's Law	Tiandho, Y., et al.	2020	Application of Gauss's Law to quantum charge distribution	Discussing Gauss's Law in the context of charge distribution
10	Multilayer Ceramic Film Capacitors for High Performance Energy Storage: Progress and Outlook	Fan, Z., et al.	2021	Multilayer ceramic films for high energy storage.	discusses the distribution of electric fields between layers, polarization gradient, and the design of multilayer structures to maximize stored energy closely related to the principles of Gauss's Law.
11	Unusual local electric field concentration in multilayer ceramic capacitors	Du, W., et al.	2022	Local electric field distribution in MLCC	The asymmetry of the internal electrode geometry causes field concentrations up to 3× the risk of breakdown. Analysis based on Gauss's Law and FEM.
12	Review of Energy Storage Capacitor Technology	Liu, W., et al.	2024	A comprehensive review of energy storage capacitors	Comparing the performance of dielectric capacitors and supercapacitors, highlighting dielectric film capacitors as a prime candidate for high-power applications in EVs.
13	Ultra-high energy density integrated polymer dielectric capacitors	Ren, Xintong., et al	2022	Development of integrated polymer capacitors based on nano composites	Achieving exceptional performance through multilayer architectural designs that minimize field

No.	Article Title	Writer	Year	Focus of Study	Key Findings/ Relevance
				with high energy density> $20\,J/cm^3$	concentration is based on the prediction of field distribution from Gauss's Law in complex structures.
14	Prospects for the Development of High Energy Density Dielectric Capacitors	Burke, A	2021	Challenges and strategies for developing high energy density dielectric capacitors	Shows that energy density depends simultaneously on permittivity and breakdown field strength(ε_r)(E_b^2),so both must be optimized together. Emphasizes the importance of material engineering (multilayer, nanocomposite, hybrid) to maximize performance without sacrificing field stability. Analysis of electric field distribution based on the principle of Gauss's Law is the basis for understanding layered dielectric design.($\varepsilon E = constant$)
15	Superior dielectric energy storage performance for high-temperature film capacitors through molecular structure design	Ding, S., et al	2024	Polymer dielectric based capacitors	High energy storage performance of polymer dielectric-based capacitors
16	Comparative study of methods for measuring energy density for dielectric capacitors	Bian, H., et al.	2025	Comparison of five methods of measuring energy density in dielectric capacitors (ceramic RFE and AFE)	The hysteresis loop integration method provides the most reliable reference, while the discharger current method tends to overestimate energy density because it does not consider losses, and the equivalent method actually underestimates high-voltage performance. This finding is relevant because it emphasizes the need for standardization of measurements in the evaluation of high-energy capacitors, which forms the basis for data validation in this review.

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No.	Article Title	Writer	Year	Focus of Study	Key Findings/ Relevance
17	Polymer composites embedded with low-dimensional materials for dielectric capacitors	Ghosh, S.K., & Lin, L.	2025	A comprehensive review of low-dimensional (0-D to multi-D) material-based polymer composites for high-energy dielectric capacitors	Demonstrates that design based on multilayer architecture, interface engineering, and selection of low-dimensional materials (such as BNNS, MXene, nanocomposites)$BaTiO_3$) allows the achievement of energy densities up to> 30 J/cm^3, high efficiency, and high temperature stability all these approaches explicitly refer to the principle of electric field distribution through Gauss's Law in heterogeneous materials $\varepsilon E = constant$.

The development of high energy capacitors and hybrid energy storage systems (HESS) for electric vehicles is based on three main interrelated themes: (1) the application of Gauss's Law in the analysis of electric field distribution, (2) optimization of dielectric geometry and materials, and (3) the potential application of high energy capacitors in electric vehicle power systems, with Gauss's Law as the theoretical basis that unites the three.

First, Gauss's Law serves as a fundamental analytical framework for understanding the electric field distribution in capacitor structures. Vasquez et al. (2022) demonstrated that Gauss's Law allows the analysis of charge and electric field distributions at the electrode–dielectric interface, which is fundamental to the design of high-performance capacitors. Building on this, (Jeanmairet et al., 2022) extended this approach through molecular simulations connecting atomic-scale charge distributions to continuum electrostatics via Gauss's Law and Poisson–Boltzmann equations. While their study focused on electrochemical double-layer systems, the underlying electrostatic principles remain relevant to understanding dielectric polarization and macroscopic electric field distributions at electrode interfaces in dielectric capacitor systems, particularly within HESS architectures.

Second, recent advancements in dielectric geometry and materials have focused on reducing electric field gradients while simultaneously increasing permittivity, both of which are critical to preventing premature electrical breakdown. Wang et al. (2021) and Zubairi et al. (2024) emphasized significance of ceramics and electroceramics free of lead in raising energy density, fulfilling the guidelines of sustainability. A breakthrough by Ding et al. (2024) demonstrated that a CBDA-BAPB-based dielectric polymer produces a high energy density and a low dissipation factor and a steady distribution of operating temperatures which are essential features for film capacitors in electric vehicles motor inverters. Conversely, Jiang et al. (2021) reported an energy density of 18.5 J/cm³ with an efficiency of 78.7% in a lead-free antiferroelectric ceramic through domain engineering, which improves both breakdown strength and electric field homogeneity. This approach is directly consistent with Gauss's Law applied to heterogeneous materials, where continuity of the normal component of electric flux displacement at material interfaces governs local field distribution.

In addition to material innovation, accurate validation of capacitor performance is an important prerequisite for the development of energy storage technology. Bian et al. (2025) highlighted that different energy density

measurement methods can produce widely varying estimates ranging from overestimating to underestimating actual performance. The study compared five measurement approaches and found that hysteresis loop integration provided the most reliable reference, while discharger current-based methods tend to ignore dielectric losses, making them unsuitable for evaluating high-energy capacitors at real-world operating voltages. These findings underscore the need for standardization of testing protocols in the dielectric capacitor literature, so that data from different studies can be objectively compared.

On the other hand, Ghosh & Lin (2025) provide a comprehensive overview of the utilization of low-dimensional materials such as boron nitride nanosheets (BNNS), MXene, and nanoparticles $BaTiO_3$ in polymer composites for dielectric capacitors. They show that interface engineering and layered architectures enable energy densities exceeding 30 J/cm^3 (> 80%), and stability at extreme temperatures, based on the principle of continuity of electric flux ($D = \varepsilon E = constant$) which is a direct expression of Gauss's Law in heterogeneous materials. This approach not only improves performance but also ensures a homogeneous field distribution throughout the dielectric volume, thereby reducing the risk of hot spots and premature failure.

On the geometry side, Du et al. (2022) revealed that internal electrode asymmetry in multilayer capacitors (MLCCs) leads to up to three orders of magnitude higher field concentrations, which increases the risk of breakdown. This finding underscores the need for Gaussian symmetry-based designs (such as cylindrical configurations) to minimize gradients. This approach has been applied practically by Cittanti et al. (2022) in the design of full ceramic capacitors for ultra-high power EV inverters, as well as by Ren et al. (2022) through a multilayer architecture on polymer capacitors designed to balance the field distribution based on the predictions of Gauss's Law. Similarly, Fan et al. (2021) and Burke (2021) further emphasized that the design of multi-layer dielectric layers should consider the continuity of electric flux transfer as an engineering basis to avoid field hot spots.

Third, in the context of system integration, ElGhanam et al. (2023) and Urooj & Nasir (2024) demonstrate that HESS architectures combining batteries and dielectric capacitors can improve regenerative braking efficiency and extend battery cycle life by leveraging the instantaneous high-power delivery of capacitors alongside the long-term energy capacity of batteries. While some HESS configurations incorporate electrochemical supercapacitors, this review focuses exclusively on purely electrostatic dielectric capacitors. As emphasized by Liu et al. (2024) in their comprehensive review, dielectric film capacitors not electrochemical supercapacitors are the most suitable candidates for high-power applications in electric vehicles, owing to their superior thermal stability, high-voltage reliability, and purely electrostatic energy storage mechanism. Consequently, HESS architectures that integrate dielectric capacitors remain fundamentally grounded in the principles of electrostatics, with Gauss's Law serving as the cornerstone for electric field analysis and capacitor design.

A quantitative synthesis of the 17 reviewed studies reveals notable performance trends. In terms of energy density, ceramic-based capacitors (Wang et al., 2021; Jiang et al., 2021; Zubairi et al., 2024) report values in the range of 10–18.5 J/cm³, while advanced polymer and nanocomposite systems (Ren et al., 2022; Ghosh & Lin, 2025) have achieved densities exceeding 20–30 J/cm³. Breakdown strength varies considerably by material class: lead-free ceramics achieve up to 400 MV/m (Zubairi et al., 2024), whereas polymer-based systems generally exhibit lower breakdown fields but superior flexibility and processability. Efficiency values range from approximately 78.7% in antiferroelectric ceramics (Jiang et al., 2021) to above 80% in optimized polymer composites (Ghosh & Lin, 2025). Temporally, the reviewed literature shows an accelerating research trend from

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2019 to 2025, with increasing focus on multilayer architectures, interface engineering, and domain engineering as primary strategies to simultaneously improve energy density and field homogeneity—all of which are grounded in Gauss's Law-based design principles. A key design trade-off identified across studies is the inverse relationship between permittivity and breakdown strength: high-permittivity ceramics tend to have lower breakdown fields, while low-permittivity polymers exhibit higher breakdown strength but lower energy density at equivalent field strengths. Addressing this trade-off through nanocomposite and multilayer engineering represents the dominant research direction in the field.

Thus, recent literature shows a clear trend: the advancement of high-energy capacitors depends not only on material innovation or system integration, but also on a deep understanding of the electric field distribution governed by Gauss's Law. A holistic approach combining materials engineering, geometry optimization, and system integration, all rooted in the principles of electrostatics, is key to realizing reliable, efficient capacitors ready for future electric vehicle applications. Beyond the immediate context of EV capacitors, the analytical principles demonstrated here carry broader cross-disciplinary relevance. The application of Gauss's Law to heterogeneous dielectric media through the continuity of electric displacement at material interfaces parallels field distribution problems encountered in biomedical devices, energy harvesting systems, and semiconductor packaging, all of which involve inhomogeneous dielectric structures under high electric fields. This suggests that Gauss's Law-based design framework developed in this review may serve as a transferable methodology across multiple engineering domains where electrostatic field control is critical.

Application of Gauss's Law in Electric Field Distribution Analysis

Gauss's Law is a fundamental principle in electromagnetism which states that the total electric flux through any closed surface is directly proportional to the total enclosed charge. This law can be expressed mathematically as

$$\oint E \cdot dA = Qenc / \varepsilon 0 \quad (2)$$

The following forms are more pertinent in a dielectric medium:

$$\oint D.dA = Q_{free}, \text{ with} D = \varepsilon E \quad (3)$$

In the equation above, D represents the electric displacement field, ε is the permittivity of the material, E is the electric field, and Q_{free} refers to the free charge enclosed by the surface. This formulation enables analysis of the electric field distribution based on the geometric symmetry of the system, without requiring direct solution of differential equations. In the context of high-energy capacitors, the electric field distribution directly governs the device's operating limits: non-uniform field concentrations at heterogeneous material interfaces or electrode edges can trigger electrical breakdown. Gauss's Law is therefore essential for understanding and predicting field distribution in capacitor design. Vasquez et al. (2022) demonstrated that the analysis of charge and electric field distributions is made possible by Gauss's Law. This approach is strengthened by Ghosh & Lin (2025), which shows that at the nanoscale, interface engineering in polymer composites of low-dimensional materials (such as BNNS and MXene) allows controlling the local electric field distribution through the principle of continuity of electric flux transfer, a direct expression of Gauss's Law in heterogeneous systems. This finding confirms that Gauss's Law remains valid and is a crucial design guide even at the nanometer scale, particularly in the optimization of multicomponent dielectric layers for high-energy capacitors ($D = \varepsilon E = constant$).

In heterogeneous dielectric materials, the continuity of the normal component of the electric displacement field at each interface directly governs the local field distribution. Jiang et al. (2021) and (Burke, 2021) highlighted that according to Gauss's Law, field homogeneity directly impacts both the energy

density and the breakdown strength of the capacitor. Du et al. (2022) further revealed that the asymmetric internal electrode geometry in multilayer ceramic capacitors (MLCCs) can produce local field concentrations up to three times the nominal value, significantly increasing the risk of dielectric breakdown. These findings confirm that understanding Gauss's Law and its application to field distribution is not merely a theoretical exercise, but a practical necessity for reliable capacitor design. Thus, Gauss's Law serves as a bridge between electrostatic field theory and practical engineering, enabling the identification and elimination of detrimental field concentrations at electrode edges or material interfaces early in the design process.

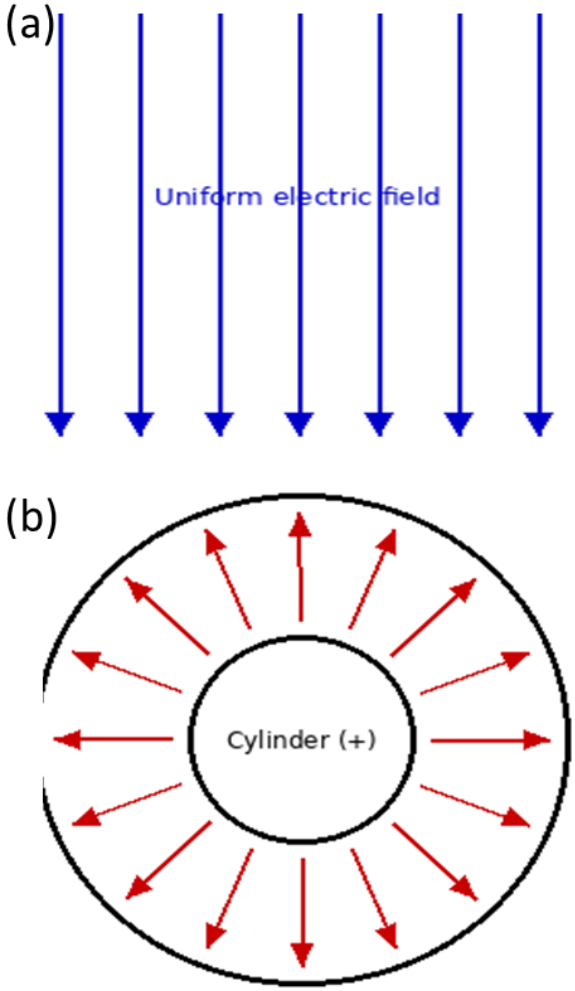

Figure 2. Gaussian distribution of electric fields in a capacitor, illustrating the electric field symmetry: a. (a), and b) Cylindrical capacitor: radial field (red lines labeled + and - that extend from the inner cylinder to the outer cylinder). (Source: the authors illustration on Griffiths 2013 pp. 72—75).

Geometry and Dielectric Material Optimization

Reliable high-energy capacitor design for electric vehicles depends critically on achieving both high energy density and uniform electric field distribution across the dielectric volume. These two objectives are directly linked through Gauss's Law and are addressed through two complementary strategies: optimizing electrode geometry and selecting appropriate dielectric materials. Both strategies aim to minimize local field gradients that could trigger electrical breakdown, particularly under the dynamic operating conditions found in EV motor inverters. According to Gauss's Law, the electric field distribution in an electrostatic system is determined by the geometry of the Gaussian surface and the spatial symmetry of the enclosed charge. Two primary capacitor configurations are commonly considered parallel-plate and cylindrical each offering different trade-offs between high-voltage reliability, capacitance, and ease of fabrication.

$$E = \frac{\sigma}{\varepsilon} = \frac{Q}{\varepsilon A} \quad (4)$$

Potential difference, so the capacitance

$$V = EdC = \frac{\varepsilon A}{d} \quad (5)$$

However, in high-voltage operation or at the microscale (e.g., in ceramic multilayer capacitors), symmetry breaks at the electrode edges, producing local field concentrations and fringing fields that increase the risk of breakdown. Du et al. (2022) demonstrated that in ceramic capacitors with multiple layers (*MLCCs*) field concentrations may rise due to the internal electrode geometry's asymmetry to three times the nominal value, which is where dielectric failure begins. An alternative configuration is the cylindrical arrangement, consisting of two concentric cylinders with inner and outer radii, which exploits radial symmetry. With a cylindrical Gaussian surface, Gauss's Law yields a radial electric field: $> 100\ MV/m$.

$$E\ (r) = \frac{\lambda}{2\pi\varepsilon r} \quad (6)$$

Potential difference:

$$V = \frac{\lambda}{2\pi\varepsilon}\ In\frac{b}{a} \quad (7)$$

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So, the capacitance per unit length is obtained:

$$\frac{C}{L} = \frac{2\pi\varepsilon_0}{In\left(\frac{b}{a}\right)} \quad (8)$$

This distribution minimizes field concentration and permits it because it does not have sharp edges when operating at higher voltages (Griffiths, 2013). In electric vehicle applications, radial symmetry-based designs offer advantages in thermal reliability, power efficiency, and voltage stability. Although cylindrical configurations are more complex to fabricate, they are frequently the optimal choice for high-performance EV capacitors. Recent innovations combine Gaussian symmetry principles with multilayer architectures. Ren et al. (2022) developed an integrated polymer capacitor with stacked layers designed to balance field gradients through Gauss's Law-based field distribution prediction. A similar approach is used in the domain engineering of antiferroelectric ceramics Jiang et al. (2021) where microstructural homogeneity reduces field hot spots.

In heterogeneous dielectric structures (e.g. double layers), Gauss's Law in the form requires continuity of the normal component of the electric displacement flux at the interface:

$$\oint D \cdot dA = Q_{free} \quad (9)$$

$$D_1 = D_2 => \varepsilon_1 E_1 = \varepsilon_2 E_2 \quad (10)$$

This allows for the engineering of high layers as a "buffer" for the field, so that thin layers are ε low (but mechanically strong) capacitors can withstand high fields without breakdown. This approach is directly used in the design of multilayer film capacitors for DC-link inverter applications (Li et al., 2022).

A recent breakthrough by (Ding et al. 2024) demonstrated that CBDA-BAPB-based dielectric polymers yield lower dissipation factors, higher storage energy densities, and more stable operating temperature distributions. Experimental data (Figure 3) demonstrate that CBDA-BAPB outperforms HPMDA-BAPB and HBPDA-BAPB, making it an ideal candidate for film capacitors in EV motor inverters. Based on the image above, it can be seen that CBDA-BAPB shows superior dielectric characteristics compared to HPMDA-BAPB and HBPDA-BAPB, with a lower dissipation factor, higher storage energy density, and a more even and stable operating temperature distribution. These advantages make CBDA-BAPB a very potential dielectric material for film capacitor applications in electric vehicle power electronics systems, especially in DC-link capacitor inverter motors, where good thermal stability, high efficiency, and the ability to work at high operating temperature conditions and high frequency switching are required to support the reliability and performance of EV propulsion systems.

Dielectric materials not only function as insulators, but also as the main determinant of energy performance and reliability. Material selection must consider four critical parameters: (1) relative permittivity (ε_r), (2) dielectric breakdown strength (E_{max}), (3) dissipation factor ($\tan\delta$), and (4) thermal stability up to operating temperature.≥ 150 ℃. Recent material innovations have shown significant progress in meeting these criteria. Electroceramics (Wang et al., 2021) and lead-free ceramics (Zubairi et al., 2024) offer high (>1000) and up to 400 MV/m, reaching energy densities of $10-20\ J/cm^3$. In addition, polyimide-based polymers CBDA-BAPB (Ding et al., 2024) show a unique combination; where energy density is $>20\ J/cm^3$, and stability up to 150℃. Thermal simulations (Figure 2c) show a more even operating temperature distribution, reflecting the homogeneity of the electric field in the dielectric resulting directly from the molecular design aligned with Gauss's Law principles. Compared to supercapacitors the dielectric capacitor-based method has advantages in thermal stability and high-voltage reliability which makes it more appropriate for applications based on Gauss's Law.

Potential Application of High Energy Capacitors in Electric Vehicle Power Systems

High-energy dielectric capacitors show great potential as high-power components in

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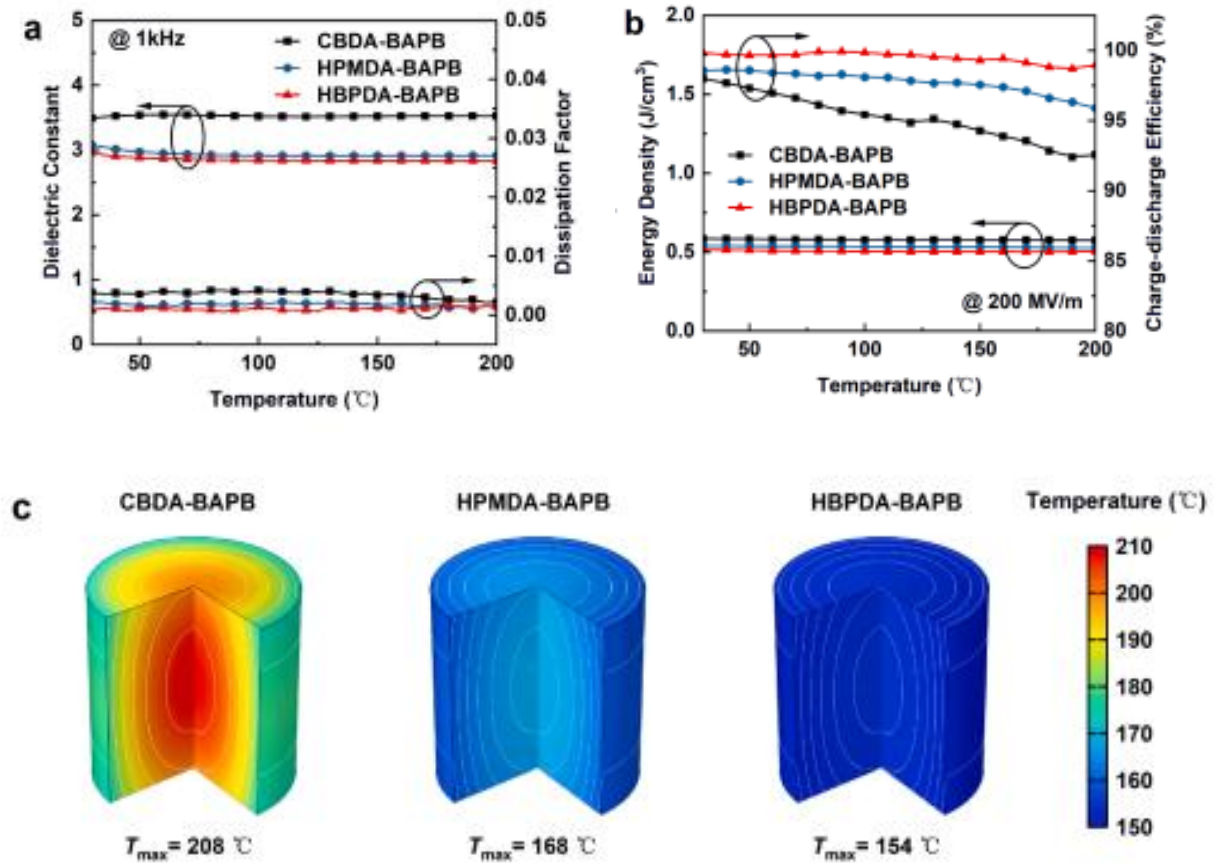

Figure 3. Temperature-dependent (a) dielectric constant and dissipation factor and (b) dielectric energy storage performance of three different polyimides. (c) Simulated steady-state temperature distributions in wound film capacitors for CBDA-BAPB, HPMDA-BAPB and HBPDA-BAPB operating at 200 MV/m and 150 °C. *(Source: Adapted from Ding et al., 2024, Chemical Engineering Journal, 493, pp. 152623).*

electric vehicle propulsion systems, particularly in motor inverters and regenerative braking systems. In inverters, the capacitor functions as a DC-link capacitor, stabilizing the voltage between the DC source (battery) and the three-phase inverter, while absorbing high-frequency ripple currents. Capacitors based on materials such as CBDA-BAPB exhibit low dissipation factors and excellent thermal stability up to 150°C, enabling reliable operation under high-frequency switching conditions Ding et al. (2024).

In regenerative braking systems, dielectric capacitors can absorb peak power in a very short time (milliseconds) during braking, reducing the high current load on the battery which is susceptible to cyclic degradation. Studies by (Cittanti et al., 2022) demonstrate the real-world implementation of a 550 kVA full ceramic capacitor in an EV inverter, which is designed based on the uniform field distribution principle derived from Gauss's Law. Similarly, (Jiang et al., 2021) achieves an energy density of 18.5 J/cm³ and an efficiency of 78.7% in lead-free antiferroelectric ceramics, making them ideal for high-power applications requiring reliability and instant response. With instant power delivery capabilities, high voltage stability, and cycle life far exceeding that of batteries, high-energy dielectric capacitors are not just complementary, but critical components in future EV power architectures, as long as their design considers electric field distribution based on fundamental electrostatic principles such as Gauss's Law.

CONCLUSION

A systematic analysis of the literature conducted over the past five years, from 2019 to 2025, shows that Gauss's Law provides an essential electrostatic framework for

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understanding electric field distribution in various dielectric capacitor geometries. The application of this law allows for accurate capacitance calculations in both parallel-plate and cylindrical capacitors and provides a basis for avoiding field concentrations that trigger breakdown.

Geometry optimization (especially cylindrical configuration) and selection of innovative dielectric materials such as lead-free ceramics and CBDA-BAPB-based polymers have been shown to increase energy density (>18.5 J/cm³) and efficiency (>78%) (Jiang et al., 2021). In a system context, high-energy dielectric capacitors are poised to support EV propulsion systems as reliable, high-power components. Although general literature often refers to supercapacitors in HESS, the focus of Gauss's Law-based design remains on dielectric capacitors, whose storage mechanism is purely electrostatic.

Thus, this study confirms that Gauss's Law is not only a fundamental theory of electrostatics, but also a practical foundation for designing reliable, efficient, and high-energy capacitors ready for future electric vehicle applications. As a recommendation, further research should link Gauss's Law-based electric field analysis with experimental tests on real capacitor prototypes to validate their practical performance.

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