engineering proceedings

MDPI

Proceeding Paper

Estimation of Energy Storage Capability of the Parallel Plate Capacitor Filled with Distinct Dielectric Materials †

Kiran Keshyagol [1], Shivashankarayya Hiremath [1,2], Vishwanatha H. M. [3,*] and Pavan Hiremath [3]

[1] Department of Mechatronics, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India; mekeshyagol@gmail.com (K.K.); sssnitk@gmail.com (S.H.)
[2] Survivability Signal Intelligence Research Centre, Hanyang University, Seongdong-gu, Seoul 04763, Republic of Korea
[3] Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India; pavan.hiremath@manipal.edu
* Correspondence: vishwanatha.hm@manipal.edu
† Presented at the International Conference on Recent Advances on Science and Engineering, Dubai, United Arab Emirates, 4–5 October 2023.

Abstract: In the present work, the behavior of parallel plate capacitors filled with different dielectric materials and having varied gaps between the plates is developed and analyzed. The capacitor model's capacitance and energy storage characteristics are estimated numerically and analytically. The simulation results of the model developed in the Multiphysics simulation package show that the capacitance of the capacitor decreases with an increase in the gap between the plates. Similarly, energy storage capacity increases with the material's dielectric constant, with PVDF showing enhanced storage capacity. Further, the results of both analytical and numerical methods were in good agreement. Thus, the developed model was validated. The findings can potentially advance the design and optimization of capacitor-based systems, enabling the development of improved sensors, actuators, and efficient energy storage applications.

Keywords: energy storage; capacitance; dielectric material; Multiphysics; SDG 7; SDG 13

Citation: Keshyagol, K.; Hiremath, S.; H. M., V.; Hiremath, P. Estimation of Energy Storage Capability of the Parallel Plate Capacitor Filled with Distinct Dielectric Materials. *Eng. Proc.* **2023**, *59*, 95. https://doi.org/10.3390/engproc2023059095

Academic Editors: Nithesh Naik, Rajiv Selvam, Suhas Kowshik CS and Ritesh Ramakrishna Bhat

Published: 21 December 2023

1. Introduction

The parallel plate capacitor is a crucial electrical component consisting of two conducting plates separated by a dielectric material. It finds extensive applications in electronics, energy storage, and sensing [1]. Characterizing dielectric materials is vital for technological advancements and addressing global challenges in renewable energy and electrification. As the demand for energy storage devices grows with the rapid expansion of renewable energy sources, dielectric materials have emerged as promising options [2,3]. They offer desirable properties, including high energy density, low loss, and efficient charge–discharge capabilities. Enhancing the electrical properties of dielectric materials, particularly their energy density and reduction of dielectric loss, remains a significant challenge. Higher energy density directly impacts the amount of energy stored in each volume or weight, making optimal energy storage solutions crucial. Additionally, minimizing dielectric loss is essential for improving the efficiency of energy storage devices. Accurate numerical approaches play a vital role in optimizing the performance of dielectric materials. Numerical methods enable the evaluation and comparison of different dielectric materials, facilitating the development of high-performance energy storage devices aligned with sustainable development goals (SDGs) 7 and 13 [4–6].

The current study focuses on developing a parallel plate capacitor model via analytical and numerical approaches. The analytical solutions offer insights into capacitor behavior under ideal conditions, while numerical simulations analyze complex capacitor configurations by varying the distance between the plates and using different materials [7].

Numerical simulations involve creating three-dimensional models, choosing physics and boundary conditions, assigning appropriate mesh and solvers, and measuring capacitance for different dielectric materials and plate gaps. Validating the simulation results using analytical methods ensures reliability and is a benchmark for further analysis and material optimization [8]. By combining numerical and analytical approaches, researchers can assess the energy storage capabilities of dielectric materials, compare their performance, and identify materials with enhanced properties for specific applications. This knowledge advances energy storage technologies and enables sustainable solutions to global challenges related to renewable energy integration and electrification. The outcomes of the current investigation via simulations and theoretical approaches provide valuable insights for designing and optimizing capacitors tailored to specific applications. This paves the way for enhanced electronics, sensing, and energy storage performance [1,9].

2. Methodology

Developing a capacitor model involves creating an analytical or computational representation of the behavior of a capacitor in response to different materials and electrical conditions. A capacitor is an electronic component that stores electrical energy as an electric field between two conductive plates separated by an insulating or dielectric material [10]. A capacitor model can range from simple ideal models to complex high-fidelity models incorporating various parasitic effects and real-world considerations. The choice of model depends on the specific application and the accuracy required for the analysis or design of electronic circuits. A three-dimensional capacitor model was created using the COMSOL Multiphysics software tool. The model enables capacitance measurement by adopting distinct dielectric materials between two parallel plates.

The work begins with representing the capacitor using its parallel plate model shown in Figure 1. The capacitor has two flat and parallel conductive plates. These plates are usually made of metal, such as aluminum or copper, providing an electrical connection to the capacitor. The space between the two plates is filled with a dielectric, insulating material that does not conduct electricity. Dielectric materials can be air, paper, plastic, glass, or ceramics. The two parameters that greatly influence the performance of the capacitor are the gap between the plates and the dielectric medium between the plates. In the current investigation, the two parameters mentioned above are varied and studied for the efficiency of the capacitor under a given set of parameters. The geometry of the parallel plate capacitor is shown in Figure 1a, where the radius of the circular plate of each plate diameter is denoted by ‘r’. The larger the diameter of the plates, the greater the capacitance of the capacitor. The distance between the two plates is denoted by ‘d’. It is also called plate separation or the distance between the electrodes. The smaller the separation distance, the higher the capacitance. Figure 1b shows the capacitor circuit; the voltage across the capacitor is denoted by ‘V’. The potential difference between the two plates determines the amount of charge stored in the capacitor.

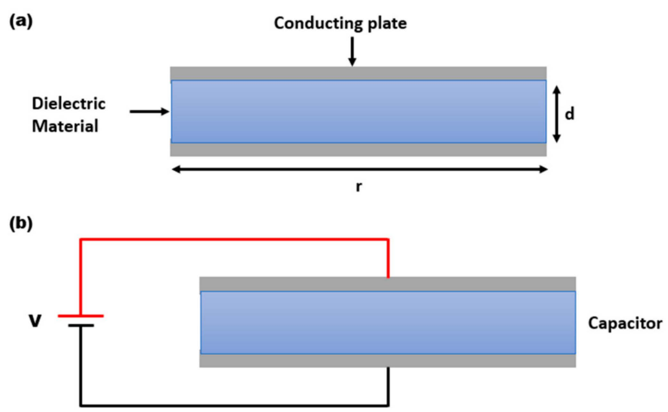

Figure 1. (**a**) Geometry of the parallel plate capacitor. (**b**) Circuit of the capacitor model.

The capacitance of the parallel plate capacitor depends on the area of the plates, the separation distance, and the permittivity of the dielectric material. It is calculated using Equation (1)

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \quad (1)$$

where

C = Capacitance (F)
ε_0 = Permittivity of free space (approximately 8.854 pF/m)
ε_r = Relative permittivity or dielectric constant of the material between the plates
A = Area of each plate (m^2)
d = Separation distance between the plates (m)

The parallel plate capacitor is a fundamental element in various electronic circuits widely used for energy storage, filtering, and smoothing applications. Its simple geometry and behavior make it essential in many electrical and electronic devices [11].

Analytical approaches are often used to obtain insight into the developed model. Thus, in a parallel plate capacitor, two parallel conductive plates are separated by a dielectric material of relative permittivity or dielectric constant. The assumption was that the homogeneous electric field concentrated in the gap between the electrodes. Also, it can be noted that the assumption may not hold when the gap becomes extremely small or when the permittivity of the dielectric material is not sufficiently high for the generation of the electric field. Therefore, the electric field spreads over a larger volume, making the field out of the vicinity [12].

The charge stored by a capacitor is directly proportional to the voltage across its terminals and its capacitance. When a voltage is applied across the capacitor, it stores an electric charge on its plates. The capacitance determines how much charge it can hold for a given voltage. Given the same voltage, a capacitor with a higher capacitance can store more charge than a capacitor with a lower capacitance. The relationship between charge (Q), voltage (V), and capacitance (C) is represented as [13]:

$$C = \frac{Q}{V} \quad (2)$$

The potential energy stored in an electric field due to the configuration of electric charges is called the electrostatic charge. When electric charges are brought together or separated, they create an electric field that stores potential energy. The amount of electrostatic energy depends on the magnitude and distribution of the charges and the distances between them. The equation for the electrostatic energy (U) of a continuous charge distribution, which forms the electric field (E) in each volume (v), is expressed as [14]:

$$U = \frac{1}{2} \varepsilon \int_v |E|^2 dv \quad (3)$$

where dv is the differential volume element, and ε is the permittivity of the medium in which the field exists.

As seen in Equation (3), the stored energy is proportional to the square of an electric field, resulting in a rapid decline in the stored energy when the electric field decreases. In other words, the main part of the energy is stored in the space near the capacitor electrodes where the electric field is stronger. Energy stored on the surface of the parallel plate capacitor is calculated using Equation (4) [15].

$$U = \frac{Qv}{2} = \frac{Cv^2}{2} \quad (4)$$

2.1. Dielectric Materials

Dielectric materials are insulating materials that do not conduct electricity. They are used in various applications to separate or insulate conductive components, prevent electrical leakage, and store electrical energy in capacitors. The choice of dielectric material depends on factors such as the desired capacitance, operating frequency, temperature stability, and specific requirements of the application. Dielectric materials play a critical role in the performance and design of electronic components, especially capacitors, which determine the energy storage capacity and overall efficiency [16]. Here are some common types of dielectric materials used in the analysis of the capacitor model. The capacitor model requires different properties that are givenin Table 1.

Table 1. Properties of different dielectric materials.

Parameter	Air	PDMS	Nylon	PVDF
Dielectric constant (ε)	1	2.4–2.7	4	10–12
Young's modulus(E) [GPa]	$0 > E < 1$	0.00075–0.00090	2	2.17
Density (ϱ) [kg/m^3]	1.293	970	1150	1.78
Poisson's ratio (ν)	-	0.49	0.4	0.40

The current investigation developed the analytical and numerical models using distinct dielectric materials such as air, polydimethylsiloxane (PDMS), nylon, and poly vinylidene fluoride (PVDF) [17]. The required properties of the chosen dielectric materials are given in Table 1. These materials may help to estimate insight into the capacitor model. Another vital constituent for parallel plate capacitors is the gap between two plates. A capacitor with a diameter of 10 mm is used in the current work. The spacing between the plates varies as 2, 4, and 6 mm. The objective is to analyze the capacitor's capacitance and energy storage characteristics under these different plate distance configurations. It is worth noting that the fringing or edge effects in the capacitor are disregarded in the current work, as these effects become less significant when the diameter of the plates is much greater than the distance between them [4].

2.2. Numerical Approach

One can use the finite element method (FEM) to numerically analyze a parallel plate capacitor. The FEM is a powerful numerical technique that can handle complex geometries and different materials and their properties [18]. The capacitor model was built with different thicknesses, followed by selecting appropriate physics and boundary conditions. The circular-shaped capacitor has been analyzed with different dielectric materials and thicknesses. In addition, the gap between the parallel plate capacitors varied. The material properties given in Table 1 were assigned to the capacitive model. The applied boundary conditions at the model's surface are positive voltage on the upper surface of the model and grounded lower surface. Variables used for the study are the gap between plates and the dielectric medium between the plates. For numerical iteration, a triangulation mesh element was created for a complete capacitive model. Numerical modeling of a circular-shaped capacitive model involves different simulating steps, as shown in Figure 2. The computational method of a circular-shaped capacitor provides valuable insights into its behavior and performance, making it a powerful tool in sensor development, optimization, and engineering applications [18,19].

Numerical and analytical approaches were adopted to analyze the capacitive model by varying the thickness and material. The simulations were carried out using commercially available COMSOL Multiphysics software, and the result was validated using an existing mathematical model.

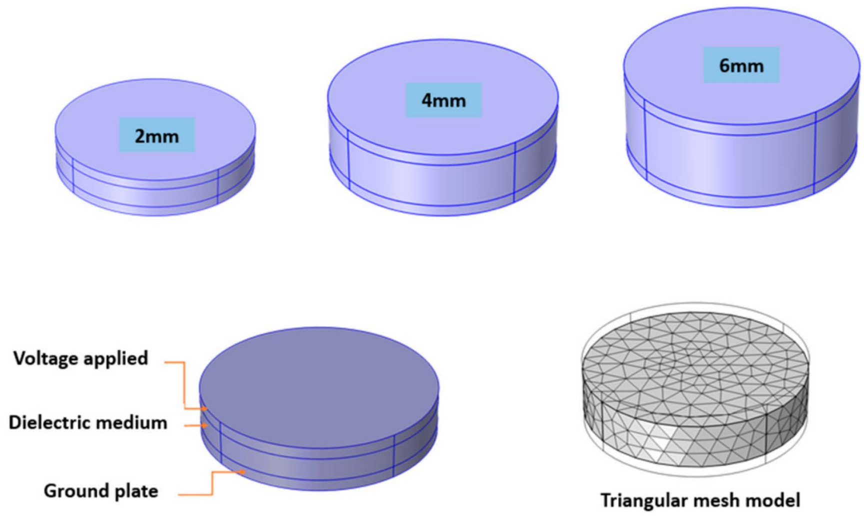

Figure 2. Modeling stages of the capacitive model.

3. Result and Discussion

The capacitive model has a radius of 1 cm and varied thickness of 2, 4, and 6 mm. The voltage supplied on the upper surface of the plate leads to an electric field difference in the capacitive model. The electric field through the capacitive model with varied thicknesses is shown in Figure 3. The electric field within the model decreases as the thickness of the dielectric material increases. It is noticed that a 2 mm thickness has a higher potential than the 6 mm thick plate model. Thus, appropriate thicknesses need to be adopted to develop the capacitive application.

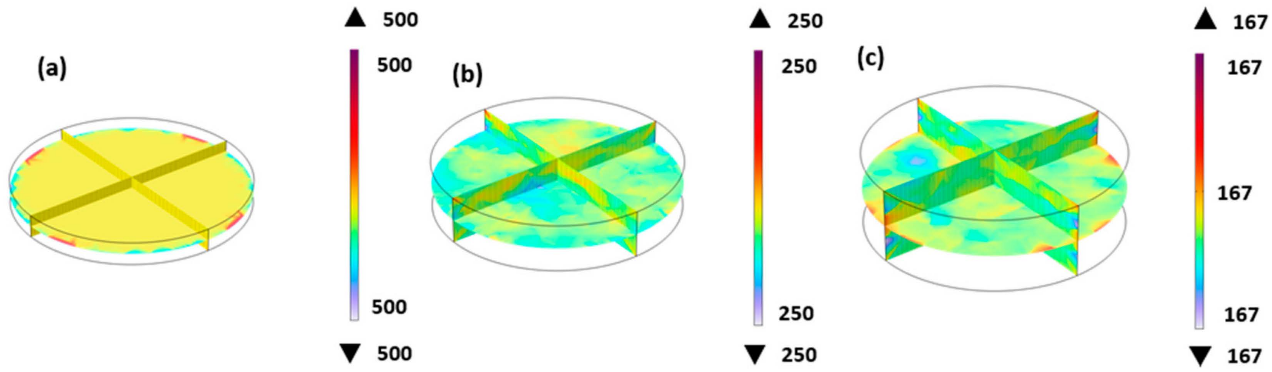

Figure 3. Electric field through (**a**) 2 mm, (**b**) 4 mm, and (**c**) 6 mm parallel plate of the capacitive model.

In continuation with the numerical model of the capacitor, the energy stored in the material can be predicted. Figure 4 shows the electric energy stored in a different dielectric medium. The results show that the PVDF dielectric material has a higher storage capacity than the other three dielectric material mediums: air, nylon, and PDMS. It is also observed that energy distribution over the capacitive model is minimal. These distributions show the flow of a high electric field from the higher potential to the lower potential energy level.

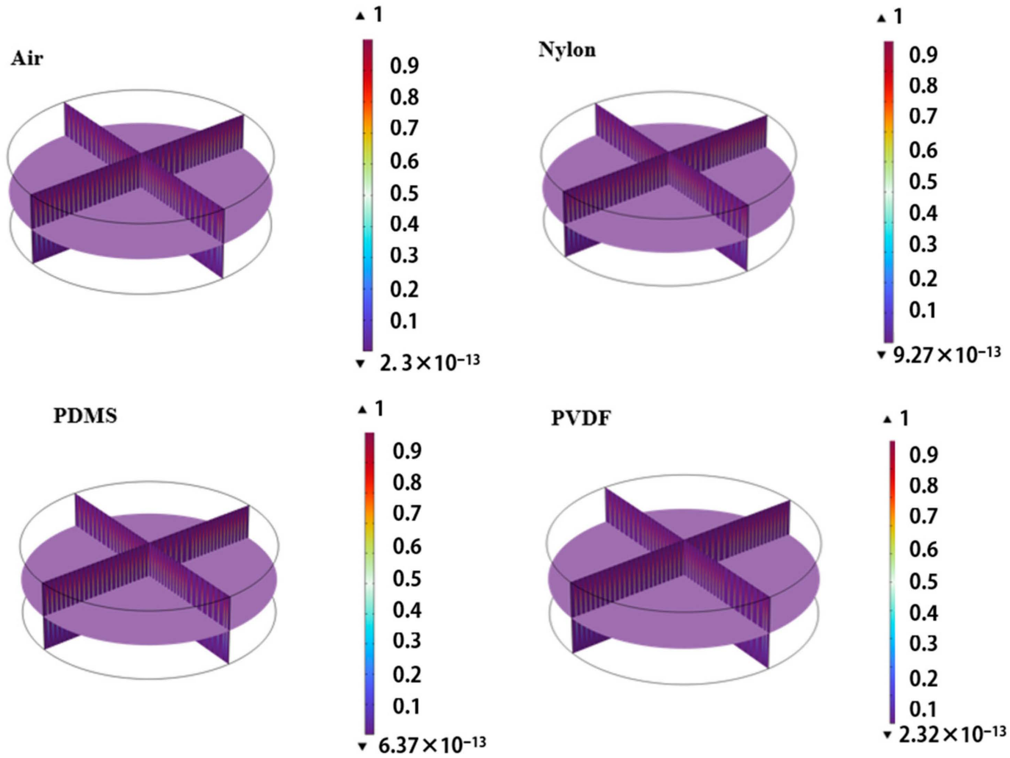

Figure 4. Energy stored due to applied voltage in the dielectric medium.

The comparative assessment of the numerical and analytical models for parallel plate capacitance is presented in Table 2. A discernible trend emerges, wherein the dielectric constant exhibits a direct proportionality to the material's capacitance. This effect is particularly pronounced in the context of PVDF, which boasts the highest dielectric constant among the considered materials. Moreover, it is noteworthy that the numerical outcomes obtained through varying materials and electrode distances exhibit remarkable proximity to those derived analytically. A salient observation is the inverse relationship between the gap distance and capacitance. As the distance between the electrodes diminishes, capacitance registers an ascent, concurrently augmenting the cumulative electric energy storage potential within the capacitors.

Table 2. Comparative analysis of the parallel plate capacitor.

Dielectric Materials	Gap d (mm)	Numerical Method (pF)	Analytical Method (pF)	Total Electric Energy Store (Joules)
Air $\varepsilon_r = 1$	6	0.4636	0.4636	0.2318×10^{-12}
	4	0.6954	0.6954	0.3477×10^{-12}
	2	1.3908	1.3908	0.6954×10^{-12}
PDMS $\varepsilon_r = 2.75$	6	1.2749	1.2746	0.6374×10^{-12}
	4	1.9123	1.9123	0.9561×10^{-12}
	2	3.8247	3.8247	1.9123×10^{-12}
Nylon $\varepsilon_r = 4$	6	1.8544	1.8542	0.9272×10^{-12}
	4	2.7816	2.7816	1.3908×10^{-12}
	2	5.5632	5.5632	2.7816×10^{-12}
PVDF $\varepsilon_r = 10$	6	4.6360	4.6361	2.3180×10^{-12}
	4	6.9540	6.9540	3.4770×10^{-12}
	2	13.9080	13.9080	6.6940×10^{-12}

Figure 5 illustrates the variation of capacitance and energy storage with the gap distance. When the gap distance between the plates increases, it decreases capacitance

(Figure 5a). This decreased capacitance corresponds to a reduced ability of the capacitor to hold and store electric charge effectively. Consequently, the overall energy stored within the capacitor experiences a decrease as well (Figure 5b). This interplay between gap distance and energy storage exemplifies a noteworthy trade-off. As the distance between the plates widens, the capacitor's ability to store energy becomes compromised due to the lower capacitance. This illustrates the delicate balance between the physical dimensions of the capacitor, specifically the plate separation, and its capability to store electrical energy.

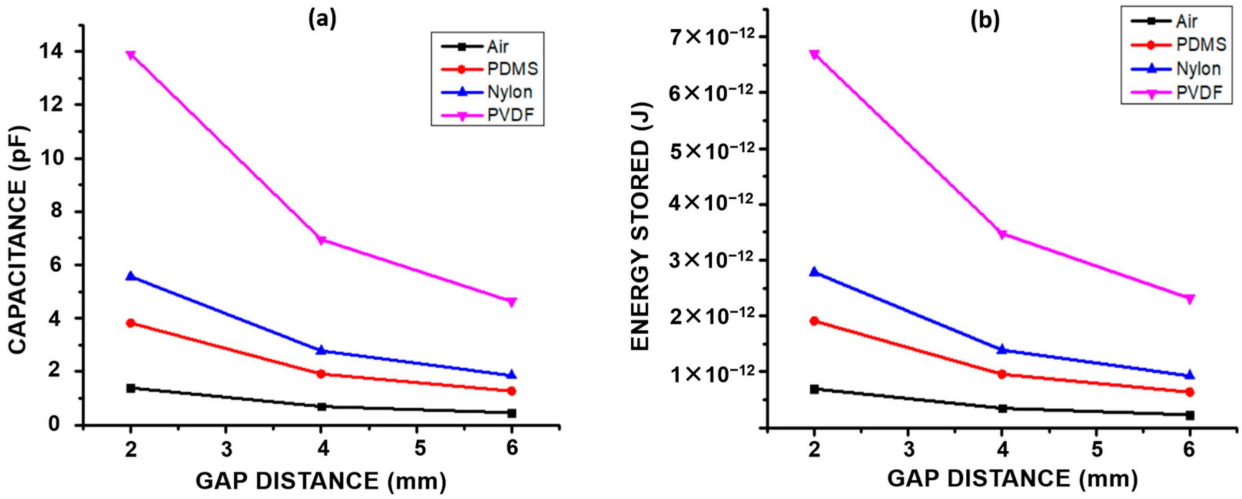

Figure 5. Effect of gap distance on the (**a**) capacitance of the model and (**b**) the energy stored with the change in the gap between the plate.

4. Conclusions and Future Scope

This study used a numerical and analytical approach to evaluate the capacitive model by varying the gap between the plate and the dielectric material between the plates. A 3D model of the capacitor was developed successfully. The robustness of the model was tested and analyzed. It was established that with the increase in the gap between plates, there is a decline in the capacitance of the parallel plate capacitor. Further, a medium with a higher dielectric constant can store more energy in the capacitor model. It was observed that the PVDF dielectric medium exhibited a higher capacitance value and greater energy storage ability than air, nylon, and PDMS. Compared to air, with a 2 mm gap between plates, PVDF material exhibited improved capacitance by 90%. Numerical simulation was also established for the parallel plate capacitor model to estimate the electric energy storage based on the different dielectric materials and changing the gap of the plate.

Consequently, this numerical study facilitates the assessment of energy storage phenomena and contributes to developing applications such as sensors, actuators, and energy storage devices. Thus, a robust model was established in the current study for estimating the capacitance of the capacitor. The capacitor can yield results by varying the dielectric medium between the plates in addition to varying the gap between the plates.

Building upon the insights gleaned from this study, several promising directions for future research can be envisaged to advance the understanding of energy storage in capacitive systems. By extending the current concept, one can investigate the impact of dynamically varying gap distances on capacitance and energy storage, which could provide a more comprehensive understanding of how these parameters interact. Further, it can also be used to explore the effects of composite dielectric materials or layered configurations, which could yield intriguing outcomes. Also, it can be a tool for investigating the temperature-dependent behavior of capacitors and its consequences on energy storage, which could lead to designs that maintain optimal performance across varying thermal conditions, etc.

Author Contributions: Conceptualization, methodology, software, writing—original draft preparation, K.K. and S.H.; validation, formal analysis, writing—review and editing, V.H.M. and P.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to thank Indian Science Technology and Engineering Facilities Map (I-STEM), a Program supported by the Office of the Principal Scientific Advisor to the Govt. of India, for enabling access to the COMSOL Multiphysics 5.6 software suite used to carry out present work.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhao, Y.; Yin, L.J.; Zhong, S.L.; Zha, J.W.; Dang, Z.M. Review of dielectric elastomers for actuators, generators and sensors. *IET Nanodielectr.* **2020**, *3*, 99–106. [CrossRef]
2. Hao, X. A review on the dielectric materials for high energy-storage application. *J. Adv. Dielectr.* **2013**, *3*, 1330001. [CrossRef]
3. Koohi-Fayegh, S.; Rosen, M.A. A review of energy storage types, applications and recent developments. *J. Energy Storage* **2020**, *27*, 101047. [CrossRef]
4. Tehrani, M.D.; Hojjat, Y.; Dadkhah, M.; Jeon, J.U.; Hojjat, Y.; Boo, S.P. Accurate Capacitance Computation of General 3D Structures Using Stored Energy Method (SEM). 2011. Available online: https://www.researchgate.net/publication/266202919_Accurate_Capacitance_Computation_of_General_3D_Structures_Using_Stored_Energy_Method_SEM?channel=doi&linkId=542c2f190cf29bbc126c09a1&showFulltext=true (accessed on 1 December 2023).
5. Trinh, V.L.; Chung, C.K. Renewable energy for SDG-7 and sustainable electrical production, integration, industrial application, and globalization: Review. *Clean. Eng. Technol.* **2023**, *15*, 100657. [CrossRef]
6. Wali, S.B.; Hannan, M.A.; Ker, P.J.; Abd Rahman, M.S.; Tiong, S.K.; Begum, R.A.; Mahlia, T.I. Techno-economic assessment of a hybrid renewable energy storage system for rural community towards achieving sustainable development goals. *Energy Strategy Rev.* **2023**, *50*, 101217. [CrossRef]
7. Li, T.; Makarov, S.N.; Ludwig, R.; Emanuel, A.E. 3D capacitance extraction with the method of moments. Ph.D. Thesis, Worcester Polytechnic Institute, Worcester, MA, USA, 2010.
8. Rizzello, G. A Review of Cooperative Actuator and Sensor Systems Based on Dielectric Elastomer Transducers. *Actuators* **2023**, *12*, 46. [CrossRef]
9. Yuan, M.; Zhang, X.; Wang, J.; Zhao, Y. Recent Progress of Energy-Storage-Device-Integrated Sensing Systems. *Nanomaterials* **2023**, *13*, 645. [CrossRef] [PubMed]
10. Zhang, T.; Chen, X.; Thakur, Y.; Lu, B.; Zhang, Q.; Runt, J.; Zhang, Q.M. A highly scalable dielectric metamaterial with superior capacitor performance over a broad temperature. *Sci. Adv.* **2020**, *6*, eaax6622. [CrossRef] [PubMed]
11. Shanmugasundram, H.P.P.V.; Jayamani, E.; Soon, K.H. A comprehensive review on dielectric composites: Classification of dielectric composites. *Renew. Sustain. Energy Rev.* **2022**, *157*, 112075. [CrossRef]
12. Chen, X.; Zhang, Z. Fringing Effect Analysis of Parallel Plate Capacitors for Capacitive Power Transfer Application. In Proceedings of the 2019 IEEE 4th International Future Energy Electronics Conference (IFEEC), Singapore, 25–28 November 2019; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2019. [CrossRef]
13. Catalan-Izquierdo, S.; Bueno-Barrachina, J.M.; Cañas-Peñuelas, C.S.; Cavallé-Sesé, F. Capacitance evaluation on parallel-plate capacitors by means of finite element analysis. *Renew. Energy Power Qual. J.* **2009**, *1*, 613–616. [CrossRef]
14. Wu, X.; Chen, X.; Zhang, Q.M.; Tan, D.Q. Advanced dielectric polymers for energy storage. *Energy Storage Mater.* **2022**, *44*, 29–47. [CrossRef]
15. Hu, H.; Zhang, F.; Luo, S.; Chang, W.; Yue, J.; Wang, C.-H. Recent advances in rational design of polymer nanocomposite dielectrics for energy storage. *Nano Energy* **2020**, *74*, 104844. [CrossRef]
16. Sun, W.; Mao, J.; Wang, S.; Zhang, L.; Cheng, Y. Review of recent advances of polymer based dielectrics for high-energy storage in electronic power devices from the perspective of target applications. *Front. Chem. Sci. Eng.* **2021**, *15*, 18–34. [CrossRef]
17. Singh, V.; Singh, B. PDMS/PVDF-MoS2 based flexible triboelectric nanogenerator for mechanical energy harvesting. *Polymer* **2023**, *274*, 125910. [CrossRef]

18. Almond, D.P.; Bowen, C.R.; Rees, D.A.S. Composite dielectrics and conductors: Simulation, characterization and design. *J. Phys. D Appl. Phys.* **2006**, *39*, 1295–1304. [CrossRef]
19. Dinulovic, M.; Rašuo, B. Dielectric Properties Modeling of Composite Materials. *FME Trans.* **2009**, *37*, 117–122.