STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 12, Special Issue 3, 2024
DOI (Journal): 10.37591/JoPC

http://engineeringjournals.stmjournals.in/index.php/JoPC/index

Exploring Composite Materials for Energy Harvesting in Electric Vehicles: A Comprehensive Review

Sunil Kumar Gupta[1,*], Javed Khan Bhutto[2], M. Venu Gopala Rao[3], Ashish Raj[4]

Abstract

Energy harvesting, an increasingly dynamic field, holds promise for powering various devices by extracting energy from surrounding sources. Composite materials, blending mechanical and electrical properties, emerge as ideal candidates for energy harvesting applications. Despite their burgeoning utilization in electric vehicle (EV) energy capture, the full realization of their potential remains subject to ongoing evaluation. This editorial comprehensively examines composite materials' mechanical properties, electrical conduction, thermal stability, and affordability concerning EV energy harvesting. Encompassing electromagnetic, piezoelectric, and thermoelectric designs, the article underscores composites' suitability for diverse energy harvesting mechanisms. Leveraging composites' exceptional stiffness-to-weight ratio enhances EV power generation and fuel efficiency compared to conventional vehicles. Assessing various composite materials, including polymer, metal, hybrid, and cement-based composites, elucidates their applicability in energy harvesting systems. Despite concerns regarding long-term reliability and cost, these materials offer promising prospects for the future. Addressing challenges such as technological maturity, the article advocates for continued research to quantify durability and reliability for energy capture applications. While composite materials present genuine energy harvesting opportunities for EVs, effective exploitation hinges on significant technological advancements. Providing insights into emerging advancements and potential scenarios, alongside delineating challenges and future research directions, this article contributes to the continuum of composite energy harvesting in electric vehicles.

Keywords: Electric vehicles, energy harvesting, composite materials and efficiency, composite materials, piezo electric, thermoelectric

INTRODUCTION

The application of a future concept of electric cars and energy harvesting is accompanied by a vast emerging tendency to composite material usage. Energy conversion from the environment voltage to the electric power is a key step of the energy harvesting approach in order to have less dependence and higher energy efficiency of the vehicle's battery [1–4]. The use of composites in the energy harvesting systems is now the latest trend as the demanding mechanical and electrical attributes of composites allow them to convert energy into electricity [1–7]. In order to give a fundamental and informed perception on composite materials suitable for electric cars' energy harvesting, this article has been written. Starting by reviewing the kinds of composite materials used for this purpose, we'll cite latest outstanding studies and give an overview of the

***Author for Correspondence**
Sunil Kumar Gupta

[1]Professor, Department of Electrical and Electronics Engineering, Poornima University, Jaipur, India
[2]Associate Professor, Department of Electrical Engineering, King Khalid University, Abha, Saudi Arabia
[3]Professor & Principal, Navkis College of Engineering, Hassan, Karnataka (India)
[4]Associate Professor, Department of Electrical and Electronics Engineering, Poornima University, Jaipur, India

Received Date: April 30, 2024
Accepted Date: June 19, 2024
Published Date: June 25, 2024

Citation: Sunil Kumar Gupta, Javed Khan Bhutto, M. Venu Gopala Rao, Ashish Raj. Exploring Composite Materials for Energy Harvesting in Electric Vehicles: A Comprehensive Review. Journal of Polymer & Composites. 2024; 12(Special Issue 3): S1–S15.

present state-of-the-art in the field. Following that, it will be accompanied with the balance beam challenge, which involves electrical conductivity, thermal stability, mechanical qualities, and cost-effectiveness as they relate to energy harvesting and composite materials. The use of diverse energy harvesting techniques which involves the application of different materials like piezoelectric, electromagnetic, and thermoelectric can also be found in this article. Last, but not least, it will cover part of that field's emerging possibilities and the to be feared threats. This paper will illustrate a comprehensive account of composite materials that is used for electric vehicle energy harvesting device that shows the significant results and contribution. People from the sectors of kinetic energy harvesting R&D and electric drivetrain development will find this tutorial invaluable. In the end, on account of the truly amazing mechanical and electrical qualities, composite materials are fabricating more and more applications in renewable energy systems. The review article on the subject of the electric car energy harvesting which is aimed at the readers interested in the specific subject allows them to catch the whiff of the constant progress taking place in the sphere of composite materials for the conduct of this task.

BACKGROUND AND CURRENT LANDSCAPE

Insights into Energy Harvesting for Electric Vehicles

Unlike the current focus on energy storage in EVs, the field of energy dissipation is a lesser-known area of study but one of the fastest evolving. This field pertains to the transformation of ambient energy into electrical power that can be utilized in EVs. The use of regenerative braking, which reduces the load on the vehicle's battery, and the enhancement of energy efficiency are key targets of this strategy. In response to the shifting demands for automobile fuel efficiency, energy harvesting in electric vehicle systems has become a widely discussed concept among researchers [7–10].

Energy harvesting in EVs employs various conversion methods such as piezoelectric, electromagnetic, and thermoelectric. The principle behind piezoelectric energy collection involves utilizing piezoelectric materials to convert mechanical energy into electrical energy. Similarly, electromagnetic energy harvesting involves extracting electricity from magnetic fields. Surface friction-generated heat represents wasted energy; however, the thermoelectric method has the potential to convert heat into electrical energy. Each energy conversion principle has its strengths and weaknesses. For example, to generate a significant amount of electrical energy, a considerable amount of mechanical energy input is required. Electromagnetic energy harvesting systems rely on strong magnetic fields for optimal performance, yet they exhibit high efficiency and can harness energy from various power sources [10–13].

Despite achieving significant efficiencies and versatility, thermoelectric energy harvesting is dependent on the presence of a temperature gradient [12–14]. Electric vehicles offer numerous benefits such as enhanced energy efficiency, reduced reliance on transmission lines, and potentially replacing gas emissions from vehicles, particularly if energy harvesting devices are installed. However, while electric vehicle technology is not new, there are still barriers to overcome before energy harvesting systems in electric vehicles become more widespread and efficient. Improving energy conversion outcomes, reducing the costs associated with energy harvesting system manufacturing, and enhancing system durability are all challenges that need to be addressed effectively.

Categories of Composite Materials Utilized in Energy Harvesting

In comparison with the conventional materials, total cost, and the energy harvesting system may yield certain advantages, however. Composites outstrip common materials with respect to some of the key features they have, for example, higher thermal conductivity, electrical conductivity, and better mechanical strength and stiffness. Besides, beside electric vehicle energy harvesting system that are mechanically and electrically different from conventional carbon composites, the customizing of composite materials can therefore meet them [15–18].

In general, polymer-based composites are highly popular in energy harvesting systems due to their many advantages such as lightweight, cost-effect, and easy production. In order to improve the capacity of these composites to harvest energy, their polymer matrices can be designed to have specific electrical and mechanic features. Carbon fiber-reinforced polymer composites (CFRP), e.g., are the subjects of intense research for energy harvesting purposes. They possess beneficial lightweight, high strength, and are also excellent conductive materials [16–20].

Another type of famous energy harvester platform is the piezoelectric composites patented of polymers. Organic characteristics of the piezoelectric materials become common as they can convert the mechanic energy into electricity thus informing this field of study. Mechanical flexibleness, electrical voltage output that is approximately the same with power output, decrease in manufacturing cost by using less expensive raw materials, and speedy operation are only but few advantages of polymeric piezoelectric composites over ceramic skeleton based composites [18–21].

Carbon fibers and a multipurpose polymer infuse the core of the battery with a simple but compact structure seen in Figure 1.

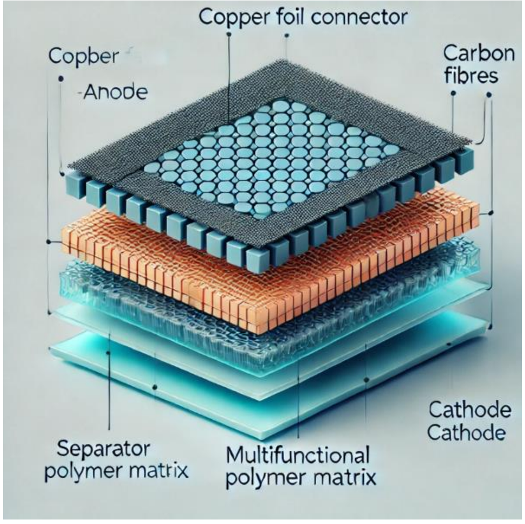

Figure 1. Integrated composite energy storage system

Figure 1 indicates schematic diagram of integrated composite energy storage system, unlike in piezoelectric ceramics or in metals, the high piezoelectric performance and outstanding flexibility of polyvinylidene fluoride (PVDF) polymer are widely preferred [12]. Several researches have been done about the performance of these piezoelectric polymers (PVDF) on those photovoltaic diode arrays, and by use of them in engineered cementitious composites (E.C.C) which leads to a more efficient novel energy harvesting system, that can generate voltage and power by using the deflection of E.C.C. This could give rise to the development of constructions avenues which are more permissive of diverse structural designs [12–30].

The next type of hardware, suitable for energy absorbing applications that is under consideration, is electrostrictive polymers. On the other hand, polymers are considered as competitors of piezoelectric ceramic materials as they may possess some specific features. Energy harvesting has been estimated via the use of a prediction model of an electrostrictive polymer composites' (E.P.C) capabilities. One current model was used in order to create a scheme similar to those of electricity on a macro level. This then was validated. The electrostrictive coefficient, dielectric permittivity, and material compliance may be used to perform empirical approximation in predicting power output. The dielectric permittivity identity is the one of importance for the energy harvesting in the Casimir-Polder systems, as per paper [21–28].

As T.E.N.G. or triboelectric nanogenerator (TNG) is another option of harvesting energy and transforms mechanical energy to electrical power, the triboelectric effect based on the T.E.N.G.'s technology is used in this conversion. The applicability of knowledge and skills demonstrates the adequacy of the level of practical and independent work. The results show that the composite polymeric materials work at best as compared to the polymeric materials used alone. Therefore, they (polymer-based composites) are flexible enough to be computed to the other geometries available, they are made affordable and in a very short period they can be supplied with enough particular voltage output that powers many devices [25–33].

Growing exploration in these areas has translated into the continuous development of new energy generation technologies, and a great variety of both polymeric and composite polymeric materials. Polymers and serve as viable substitutes for traditional materials, especially in applications such as aircraft, wind turbines, and medical devices. Electromagnetic energy harvesting deals with the conversion of electromagnetic-matter interactions into mechanical energy, thus these composites play a key role in the development of this technology. For reaching the maximum potential energy harvesting capability, the feature of the metal matrices of these composites can be modified to show of such characteristics.

The heavy metal matrix used in energy harvesting application made a headway alongside the weight reduction of its composites. This avenue of technology is poised to change the paradigm of many industries, including the commercial aerospace, automobile and sports equipment. Along with these, the FeCo/AlSi combo can be mentioned due to the excellent compressional energy conversion capacity, which distinguishes it from the rest. The different structural design and application of reverse magnetic field are among the most popular research objects in this field which were examining the energy conversion ability of them. The findings show that the magnetostrictive FeCo/AlSi composite can achieve superior mechanical property performances by using Calibrate FeCo instead of FeCo wire. Recent explorations indicate that N-N dominated orientation reversed magnetic switching increases the energy conversion efficiency greatly [29–32].

Further study has been conducted regarding the energy-harvesting features of FeCo/AlSi materials which used to be an impact loading circumstance. In this study, research was focused on molding composites and their compressive loading-hesitation properties which result from negative magnetostriction. Besides, two magnet and wound iron-based coil specimens from the FeCo/AlSi composite material were examined by cyclic in addition, ramming tests were conducted. These tests indicated that the devices were not only able to be used and withstand impact loads; also, occasionally these devices started to show results like collecting the energy due to the impact and using it to run the device. The effect of the interface breaking and chemical interaction between non-uniform FeCo fiber and AlSi matrix on the energy harvesting capability of the device is also observed to be amplified because of the interface zigzag morphology. Thus, these characteristics directly correspond to the transmission of stress and strains. In other words, the efficiency of these devices very highly depends on these parameters. The copper and air-based composite thus seem to be a very appealing material that can be utilized as an n/a agent in electric vehicles and different energy-harvesting applications. Investigations carried out on different kinds of bio-waste to be used as multiple piezoelectric and hyper thermoelectric material, specifically, pomegranate peel, orange peel, and fish scales among the others have been used to reformulate polymer matrixes to introduce new piezoelectric properties.

Thus, they are among the unique materials the scientist take advantage of for implementing the energy harvesting technology due to the exceptional piezoelectric properties ranging from 28.5 µW/cm2 to 135 W/cm^2 [33–36]. The study referenced here showed that by adding a little of orange peel powder to an eco-friendly polymer, the component of the polymer matrix became piezoelectric, with the end result being 70% of active phase in the product. This intermixed material gave rise to an energy harvesting device which was innovative and integrative in nature. The benefit comes when sun rises, the device can deliver 90 V open-circuit voltage and 135 W/cm^2 of electricity from the sunlight with tapping its finger. A version of the hybrid generator, which was developed for the lights and motions such as walking, bending and a sliding door proved the power generation capability.

To unveil the mechanism responsible for the enhanced piezoelectricity of the piezoelectric hybrid, structural, morphological, and thermal investigation techniques were employed, as outlined in references [13–16]. Similarly, research on fish scale-polymer hybrids was conducted, focusing on the self-aligned fish scale collagen fibers, which were hybridized with bio-waste to power nanogenerators. The presence of fillers in the matrix enhanced the scales, leading to a synergistic effect termed the electrocative phase. Consequently, these fillers dispersed evenly within the polymer matrix, forming a γ-phase array. The resulting waste device exhibited a higher open-circuit voltage of 22 V and a more significant energy density of 28.5 mW/cm^2, highlighting the potential of bioresources to generate energy and surpassing previous studies utilizing waste as a resource [37–38].

Piezoelectric conversion in the polymer matrix was investigated in a recent study employing a blend of natural pomegranate peel and poly (vinylidene fluoride). XRD, spectroscopic, and calorimetry measurements revealed the interplay of piezoelectric activities between the matrix and filler phases.

The device presented was able to make electricity from high human motion such as walk, twist and bend, with an open circuit voltage of 65 V and thickness of 84 µW/cm^2. A piezoelectric energy collecting procedure can be hybridized from bio-waste materials, which could be considered a promising way for the future. Markedly, these hybrids are proficient for energy-harvesting processes, and they are capable of producing large piezoelectric force and can be efficiently applied to different human motions. By using the methods of structural, morphological, and thermal studies, deformed the way the heterogeneous act has been exposed. As one of the long-term solutions for problems caused by landfill capped and contaminated, a bio-waste energy harvesting shows a great prospect in the area of waste management.

These past few years, these cement concrete blends have the potential of being a very appropriate material for energy harvesting from a lot of situations. Another positive application of thermoelectric based composites used in cement is converting the heat difference between indoors and outdoors adjacent to cement structure surfaces of buildings into electricity. Several papers dealing with utilizing composite materials for thermoelectricity for sensing and energy conversion were reviewed in this review paper. These materials are found in many different fields, be it buildings, highway or pathways, homes, bridges and even dams. With application to thermal department, we may look for cement industrial materials that are thermo-conductive and may absorb solar energy will store and use this energy. To illustrate, although the carbon fiber reinforced cement (0.8 µV/°C) is rather more electrically conductible comparing with the pure carbon fibers (17 µV/°C), the combination of the carbon fibers with cement markedly improves the hole conduction, which is equal to 17 µV/°C. Therefore, when the volume contribution of steel fibers is just 1%, the nominal volume electrical resistivity of steel fiber cement pastes holds stronger than that of carbon fiber cement pastes [38–42]. The best ECR of 16.2 Scm^{-1} and SCF of 34.0 μVK^{-1} were found in a work that studied the application of GNPs in cement-based composites to obtain an energy harvesting effect. High semiconductor conductivity is the dominating properties of the examined specimens, which turn out to be typical to the p-type semiconductors. Using the Hall coefficient measurement, they are characterized. Besides, at 70 °C we saw the best diffusivity data (0.44 10−3U2).

E.G.C.C., or extended graphite/cement-based composites, were focused on in a case-study looking at its thermoelectric characteristics that was designed for it. The innovative composition drying and order technique were utilized for fabrication of the novel composites. Among 30 to 100 ◦C, researchers found out that E.G.C.C. had a positive Seebeck coefficient and intentionally modulated semiconductor electrical activities. E.G.C.C. has had conducted the extraordinary for a cement-based materials electrical conductivity of 24.8 S/cm because of their developmental patterns. The power factor and TM increased simultaneously to 6.82 10−4, a significant enhancement. On the other hand, the thermal conductivity was kept unchanged at 3.213 Wm−1K−1. 106.51 MPa [mpa stands for Megapascal] of maximum compressive strength achieved by E.G.C.C. [egcc stands for ethylene glycol carbamate gel composite] [39, 40] is ever more significant. The main focus of the paper which is under analysis now is to invest in pioto catalysis the possibility for environmental cleanup. The piezoelectric materials have been found to show a direct relationship between mechanical stimulation and catalytic activity. This is referred to as the piezocatalysis effect. Water treatment, especially in the light of the fact that constructions of these kind are effectively part of the wastewater treatment has been relying on cements since its early days [41–43]. Such outcomes demonstrate that cementitious composites are of great value in and of themselves within many types of applications. However, despite the fact that these challenges need to be overcome, such as waste-to-energy systems that use thermal processes, decreasing costs, durability and better mass manufacturing, these are the significant obstacles for efficient large-scale implementation. The entire life cycle energy-utilization potential of cement-based composites ranges from improvement in the production process to the use of recycled materials in the end product, which demand further research in the remaining areas. In Table 1, the notable composites and benefits for the purpose of energy harvesting are the professionals expressed which could tell for what reason might these composites be used [44–46].

Table 1. Comparative Analysis of Composite Materials for Energy Harvesting

Composite Material	**Advantages**	**Applications**
Cement-based composites	Capability to convert temperature variations into electrical energy. - Versatility in structural applications.	Utilized in piezo catalysis for environmental remediation. - Applied in thermoelectric-based cement composites.
Bio-waste-based hybrid composites	Notable piezoelectric properties enabling power generation from human movement.	Energy harvesting facilitated by the development of piezoelectric hybrids.
Metal-based composites	High electrical conductivity coupled with robustness and durability. - Customizable design for specific requirements.	Automotive and aerospace industries. - Sporting goods. - Electromagnetic energy harvesting applications.
Polymer-based composites	Customizable design tailored to specific needs. - Cost-effective and easy to manipulate. - Offers flexibility in applications.	Utilized in triboelectric nanogenerators. - Applied in electric vehicles. - Utilized in various industries requiring flexible material solutions.
Piezoelectric composites	Capability for energy generation through mechanical stress. - Versatile and adaptable for various applications.	Deployment in electric vehicles and other energy harvesting systems.

Review of Existing Studies on Composite Materials for Energy Harvesting in Electric Vehicles: Numerous studies have delved into the utilization of composite materials for energy harvesting in electric vehicles, with piezoelectric energy harvesting systems emerging as one of the most promising applications among them

Numerous works focus on the application of composites in the electric vehicle energy harvesting, and researchers find a piezoelectric energy-harvesting system as among the most useful applicants of this technology. Mechanical stress triggers piezoelectric materials to transform into electrical charge, and composites showcase impressive piezoelectric behaviour.

Integrate composite materials for electric vehicles to create piezoelectric energy harvesting has been the subject of several of the investigations. Studies in this field deal with quite a lot of matters regarding the probable applications, such as the vibration energy accumulation and the generation of energy from the roads. Another function that composites carry is electromagnetic energy conversion to electrical power through the microplate. This electromagnetic energy harvesting technology is well known. These kinds of units have a positive ratio of their remarkable electric conductivity as their main benefit. Authorities of quite a few link makers have examined the concerns of composites materials for energy generation through electromagnetic radiation among vehicles (including wireless power transferring and passive energy collecting) [46–49].

Renewable forms of electricity production can be generated using a technique referred to as thermoelectric energy extraction. Thermoelectric power harvesting devices which are made of composite materials have become a major component in the applied electrical vehicles technology. This is due to their thermal stability. Various materials based on composite technology have been examined in this area, such as converting exhaust gases and the environment into energy sources. These materials are really suitable for use in autonomous systems of energy saving because possess the unique set of mechanical and electrical properties, having in first place the high piezoelectric output, as the electric conductivity and the extreme thermal stability. Studies on supporting materials for composite energy generation in electric vehicles are still at early stage, however, judging from the information there is available, it is evident of efficiency in the area. Thoughtful research into composite materials' energy-harvesting capability would be desirable to realize the full potential of this material.

Yet another way technological innovation is revolutionizing electric vehicle storage is through the development of structures with low dimensionality which has great prospects in improving the energy storage capacity of EVs.

A variety of low dimensional systems storage parameters are displayed in Figure 2 [13]. Just a list of very few typical examples should, undoubtedly, demonstrate that the field of electric vehicle energy storage is being investigated with the use of nano technologies like carbon nanotubes, graphene, and metal organic frameworks [48]. This key information can be found in such research works that low-dimensional structures overall are great for electric vehicle energy storage as they have a high surface area, good electrical conductivity and strong mechanical strength.

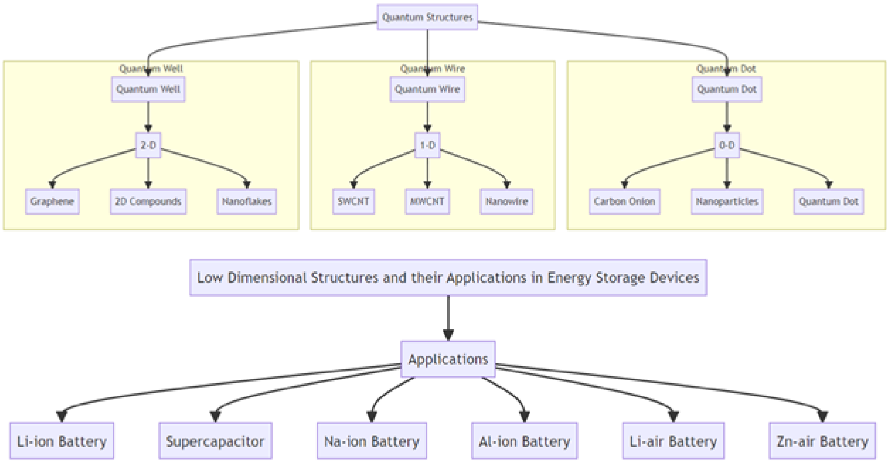

Figure 2. Nanostructures and Their Applications in Energy Storage Devices

CHARACTERISTICS OF COMPOSITE MATERIALS FOR ENERGY HARVESTING

Mechanical Properties

Composite types for electric vehicle (EV) energy harvesting applications have genetic mechanisms that are under the control of mechanical traits. By virtue of their capacity to experience loads while being subject to energy conversion in diverse situations it's the materials which affect the success of energy harvesting devices. The reinforcement and matrix components found in composites mainly affect the overall mechanical properties of end product. With respect to this, the main advantage of polymer composites is undoubtedly their great resistance and flexibility to be worked on. These fibrous composites have as all-fiber matrix, which could be made of any fiber, such as carbon, glass, ceramic, and so on. However, unlike composites built out of metals, for which reinforcement of metallic matrix with ceramic and polymer fibers boosts strength and stiffness properties [41–43], composites made of metal have no inherent ability for self-healing.

Such mechanical properties are crucial in composite materials for significant energy harvesting projects. Evaluating these properties is essential to establish sufficient criteria such as abuse distance, modulus of elasticity, tensile strength, compressive strength, and shear modulus, among others. Ensuring that an electric vehicle energy harvesting system can deliver reliable, long-lasting, and effective results requires optimizing the motor features of composite materials.

Among the numerous composite materials available, it is imperative to study the most suitable ones considering their mechanical properties and energy conversion performance, including thermal stability and electrical conductivity, to effectively apply them to electric vehicle energy harvesting. For harvesting energy technology to truly make a positive impact, the aforementioned approaches must be integrated.

Electrical Conductivity

In the direction of getting electric vehicle energy harvesting done with composite materials, electrical conductivity is much to be discussed since it is essential to be taken into consideration. The effective or failed performance of the energy harvesting enterprise is solely based on the materials' efficiency in power transfer. The electrical conductivity of Carbon Composites is characterized by the interplay between the elements of the matrix and reinforcing [14, 15]. Composites consisting of metal normally have much better electrical conductivity then ones marketed under the brand of polymers. Using fillers or fibers with conductive properties can be the basis when constructing polymer-based composites. The end result is a much better electrically conductive structure. Although the conductivity of electric current has got a great influence on the evaluation of composite as a viable energy harvesting agent, that does not mean we can only rely on it alone. One of the main ideas here would be to pay attention to the both characteristics at the same time. Renewable energy getter projects in EVs are greatly affected by the entire conductivity of composite compounds, whether it be high or low [22–28].

Thermal Stability

EV components, particularly for thermal management, must have good timing stability. Composite materials should be selected instead of other materials that are sensitive to temperature fluctuation in order to cater for the fact that energy harvesting systems in electric vehicles are prone to generating heat when operating and hence heat stress. In composite thermally, stable property is decided by selected matrix and fibrous materials. It is even more important to notice that alloys most frequently demonstrate outstanding thermal stability, while a great number of polymers lack proper thermal resilience. Keeping consistent with the quality and lifetime of energy harvesting systems and providing with the thermal stability is one of the most essential. Energy harvesting systems fail to be efficient due to heat resistance, and they might make dangerous at high temperatures in which materials degrade and even fail. Consequently, in the screening process for the composite, the materials' thermal stability also needs to be taken into account [9–15].

Cost-Effectiveness

Picking composite materials for energy collection purposes in car electricity values is of paramount importance that requires you to think about the cost Automobiles are the main user, as it is cheap for them to use energy harvesting technologies. The plate tectonics that are used for further reinforcement, the kind of matrix which is employed, and different variables altogether all affect the final price of a composite material.

Because of the mechanical complexity it demands, metal based composites are generally costly therefore requiring a serious financial investment. To note, however, metal-based piezoelectric composites are a cost-effective solution to higher mechanical stresses come with their better performance that makes their higher cost ranklet's. On the contrary, sometimes composites containing polymers as matrix cost less because the cost of the polymer matrix is rather cheap. Even though these composite materials perhaps won’t have as good performance in the energy harvesting systems as other options would, the cost factor may ultimately motivate them to be considered for use when other forms of renewables may prove expensive.

A prudent balance between performance and cost is needed to ensure the cost-effectiveness of composite materials for energy harvesting in electric cars. The selection of composite materials for electric vehicle energy harvesting must be made with careful consideration of the balanced weights among cost, load-bearing capacity, and lifecycle of the products. Research and industry development should focus on creating composite products that are both cost-effective and offer superior performance for electric car applications aimed at energy harvesting [18–29].

Composite materials, by far, have the most favorable features for converting EV energy; thus, this process could be performed most effectively through their utilization. It includes the mechanical properties such as the strength, ductility, stiffness, electrical conductivity, thermal stability and the economic-effectiveness. This is true of electric car energy harvesting composites as they are process-specific and material-specific and the transfer properties of the reinforcement and matrix are very much dependent on the reinforcement and matrix materials selected. The possible approach that one can apply is to go for the best available composites that will realize the meant objectives for both the efficiency and the affordability criteria.

UTILIZATION OF COMPOSITE MATERIALS FOR ENERGY HARVESTING IN ELECTRIC VEHICLES

Piezoelectric Energy Harvesting

Through the application of piezoelectric materials, piezoelectric energy harvesting can convert mechanical energy into electrical energy. These materials, capable of generating electric potential under mechanical stress, are suitable for integration into electric vehicle energy harvesting systems. The next generation of piezoelectric energy harvester devices for EVs is being designed using polymeric and piezoelectric ceramic composites. These composites acquire mechanical properties such as stress resistance and flexibility from the inclusion of polymers, thereby enhancing the efficiency of the composite. Additionally, the conductivity is enhanced by incorporating piezoelectric ceramics Nevertheless, it cannot be underestimated that piezoelectric energy harvesting has its drawbacks. Compared to other energy gathering systems, the output from this one is usually small which makes it better suited for those devices that do not require large power such as car sensors, electric car and other devices with modest power requirements [28–32]. In spite of this shortcoming, the utilization of piezoelectric energy harvesting is still a nice way of increasing the efficiency of EVs.

Electromagnetic Energy Harvesting

With the assistance of electromagnetic generators, electromagnetic energy can be converted into electrical energy, a process known as electromagnetic energy harvesting. An electromagnetic energy harvesting system for an electric vehicle can be constructed using composite materials, such as metal matrix composites, which serve as the building blocks of electromagnetic generators. Among the materials used for electromagnetic energy harvesting, composites based on metal matrix composites offer various benefits. One notable feature of MMCs is their high electrical conductivity, enabling them to efficiently convert electromagnetic fields into electricity. Given that electric vehicle systems often operate in high-temperature environments, the thermal stability of these systems makes them well-suited for this application.

However, a drawback of electromagnetic energy harvesting is the requirement for powerful electromagnetic fields to produce electrical energy. Consequently, applications with strong electromagnetic fields, such as high-speed electric cars, are ideal candidates for electromagnetic energy harvesting [19–25].

Thermoelectric Energy Harvesting

This process, utilizing thermoelectric materials, is known as thermoelectric energy harvesting, which transforms thermal energy into electrical energy. Due to their ability to generate electrical potential through temperature gradients, these materials are a viable option for energy harvesting systems in electric vehicles. Electric vehicle thermoelectric energy harvesting systems heavily rely on composite materials comprising thermoelectric polymers and ceramics. The utilization of these composites offers several advantages. Firstly, the mechanical properties of these composites are enhanced by the introduction of polymers, making them more flexible and resistant to mechanical forces. Additionally, composite materials embedding thermoelectric ceramics exhibit higher electrical conductivity, thereby becoming more effective in producing electric power [21–28].

However, a limitation of thermoelectric energy harvesting is the generation of small amounts of energy through thermoelectric energy conversion systems. In summary, thermoelectric energy harvesting primarily finds its application in low-power scenarios, such as electric car sensors and other devices with low energy demands.

Analyzing the Benefits and Drawbacks of Each Application

The three building blocks of generating energy that were mentioned each have their own pros and cons. Harvesting piezoelectric energy is just right for the sensors and other electronics in electric cars that need very little power. By using composite materials, which are a combination of piezoelectric ceramics and polymers, energy harvesting systems turn out to be much longer in service life and more effective [13–25].

On the other hand, rapid electric cars and a number of places having strong electromagnetic waves are a source of electromagnetic energy harvesting. Composite materials including metal matrix composites can have electrical conductibility and thermal stability capacity of electromagnetic energy harvesting devices. The harvesting of electromagnetic energy requires a powerful electromagnetic field, which might not be the case for all electric vehicles [8–18].

Thermoelectric energy conversion is suitable not only for high power applications like replacing grid energy supply to electric cars but also for low-power demands such as supplying electricity to vehicles' sensors and other apparatuses The efficiency growth of both mechanical and electrical features of Energy harvesting system can be achieved by introducing thermoelectric ceramic/polymer blended composite materials. This may extend the system's lifetime and reduce its cost, in terms of both initial investment and further maintenance. What needs to be acknowledged though, is the fact that the thermoelectric energy harvesting system has a comparatively lower energy yield when compared with other power harvesting devices.

Last but definitely not least there are a few energy harvesting systems namely wind, tidal, and solar each with their own pro and con argument. Application of composite materials offers a chance to enrich features and provide for energy harvesting systems in the EV powering in any way desired. On the other hand, all applications in electric vehicle have specific requirements; taking this extreme condition of electric vehicle power system, an energy harvesting system has to be selected in the last minute. Visualizing the overall better picture, Table 2 shows a comparative analysis of several energy harvesting methods and technologies, reporting their advantages, drawbacks, and possible fields of application to see which one could be appropriate in a given specific context [7–13].

Table 2. Comparative Analysis of Energy Harvesting Methods.

Technique	Principle	Advantages	Disadvantages	Applications
Thermoelectric	Converts heat energy into electrical power through thermoelectric materials	Efficiently generates electric potential from temperature differences. - Enhanced mechanical properties and conductivity in composites with polymer integration.	Limited energy output compared to alternative methods.	Electric vehicle energy harvesting
Electromagnetic	Transforms electromagnetic energy into electrical power using electromagnetic generators	Metal matrix composites offer high electrical conductivity. - Ensures stability against heat.	Demands a robust electromagnetic field for effective power generation.	Applications with robust electromagnetic fields, energy harvesting systems for electric vehicles
Piezoelectric	Converts mechanical pressure into electricity via piezoelectric materials	Polymers in composites provide flexibility and resilience to mechanical stress. - Piezoelectric ceramics enhance electrical conductivity.	Typically yields less power compared to other methods.	Low-energy applications like sensor power supply.

CHALLENGES AND OPPORTUNITIES IN COMPOSITE MATERIALS FOR ENERGY HARVESTING

Obstacles in the Development and Integration of Composite Materials for Energy Harvesting

A bunch of barriers prevents composite materials to be utilized in electric vehicle energy harvesting. Discovering the right combination of materials that furnishes the required electrical conductivity as well as thermal stability and mechanical properties is a big problem. Finding the balance between these features is not an easy task since they frequently involve trade-offs. As another example, if a composite material's electrical conductivity is increased, the thermal stability may drop, and the material will be unsuitable for use in high-temperature environments.

The utilization of composite materials in energy harvesting systems is fairly expensive, which is another major barrier. The quantity of energy harvesting systems in large-scale electric cars may be reduced because of the high cost of the materials, particularly in comparison to batteries. One other challenge is that composite materials used for energy harvesting are not yet standardized. If harvesting energy systems have to be consistent, reliable and cost effective, standardization should be done on the materials, manufacturing techniques and testing procedures. In addition, the uncertainty as to how well and how long composite material works for electric car energy collecting exists. Practical performance and long-term behavior may need more of study.

Concluding, there are many difficulties that should be overcome when creating and deploying the composite materials for energy harvesting in electric vehicles. These include how to assemble different materials, the high cost of these materials, their poor standardization and lack of information on their long-term effectiveness and durability. To properly tackle composite material application for electric vehicle energy harvesting, these problems needs to be taken into consideration [47–49].

Exploring Future Avenues for Research and Development

Composites for EV energy harvesting will certainly become one of the hot topics and have a lot of potential in the next years. The development of new composite materials, which could lead to increased efficiency and effectiveness in various energy harvesting devices, is one of the research areas that deserve deep attention. As an upshot of the new materials, their superior qualities such as improved electric conductivity, heat stability, and mechanical strength might include. The development of composites, which are made of bio waste and cement-based composites, can be an additional step in reducing landfill loads because they can provide energy-generating solutions, as well as stimulate waste re usage. The other significant issue for forthcoming research is developing new composite material making processes. Utilizing composite materials for creating energy harvesting systems to be widely used requires implementation sophisticated and scalable production techniques. One probable approach to go about this situation may be by producing unique and intelligent composite structures using latest production techniques like 3D printing and nanotechnology. Also, the future researches should center on designing energy harvesting devices that can exclusively use the composite materials that already exist in EVs.

This would lead to the quest for energy harvesting systems that are at the same time more efficient yet more scalable, and eventually integrating them into the existing structures for e-mobility. The research predominantly concentrates on the creation of high-rate, economic, and eco-friendliest energy generators to satisfy the enormous amount of energy required by EVs. The composite materials for energy harvesting in electric cars will be effective and durable in the long run is another important subject that has not been researched adequately. Long-term studies are needed to assess the ultimate performance and reliability of these materials, and the extent to which they will provide the expected durability in practical settings. Apart from energy drawing devices and related materials, the research should examine the techniques of not only theory but also practice.

The last, but not the least, is the research for novel uses of composite materials in energy harvesting systems to be done as the topic for future study. A possible solution here is to sort out new-fangled power-generating systems that can convert waste-heat into working energy or involve regions with no grid access. The next task is to investigate whether energy producing devices can be integrated into new applications such as sustainable transportation, clean fuel generation, and storage of green energy. However, there is still large unexplored potential for using composite materials in electric vehicle energy harvesting, which provides numerous possibilities for further investigation. The success of composite materials in electric vehicle energy harvesting will require that these barriers be considered and the opportunities be exploited in order to improve the state of sustainable energy and transportation systems significantly.

CONCLUSION

Composite materials provide many advantages over traditional materials, for instance, improved mechanical stiffness, conductivity, thermal stability, and lower costs which makes them a suitable choice for electric vehicles. Many researchers have made a variety of composites and tried them for energy harvesting for electric vehicles resulting in the energetic sector of study. The wide number of conceivable applications of composite materials in electric vehicle energy harvesting, such as, piezoelectric, electromagnetic, and thermoelectric types, will be a crucial point to consider from this paper. The research should be intensified towards obtaining peak performance and efficiency of those apps as each on has its pros and cons.

The future supply prognosis for composites in energy harvesting for electric vehicles has a hole; however, the technical barriers for their deployment are not insurmountable. These hindrances incorporate generating the cost-effective as well as scalable manufacturing processes, producing stronger systems and the starting of the long-term stability and performance evaluations. Research advancements consisting of the development of novel composite materials, enhancing production processes, embedding composite materials in energy harvesting systems as well as enlarging the range of their applications are obvious examples of promising areas for the future research and development. Ultimately, I believe electric vehicle energy harvesting with composite materials is a propitious way to go and there is a lot of scope for development in this area as the area offers a rich area for R&D. Smart creation of energy harvesting systems for electric vehicles to be more efficient, stable and affordable can be done through tackling some challenges and seizing other opportunities of composite materials. It will in fact ensure that we move a very big step further in powering the future sustainable energy as well as transportation systems, and increase the quality of the vehicles in themselves.

REFERENCES

1. Anton SR, Sodano HA. A review of power harvesting using piezoelectric materials (2003–2006). Smart Mater Struct. 2007;16
2. Sullivan J, Gaines L. A review of battery life-cycle analysis: state of knowledge and critical needs. ANL/ESD/ 10-7 Argonne National Laboratory (ANL); 2010. Available from: https://doi.org/10.2172/1000659.
3. Paulo J, Gaspar P. Review and future trend of energy harvesting methods for portable medical devices. Proc. of the World Congress on Engineering; 2010. Available from: http://www.iaeng.org/publication/WCE2010/WCE2010_pp909-914.pdf.
4. Mitcheson PD, et al. Energy harvesting from human and machine motion for wireless electronic devices. Proc IEEE. 2008;96:1457–86.
5. Kanoun O. Energy harvesting for wireless sensor networks. Berlin, Boston: De Gruyter Oldenbourg; 2018. Available from: https://www.degruyter.com/view/product/462297.
6. Seah WK, Eu ZA, Tan H-P. Wireless sensor networks powered by ambient energy harvesting (WSN-HEAP)-Survey and challenges. 2009 st International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronics Systems Technology (IEEE); 2009. Available from: https://doi.org/10.1109/WIRELESSVITAE.2009.5172411.
7. Shaikh FK, Zeadally S. Energy harvesting in wireless sensor networks: A comprehensive review. Renew Sustain Energy Rev. 2016;55:1041–54.

8. Yan X, et al. Large, solution-processable graphene quantum dots as light absorbers for photovoltaics. Nano Lett. 2010;10:1869–73.
9. Frischmann PD, Mahata K, Würthner F. Powering the future of molecular artificial photosynthesis with light-harvesting metallosupramolecular dye assemblies. Chem Soc Rev. 2013;42:1847–70.
10. Gibson RF. A review of recent research on mechanics of multifunctional composite materials and structures. Compos Struct. 2010;92:2793–810.
11. Bai S, Liu C. Overview of energy harvesting and emission reduction technologies in hybrid electric vehicles. Renew Sustain Energy Rev. 2021;147:111188.
12. Nechibvute A, Chawanda A, Luhanga P. Piezoelectric Energy Harvesting Devices: An Alternative Energy Source for Wireless Sensors. Smart Mater Res. 2012;2012:853481.
13. Bowen CR, Arafa MH. Energy harvesting technologies for tire pressure monitoring systems. Adv Energy Mater. 2015;1401787.
14. Mori T, Priya S. Materials for energy harvesting: At the forefront of a new wave. MRS Bull. 2018;43:176–80.
15. Fan FR, Tang W, Wang ZL. Flexible Nanogenerators for Energy Harvesting and Self-Powered Electronics. Adv Mater. 2016;28:4283–305.
16. Plesa I, Notingher PV, Schloegl S, Sumereder C, Muhr M. Properties of polymer composites used in high-voltage applications. Polymers. 2016;8:173.
17. Qiu W, Hao Q, Annamareddy SHK, Xu B, Guo Z, Jiang Q. Electric Vehicle Revolution and Implications: Ion Battery and Energy. Eng Sci. 2022;20:100–9.
18. Venugopal P, Shekhar A, Visser E, Scheele N, Chandra Mouli GR, Bauer P, Silvester S. Roadway to self-healing highways with integrated wireless electric vehicle charging and sustainable energy harvesting technologies. Appl Energy. 2018;212:1226–39.
19. Sabri MFM, Danapalasingam KA, Rahmat MF. A review on hybrid electric vehicles architecture and energy management strategies. Renew Sustain Energy Rev. 2016;53:1433–42.
20. Bhatti G, Mohan H, Raja Singh R. Towards the future of smart electric vehicles: Digital twin technology. Renew Sustain Energy Rev. 2021;141:110801.
21. Bai Y, Jantunen H, Juuti J. Energy harvesting research: The road from single source to multisource. Adv Mater. 2018;30:1707271.
22. Sezer N, Koç M. A comprehensive review on the state-of-the-art of piezoelectric energy harvesting. Nano Energy. 2021;80:105567.
23. Carneiro P, Soares dos Santos MP, Rodrigues A, Ferreira JAF, Simões JAO, Marques AT, Kholkin AL. Electromagnetic energy harvesting using magnetic levitation architectures: A review. Appl Energy. 2020;260:114191.
24. Enescu D. Thermoelectric Energy Harvesting: Basic Principles and Applications. In: Green Energy Advances. London, UK: Intech Open; 2019.
25. Elvin N, Erturk A, editors. Advances in Energy Harvesting Methods. New York, NY, USA: Springer; 2013. ISBN 9781461457053.
26. Ahmad TJ, Arsalan M, Black MJ, Noui-Mehidi MN. Piezoelectric based flow power harvesting for downhole environment. In: Proceedings of the Society of Petroleum Engineers—S.P.E. Middle East Intelligent Oil and Gas Conference and Exhibition; 2015 Sep 15–16; Abu Dhabi, United Arab Emirates.
27. Cappelli I, Parrino S, Pozzebon A, Salta A. Providing energy self-sufficiency to LoRaWAN nodes by means of thermoelectric generators (T.E.G.s)-based energy harvesting. Energies. 2021;14:7322.
28. Bizon N, Tabatabaei NM, Blaabjerg F, Kurt E, editors. Energy Harvesting and Energy Efficiency. Technology, Methods, and Applications; Lecture Notes in Energy; Volume 37. Cham, Switzerland: Springer International Publishing; 2017. ISBN 9783319498744.
29. Tan O, Gunduz D, Poor HV. Increasing smart meter privacy through energy harvesting and storage devices. IEEE J Sel Areas Commun. 2013;31:1331–41.
30. Shivamurthy B, Naik N, Thimappa BHS, Bhat R. Mechanical property evaluation of alkali-treated

jute fiber reinforced bio-epoxy composite materials. Mater Today Proc. 2020;28:2116–20.

31. Bhat R, Mohan N, Sharma S, Pratap A, Keni AP, Sodani D. Mechanical testing and microstructure characterization of glass fiber reinforced isophthalic polyester composites. J Mater Res Technol. 2019;8:3653–61.
32. Srikanth V, Kowshik S, Narasimha D, Patil S, Samanth K, Rathee U. Finite Element Modelling and Analysis of Fiber Reinforced Concrete under Tensile and Flexural Loading. J Comput Mech Manag. 2022;1:12–8.
33. Bhat R, Mohan N, Sharma S, Rao S. Influence of Seawater Absorption on the Hardness of Glass Fiber/Polyester Composite. J Comput Mech Manag. 2022;1:1–11.
34. Crossley S, Whiter RA, Kar-Narayan S. Polymer-based nanopiezoelectric generators for energy harvesting applications. Energy Mater Mater Sci Eng Energy Syst. 2014;9:1613–24.
35. Mishra S, Unnikrishnan L, Nayak SK, Mohanty S. Advances in Piezoelectric Polymer Composites for Energy Harvesting Applications: A Systematic Review. Macromol Mater Eng. 2019;304:1800463.
36. Mathew AA, Vivekanandan S, Chandrasekhar A. Polymer-based composite materials for triboelectric energy harvesting. In: Engineered Polymer Nanocomposites for Energy Harvesting Applications. Amsterdam, The Netherlands: Elsevier; 2022. p. 181–202. ISBN 9780128241554.
37. Wang Z, Kurita H, Nagaoka H, Narita F. Potassium sodium niobate lead-free piezoelectric nanocomposite generators based on carbon-fiber-reinforced polymer electrodes for energy-harvesting structures. Compos Sci Technol. 2020;199:108331.
38. Nagaoka H, Wang Z, Narita F. Fabrication and impact output voltage characteristics of carbon fiber reinforced polymer composites with lead-free piezoelectric nano-particles. Proc Mech Eng Congr Jpn. 2019;2019
39. Su YF, Kotian RR, Lu N. Energy harvesting potential of bendable concrete using polymer based piezoelectric generator. Compos Part B Eng. 2018;153:124–9.
40. Cottinet PJ, Guyomar D, Guiffard B, Putson C, Lebrun L. Modeling and experimentation on an electrostrictive polymer composite for energy harvesting. IEEE Trans Ultrason Ferroelectr Freq Control. 2010;57:774–84.
41. Rodrigues-Marinho T, Castro N, Correia V, Costa P, Lanceros-Méndez S. Triboelectric Energy Harvesting Response of Different Polymer-Based Materials. Materials. 2020;13:4980.
42. Tiwari R, Kim KJ, Kim SM. Ionic polymer-metal composite as energy harvesters. Smart Struct Syst. 2008;4:549–63.
43. Seino M, Jiang L, Yang Z, Katabira K, Satake T, Narita F, Murasawa G. Impact energy harvesting by Fe-Co fiber reinforced Al-Si matrix composite. Materialia. 2020;10:100644.
44. Yang Z, Nakajima K, Jiang L, Kurita H, Murasawa G, Narita F. Design, fabrication and evaluation of metal-matrix lightweight magnetostrictive fiber composites. Mater Des. 2019;175:107803.
45. Yang Z, Wang Z, Seino M, Kumaoka D, Murasawa G, Narita F. Twisting and Reverse Magnetic Field Effects on Energy Conversion of Magnetostrictive Wire Metal Matrix Composites. Phys Status Solidi Rapid Res Lett. 2020;14:2070039.
46. Wang Z, Mori K, Nakajima K, Narita F. Fabrication, Modeling and Characterization of Magnetostrictive Short Fiber Composites. Materials. 2020;13:1494.
47. Kurita H, Lohmuller P, Laheurte P, Nakajima K, Narita F. Additive manufacturing and energy-harvesting performance of honeycomb-structured magnetostrictive Fe52-Co48 alloys. Addit Manuf. 2022;54:102741.
48. Kumar C, Gaur A, Tiwari S, Biswas A, Rai SK, Maiti P. Bio-waste polymer hybrid as induced piezoelectric material with high energy harvesting efficiency. Compos Commun. 2019;11:56–61.
49. Gali V, Varaprasad MV, Gupta SK, Gupta M. Performance investigation of multifunctional grid connected PV interleaved inverter with power quality enhancement. Energy Systems. 2021;1–23.