E3S Web of Conferences **547**, 03018 (2024) https://doi.org/10.1051/e3sconf/202454703018
ICSGET 2024

Harnessing Supercapacitors for Sustainable Energy Storage: A Technical Overview and Critical Analysis

Santosh Kumar Sahu[1]*, *P. S. Rama Sreekanth*[1], *Nitesh Dhar Badgayan*[2], *Tunji John Erinle*[3]

[1]*School of Mechanical Engineering, VIT-AP University, Besides A.P. Secretariat, Amaravati 522237, Andhra Pradesh, India*
[2]*Symbiosis Centre for Management Studies, Bengaluru Campus, Symbiosis International (Deemed University), Pune, India*
[3]*Mechanical Engineering Department, Federal Polytechnic, Ado-Ekiti, Ekiti State, Nigeria*

Abstract. The historic United Nations summit on 01st January 2016 adopted the 17 Sustainable Development Goals (SDGs) and set the 2030 Agenda for Sustainable Development. Energy is a key part of the sustainable development agenda however the current renewable energy system faces several limitations like intermittency, grid integration challenges, and energy storage efficiency. Supercapacitor possesses high energy storage efficiency, high power density, and resource efficiency which enables them to contribute to different SDGs like promoting clean energy generation when integrated with renewable energy solutions (SDG 7), in industrial processes like water treatment plants it can energy efficiency reduce operational cost (SDG 6), it can also improve electric vehicle performance by improving energy efficiency and thereby contributing to SDG 11. Considering the different applications of supercapacitors in achieving sustainability, the current review article focuses on the importance of supercapacitors and their types. It also reviews different materials for electrodes and electrolytes and a note on future scope besides applications.

1 Introduction

Greenhouse and climate change are the two major concerns worldwide due to the significant dependency on fossil fuels, coal, and natural gas for energy sources. Therefore, there is a continuous demand for alternate, renewable, and eco-friendly sources for energy consumption. Although solar and wind are alternate sources, these have drawbacks in terms of fluctuating energy sources. The electrical system was introduced to overcome this problem, which constantly supplies energy without any fluctuation. The prime role of electrical energy storage devices is to act as a reservoir that stores the energy during production and supplies during requirements. The researchers are actively working on achieving the enhancement of the efficiency of devices used for storing electrical power. Unlike the conventional storage device that possesses a longer charging time and quick discharge drawback, supercapacitors (S.C) are the new era of technology that fulfils the above lacuna to a great extent. These devices boast exceptional power density, rapid charge and discharge capabilities, long lifespan, and eco-friendliness [1]. Fig. 1a shows the plot between specific power (S.P.) vs specific energy (S.E.) for different energy sources. The highest specific energy is exhibited by fuel cells with lower specific power; however, the supercapacitor demonstrates the high-power output and moderate energy capacity. Nevertheless, the batteries showed intermediate potential in both S.P. and S.E. values. There is a huge demand for supercapacitors globally. The need for supercapacitors in the global market in 2014 was 0.46 billion dollars and is projected to grow to 8.33 billion dollars with an annual compound growth rate of 30 % by 2025 Fig. 1b [2].

The study provides a thorough examination of supercapacitors, emphasizing their importance in addressing environmental concerns. It systematically explores the global energy landscape, detailing the need for sustainable energy solutions. Through careful classification, it explores supercapacitors' workings, benefits, and applications. It also examines critical factors like electrode and electrolyte materials. The conclusion stresses the growing demand for hybrid supercapacitors and the need for ongoing advancements.

2 Classification of supercapacitor

Supercapacitor consists of two solid electrodes and a liquid electrolyte, which is different from a ceramic or electrolytic type of capacitor.

---

* Corresponding author: sksahumech@gmail.com

These electrodes of S.C.s are separated by a separator, which is polarized by the voltage applied. The Supercapacitors (S.C.s) are classified into electric double-layer (EDL) capacitors, pseudo capacitors, and hybrid capacitors as shown Fig. 2.

2.1 Electric double-layer (EDL) capacitors

Helmholtz conceptualized the Electric double-layer (EDL) capacitor phenomenon [3]. The typical EDL capacitor is shown in Fig.3a. This capacitor works with the principle of forming double layers of electrochemical separation to store electrical energy. When a sufficient voltage is applied across the capacitor, the two layers of polarized ions are produced at the interfaces of electrodes. The first layer is induced within the solid electrode. The second layer, having opposite polarity, is customs from the dissolved and solvated ions disseminated in the electrolyte and moves near to the polarized electrode. A single layer of solvent molecules separates these two polarized ionic layers.

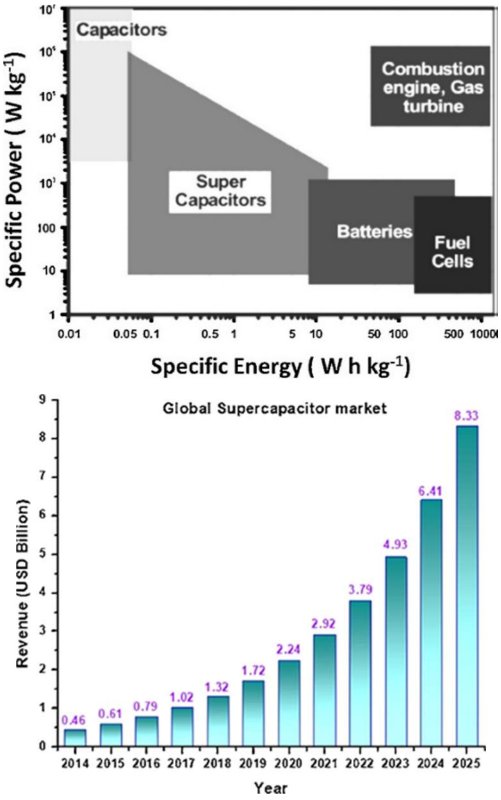

Fig. 1. (a) Specific power vs. Specific energy, (b) Global supercapacitor market [2]

The capacitance is calculated using the standard equation [4]-

$$C=(A\epsilon_0)/d \qquad \text{- - - (1)}$$

Here,

'C' denotes the capacitance in farads,

'A' stands for the surface area,

'ϵ_0' signifies the permittivity of free space,

'd' represents the effective thickness of the electric double-layer

2.2 Pseudo capacitors

The typical pseudo-capacitors is shown in Fig.3b. Pseudo-capacitors are the capacitors that charge the electrode due to electrochemical reactions without forming an intermediate layer. The energy density and capacitance obtained from Pseudo capacitors is higher than from EDL capacitors. The charging mechanism of Pseudo capacitors is fundamentally different from EDLC and works on the principle of pseudo-capacitive intercalation and the surface redox reaction. There is no phase transformation in this capacitor, so the charging process can be fast. The capacitance of the pseudo capacitors is obtained as per the following formula [5]-

$$C=(d(\Delta q))/(d(\Delta V)) \qquad \text{- - - (2)}$$

Here, 'Δq' represents the charge acceptance, and 'ΔV' denotes the change in potential.

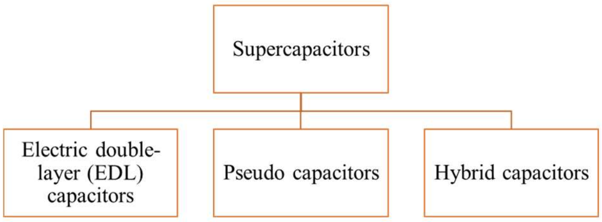

Fig. 2. Classification of supercapacitors

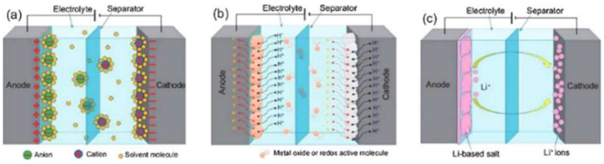

Fig. 3. Photograph of (a) electrical double-layer (EDL) capacitor (b) pseudo capacitor (PC) and (c) hybrid capacitor (HC) [2]

2.3 Hybrid capacitors

The conception of hybrid supercapacitors (HSCs) came into reality to enhance the energy density range, higher voltages, and less self-discharge [6]. The typical HSC is shown in Fig. 3c. This type of capacitor works on the principle of electrostatically and electrochemically charging the electrode, which replaces one of the EDLC electrodes with the coupling of different redox (Rox) and materials like graphene, activated carbon, metal oxides, and conducting polymers [7]. The combination has higher operational potential and can yield higher capacitance, about three times more than conventional EDL and pseudo capacitors. The specific capacitance (Cs) for hybrid capacitors is measured as per the following equation [8]-

$$Cs=I/(dV/dt(w)) \qquad \text{- - - (3)}$$

In this context, 'I' signifies the average current in amperes, 'w' refers to the total mass of the electrode, and dV/dt indicates the rate of voltage change over time.

3 Materials

The capacitors' functionality, electrical, and thermal characteristics depend on the type of electrode material, their combination, type of electrolyte, and separators materials. The followings are some essential materials concerning the supercapacitor materials-

3.1 Electrode materials

Electrodes materials used in supercapacitors are usually thin coatings of layers of conductive material on a metallic rod. The prime requirement for electrodes is fundamental properties like decent conductivity, superior temperature stability, high chemical stability, eco-friendliness, corrosion resistance, high surface areas, high specific volume, and low cost [9]. The commonly used electrodes for S.C. are- carbon-based, metal oxides, conductive polymers and nanocomposites.

3.1.1 Carbon-based material

Carbon-based electrodes are frequently used electrode for supercapacitors. This is due to high availability, conventional production processes, and low cost [10]. Carbon electrodes are available in various dimensional structures (i.e. from 1D to 3D), such as tube to sheet, and in the form of foam. The specific capacitance (C_s) increases with the surface area of the electrode.

3.1.2 Metal oxide

Metal oxide materials are also viable options for electrode usage in supercapacitors due to their high specific capacitance and minimal resistance. The construction of a supercapacitor is simple and low cost and produces high energy and power. Commonly used metal oxide materials include nickel oxide (NiO), ruthenium dioxide (RuO_2), manganese oxide (MnO_2), and iridium oxide (IrO_2). [11].

3.1.3 Conductive polymer

Conducting polymers is one of the electrode materials in supercapacitors. Researchers are highly interested in this subject due to its considerable potential applications, simple manufacturing process, and affordability [12]. Conductive polymers use different electrodes configurations. In one setup, known as the n/p type, one component carries a negative charge while the other bears a positive charge. In this arrangement, the storage and release of energy involve the reduction-oxidation process.

3.1.4 Nanocomposite

Nanocomposite materials are two-phase materials, where one is a continuous phase called matrix and the other is of dispersed phase at the nanoscale [13, 14, 15]. These materials are stronger, stiffer, superior thermal, electrical mechanical properties than those of virgin material [16, 17]. Nanocomposite electrodes are the type of electrode where a nanoparticle, usually carbon-based material, is filled in the matrix of either metal oxide or conducting polymer [18]. This resulting nanocomposite offers an advanced means of physical and chemical charge storage compared to a single pristine electrode. Various types of nanocomposites include carbon-carbon, carbon-metal oxide, and carbon-conductive polymer composites. Table 1 summarizes different electrode materials utilized in supercapacitors, detailing their specific capacitance (C_s) measured in Farads per gram (Fg^{-1}) and energy density (E_d) in Watt-hours per kilogram ($WhKg^{-1}$). The materials encompass Multi-Walled Carbon Nanotubes (MWCNT), Graphene, Manganese Oxide/Carbon Nanotube composite (MnOx/CNT), Nitrogen-Doped Graphene, Manganese Oxide ($Mn3O_4$), Ruthenium Dioxide (RuO_2), a composite of Polyaniline/Carbon Nanofiber/Graphene Nanoplatelet (PANI/CNF/GNP), a composite of Polythiophene/Multiwalled Carbon Nanotube, and a composite of Poly(3,4-ethylenedioxythiophene) nanowires/Carbon Cloth (PEDOT-NWs/CC).

Table 1: Different electrode materials for supercapacitors

Electrode material	Specific capacitance (C_s) Fg^{-1}	Energy density (E_d) $WhKg^{-1}$	Reference
MWCNT	50	-	[19]
Graphene	-	85.6	[20]
MnOx / CNT	388	-	[21]
Nitrogen-Doped Graphene	248.4	-	[22]
Mn_3O_4	72	23.4	[23]
RuO_2	1715	-	[24]
PANI/CNF/GNP	421.5	25.3	[25]
Polythiophene/multiwalled carbon nanotube	216	-	[26]
PEDOT-NWs/CC	256.1	182	[27]

3.2 Electrolyte materials

The primary function of electrolytes is to act as a medium that offers the mechanism for ion transport between the cathode and anode. Electrolytes are crucial for the operation of supercapacitors. To ensure smooth charging, the electrolyte concentration must be sufficiently high to prevent depletion issues. The key properties of electrolytes include conductivity and temperature coefficient [28], which determine the equivalent series resistance of supercapacitors. Table 2 summarizes various electrolyte materials used in supercapacitors. The listed materials include solutions such as 0.5 M $K2SO_4$, 2 M Li2SO4, 1 M KOH (at a rate of 5 mVs^{-1}), 2 M KOH, 6 M KOH, 0.1 M H_2SO_4, and 1 M $LiClO_4$. These electrolyte solutions demonstrate varying specific capacitance and energy density values, reflecting their potential utility in supercapacitor applications.

Table 2. Different electrolyte materials for supercapacitors

Electrolyte material	Specific capacitance (C_s) Fg^{-1}	Energy density (E_d) $WhKg^{-1}$	Reference
0.5 M K_2SO_4	110	20	[29]
2 M Li_2SO_4	1145	57	[30]
1 M KOH	1376 at (5 mVs^{-1})	0.55 ($mWhcm^{-3}$)	[31]
2 M KOH	1065	-	[32]
6 M KOH	1045	51	[33]
0.1 M H_2SO_4	380	-	[34]
1 M $LiClO_4$	20.7 (F/cm^3)	1.5 ($mWh\ cm^{-3}$)	[35]

4 Applications

The advanced supercapacitors with superior performance have many applications like automobile, computer and memory chips, medical and industrial applications, electric grids, battery monitoring, etc. The supercapacitors also have defence applications like avionics, emergency power, munitions, radar, radio frequency communications and vehicles [7] as shown in Fig.4.

Fig. 4. Defence application of supercapacitors [7]

5 Conclusion

This chapter expounds the advancement in the field of supercapacitor and offers an insight into the requirement for supercapacitors in the modern era. The basic principles, the storage mechanism, the classification of different types of supercapacitors (S.C.) and the materials for electrodes and electrolytes have been reported. It is observed that supercapacitors like EDLC and pseudo capacitor has limited usage and the development of hybrid S.C. systems is currently the essential requirement to enhance the applicability range. The demand for hybrid supercapacitors is growing rapidly, particularly in the realm of hybrid electric vehicles and military uses.

6 Future Scope

The future scope of supercapacitors toward sustainability and SDGs is promising, spanning various avenues. Potential improvements and ongoing research areas are summarized in Table 3 below:

Table 3. Potential improvements and ongoing research

Area	Scopes of Improvement	Reference
Advanced Energy Storage Solution	Supercapacitors have the potential for further advancements in energy storage. The potential areas of improvement can focus on improving energy density, efficiency, and lifespan of capacitors. It acts as an enabler for more widespread adoption of renewable energy sources, thereby contributing to SDG 7.	[36,37,38, 39]
Grid Integration and Stability	Capacitors can be pivotal for enhancing grid stability and reliability. It can provide fast-response energy storage solutions. Attempts in future research are focussed on developing smart grid technologies that integrate capacitors to manage fluctuations in renewable energy generation and demand. It will thereby support SDG 9 by improving the resilience and efficiency of energy infrastructure.	[40, 41,42,43]
Electrification of Transportation:	Capacitors have potential in applications in electric vehicles (EVs) and hybrid electric vehicles (HEVs). However, the charging capabilities of capacitors have to improve, and thereby the range and performance of EVs will increase. It will contribute to SDG 11 by reducing greenhouse gas emissions from transportation.	[44,45,46, 47]
Decentralized Energy Systems:	Decentralized energy systems can enable communities to generate, store, and distribute their own renewable energy locally. Capacitors can play a cardinal role on the same by exploring avenues to integrate capacitors into microgrid and off-grid systems. It will enhance energy access, affordable material, and resilience in underserved areas, supporting SDG 7 and SDG 13.	[48,49, 50,51,52,53]

References

1. Libich, J., Máca, J., Vondrák, J., Čech, O. and Sedlaříková, M., 2018. Supercapacitors: Properties and applications. Journal of Energy Storage, 17, pp.224-227.
2. Raghavendra, K.V.G., Vinoth, R., Zeb, K., Gopi, C.V.M., Sambasivam, S., Kummara, M.R., Obaidat, I.M. and Kim, H.J., 2020. An intuitive review of supercapacitors with recent progress and novel device applications. Journal of energy storage, 31, p.101652.
3. Jia, M., Zhang, C. and Cheng, J., 2021. Origin of Asymmetric Electric Double Layers at Electrified Oxide/Electrolyte Interfaces. The journal of physical chemistry letters, 12(19), pp.4616-4622.
4. Lu, M., 2013. Supercapacitors: materials, systems, and applications. John Wiley & Sons.
5. Brousse, T., Bélanger, D. and Long, J.W., 2015. To be or not to be pseudocapacitive?. Journal of The Electrochemical Society, 162(5), p.A5185.
6. Chatterjee, D.P. and Nandi, A.K., 2021. A review on the recent advances in hybrid supercapacitors. Journal of Materials Chemistry A, 9(29), pp.15880-15918.
7. Muzaffar, A., Ahamed, M.B., Deshmukh, K. and Thirumalai, J., 2019. A review on recent advances in hybrid supercapacitors: Design, fabrication and applications. Renewable and Sustainable Energy Reviews, 101, pp.123-145.
8. Rajkumar, M., Hsu, C.T., Wu, T.H., Chen, M.G. and Hu, C.C., 2015. Advanced materials for aqueous supercapacitors in the asymmetric design. Progress in Natural Science: Materials International, 25(6), pp.527-544.
9. Iro, Z.S., Subramani, C. and Dash, S.S., 2016. A brief review on electrode materials for supercapacitor. Int. J. Electrochem. Sci, 11(12), pp.10628-10643.
10. Jian, X., Liu, S., Gao, Y., Tian, W., Jiang, Z., Xiao, X., Tang, H. and Yin, L., 2016. Carbon-based electrode materials for supercapacitor: progress, challenges and prospective solutions. J. Electr. Eng, 4(2), pp.75-87.
11. Yadav, M.S., 2020. Metal oxides nanostructure-based electrode materials for supercapacitor application. Journal of Nanoparticle Research, 22(12), pp.1-18.
12. Wang, Y., Ding, Y., Guo, X. and Yu, G., 2019. Conductive polymers for stretchable supercapacitors. Nano Research, 12(9), pp.1978-1987.
13. Sahu, S.K., Badgayan, N.D. and Rama Sreekanth, P.S., 2022. Rheological Properties of HDPE based thermoplastic polymeric nanocomposite reinforced with multidimensional carbon-based nanofillers. Biointerf Res Appl Chem, 12, pp.5709-5715.
14. Badgayan, N.D., Sahu, S.K., Samanta, S. and Sreekanth, P.S., 2019. Evaluation of dynamic mechanical and thermal behavior of HDPE reinforced with MWCNT/h-BNNP: an attempt to find possible substitute for a metallic knee in transfemoral prosthesis. International Journal of Thermophysics, 40(10), pp.1-20.
15. Sahu, S.K. and Rama Sreekanth, P.S., 2022. Mechanical, thermal and rheological properties of thermoplastic polymer nanocomposite reinforced with nanodiamond, carbon nanotube and graphite nanoplatelets. Advances in Materials and Processing Technologies, pp.1-11.
16. Badgayan, N.D., Sahu, S.K., Samanta, S. and Sreekanth, P.R., 2020. An insight into mechanical properties of polymer nanocomposites reinforced with multidimensional filler system: a state of art review. Materials Today: Proceedings, 24, pp.422-431.
17. Pradhan, S., Sahu, S.K., Pramanik, J. and Badgayan, N.D., 2022. An insight into mechanical & thermal properties of shape memory polymer reinforced with nanofillers; a critical review. Materials Today: Proceedings, 50, pp.1107-1112.
18. Lu, W., Hartman, R., Qu, L. and Dai, L., 2011. Nanocomposite electrodes for high-performance supercapacitors. The Journal of Physical Chemistry Letters, 2(6), pp.655-660.
19. Fuoss, R.M., 1934. Properties of Electrolytic Solutions. XI. The Temperature Coefficient of Conductance. Journal of the American Chemical Society, 56(9), pp.1857-1859.
20. Peng, C., Jin, J. and Chen, G.Z., 2007. A comparative study on electrochemical co-deposition and capacitance of composite films of conducting polymers and carbon nanotubes. Electrochimica Acta, 53(2), pp.525-537.
21. El-Kady, M.F., Strong, V., Dubin, S. and Kaner, R.B., 2012. Laser scribing of high-performance and flexible graphene-based electrochemical capacitors. Science, 335(6074), pp.1326-1330.
22. Dai, K., Lu, L., Liang, C., Geng, L. and Zhu, G., 2016. Large-scale synthesis of cobalt sulfide/carbon nanotube hybrid and its excellent electrochemical capacitance performance. Materials Letters, 176, pp.42-45.
23. Wen, Z., Wang, X., Mao, S., Bo, Z., Kim, H., Cui, S., Lu, G., Feng, X. and Chen, J., 2012. Crumpled nitrogen-doped graphene nanosheets with ultrahigh pore volume for high-performance supercapacitor. Advanced materials, 24(41), pp.5610-5616.
24. Dubal, D.P., Jagadale, A.D. and Lokhande, C.D., 2012. Big as well as light weight portable, Mn3O4 based symmetric supercapacitive devices: Fabrication, performance evaluation and demonstration. Electrochimica Acta, 80, pp.160-170.
25. Das, R.K., Liu, B., Reynolds, J.R. and Rinzler, A.G., 2009. Engineered macroporosity in single-wall carbon nanotube films. Nano letters, 9(2), pp.677-683.
26. Zheng, W., Lv, R., Na, B., Liu, H., Jin, T. and Yuan, D., 2017. Nanocellulose-mediated hybrid

polyaniline electrodes for high performance flexible supercapacitors. Journal of Materials Chemistry A, 5(25), pp.12969-12976.

27. Zhang, H., Hu, Z., Li, M., Hu, L. and Jiao, S., 2014. A high-performance supercapacitor based on a polythiophene/multiwalled carbon nanotube composite by electropolymerization in an ionic liquid microemulsion. Journal of Materials Chemistry A, 2(40), pp.17024-17030.
28. Hsu, Y.K., Chen, Y.C., Lin, Y.G., Chen, L.C. and Chen, K.H., 2013. Direct-growth of poly (3, 4-ethylenedioxythiophene) nanowires/carbon cloth as hierarchical supercapacitor electrode in neutral aqueous solution. Journal of power sources, 242, pp.718-724.
29. Liu, Y., Zhang, B., Yang, Y., Chang, Z., Wen, Z. and Wu, Y., 2013. Polypyrrole-coated α-MoO 3 nanobelts with good electrochemical performance as anode materials for aqueous supercapacitors. Journal of Materials Chemistry A, 1(43), pp.13582-13587.
30. Lang, X., Hirata, A., Fujita, T. and Chen, M., 2011. Nanoporous metal/oxide hybrid electrodes for electrochemical supercapacitors. Nature nanotechnology, 6(4), pp.232-236.
31. Yu, Z. and Thomas, J., 2014. Energy storing electrical cables: integrating energy storage and electrical conduction. Advanced materials, 26(25), pp.4279-4285.
32. Du, F., Yu, D., Dai, L., Ganguli, S., Varshney, V. and Roy, A.K., 2011. Preparation of tunable 3D pillared carbon nanotube–graphene networks for high-performance capacitance. Chemistry of Materials, 23(21), pp.4810-4816.
33. Cai, J., Niu, H., Li, Z., Du, Y., Cizek, P., Xie, Z., Xiong, H. and Lin, T., 2015. High-performance supercapacitor electrode materials from cellulose-derived carbon nanofibers. ACS applied materials & interfaces, 7(27), pp.14946-14953.
34. Safavi, A., Kazemi, S.H. and Kazemi, H., 2011. Electrochemically deposited hybrid nickel–cobalt hexacyanoferrate nanostructures for electrochemical supercapacitors. Electrochimica acta, 56(25), pp.9191-9196.
35. Wang, Y., Yang, Y., Zhang, X., Liu, C. and Hao, X., 2015. One-step electrodeposition of polyaniline/nickel hexacyanoferrate/sulfonated carbon nanotubes interconnected composite films for supercapacitor. Journal of Solid State Electrochemistry, 19(10), pp.3157-3168.
36. Iyer, M.S., Rajkumar, P., Sanghavi, B., Parvathy, G., Aravinth, K. and Kim, J., 2024. Elevating energy storage performance of bismuth antimonate coupled with MXene and graphitic nanofibers in advanced supercapacitors. Journal of Power Sources, 602, p.234379.
37. Yesaswi, C.S. and Sreekanth, P.R., 2022. Characterisation of Silver-coated Teflon fabric-reinforced Nafion ionic polymer metal composite with carbon nanotubes and graphene nanoparticles. Iranian Polymer Journal, 31(4), pp.485-502.
38. Nayak, A., Rama Sreekanth, P.S., Sahu, S.K. and Sahu, D., 2017. Structural tuning of low band gap intermolecular push/pull side-chain polymers for organic photovoltaic applications. Chinese Journal of Polymer Science, 35(9), pp.1073-1085.
39. Lencwe, M.J., Olwal, T.O., Chowdhury, S.D. and Sibanyoni, M., 2024. Nonsolitary two-way DC-to-DC converters for hybrid battery and supercapacitor energy storage systems: A comprehensive survey. Energy Reports, 11, pp.2737-2767.
40. Diaz-Gonzalez, F., Chillón-Antón, C., Llonch-Masachs, M., Galceran-Arellano, S., Rull-Duran, J., Bergas-Jane, J. and Bullich-Massagué, E., 2022. A hybrid energy storage solution based on supercapacitors and batteries for the grid integration of utility scale photovoltaic plants. Journal of Energy Storage, 51, p.104446.
41. Sahu, S.K., Badgayan, N.D. and Sreekanth, P.R., 2020. Numerical investigation on the effect of wall thickness on quasistatic crushing properties of nylon honeycomb structure. Materials Today: Proceedings, 27, pp.798-804.
42. Argyrou, M.C., Marouchos, C.C., Kalogirou, S.A. and Christodoulides, P., 2021. Modeling a residential grid-connected PV system with battery–supercapacitor storage: Control design and stability analysis. Energy Reports, 7, pp.4988-5002.
43. Sahu, S.K, Badgayan, N.D, Samanta, S. and Sreekanth, P.S.R, 2018, May. Dynamic mechanical thermal analysis of high density polyethylene reinforced with nanodiamond, carbon nanotube and graphite nanoplatelet. In Materials Science Forum, 917, pp. 27-31.
44. Guo, L., Hu, P. and Wei, H., 2023. Development of supercapacitor hybrid electric vehicle. Journal of Energy Storage, 65, p.107269.
45. Sahu, S.K. and Sreekanth, P.R., 2022. Experimental investigation of in-plane compressive and damping behavior anisotropic graded honeycomb structure. Arabian Journal for Science and Engineering, 47(12), pp.15741-15753.
46. Swaminathan, R., Pazhamalai, P., Krishnamoorthy, K., Natraj, V., Krishnan, V. and Kim, S.J., 2024. Tungsten trioxide based high-performance supercapacitor for application in electric vehicles. Journal of Energy Storage, 83, p.110642.
47. Paladugu, S.R.M., Sreekanth, P.R., Sahu, S.K., Naresh, K., Karthick, S.A., Venkateshwaran, N., Ramoni, M., Mensah, R.A., Das, O. and Shanmugam, R., 2022. A comprehensive review of self-healing polymer, metal, and ceramic matrix composites and their modeling aspects for aerospace applications. Materials, 15(23), p.8521.
48. Shirkhani, M., Tavoosi, J., Danyali, S., Sarvenoee, A.K., Abdali, A., Mohammadzadeh, A. and Zhang, C., 2023. A review on microgrid decentralized

energy/voltage control structures and methods. Energy Reports, 10, pp.368-380.

49. Sahu, S.K. and Sreekanth, P.R., 2022. Artificial neural network for prediction of mechanical properties of HDPE based nanodiamond nanocomposite, Polymer (Korea), 46(5), pp.614-620.
50. Shadabi, H. and Kamwa, I., 2022. A decentralized non-linear dynamic droop control of a hybrid energy storage system blue for primary frequency control in integrated AC-MTDC systems. International Journal of Electrical Power & Energy Systems, 136, p.107630.
51. Kushwaha, Y.S., Hemanth, N.S., Badgayan, N.D. and Sahu, S.K., 2022. Free vibration analysis of PLA based auxetic metamaterial structural composite using finite element analysis. Materials Today: Proceedings, 56, pp.1063-1067.
52. Badgayan, N.D, Sahu, S.K, Samanta, S. and Sreekanth, P.S.R, 2018, May. Assessment of bulk mechanical properties of HDPE hybrid composite filled with 1D/2D nanofiller system. In Materials Science Forum, 917, pp. 12-16.
53. Sahu, S.K. and Rama Sreekanth, P.S., 2022. Multiscale RVE modeling for assessing effective elastic modulus of HDPE based polymer matrix nanocomposite reinforced with nanodiamond. International Journal on Interactive Design and Manufacturing, https://doi.org/10.1007/s12008-022-01080-z