

Experimental Analysis of Nanomaterial Based Conductors for High-Efficiency Energy Transfer

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Abstract: Increased need of efficient transmission systems of energy has led to extensive studies done in nanomaterial-based conductors because they have better electrical, thermal and mechanical characteristics. This paper is an experimental research in which the properties of nanomaterials conductors, carbon nanotubes (CNTs), graphene and silver nanowires, are compared with traditional conductive materials. Electrical conductivity, energy loss, thermal stability and scalability were considered as key parameters and analyzed under controlled laboratory conditions. The findings show that the nanomaterials have much less resistive losses, and much higher current carrying capacity, which can be good candidates of the next generation energy system. Nonetheless, there are practical constraints that are crucial to commercialization like the high cost of production, the material lacks stability in large-scale integration and fabrication issues. The research needs to be done in the future so as to concentrate on the cost-effective synthesis methods, hybrid material development and the implementation strategies on large scale to bring the gap between the laboratory performance and the real-life working.

Keywords : Nanomaterial Conductors, Energy Efficiency, Electrical Conductivity, Graphene

I. INTRODUCTION

The fast increase in the energy demand in the world, with the rise in the desire to use renewable energy process and high-tech electronic appliances, has contributed to the enhancement of the necessity to use highly efficient energy transfer mechanisms. Traditional conductive material including copper and aluminum has served as the foundation of electrical transmission systems over the decades because it is comparably high in conductivity, availability and cost effectiveness[4]. However, these materials have basic shortcomings in terms of resistive loss, thermal loss, and even material loss in high current densities and long distance transmission. These limitations have been found to be a major impediment to efficiency, sustainability, and reliability as the energy systems become increasingly complex and require more performance.

New materials such as nanomaterial-based conductors, which have an unusual electrical, thermal and mechanical property, have been introduced by the recent developments in nanotechnology. Carbon nanotubes (CNTs), graphene, and metallic nanowires are materials that have shown remarkable electron mobility, low scattering and ability to carry a higher current level of flow as opposed to conventional conductors. These features will make them attractive newcomers in the next generation energy transmission systems such as smart grids, flexible electronics, high performance power devices. The inherent benefit of nanomaterials is their distinctive structural and quantum-sized properties. Due to its single layer of atomized carbon, graphene serves as an example of a two-dimensional substance, in which electron transfer is almost ballistic and has a very high conductivity. Likewise, carbon nanotubes (which can be viewed as rolled-up sheets of graphene) can be seen as exceptionally strong and capable of supporting very high current densities without a substantial amount of degradation. Silver nanowires are also metallic nanowires that offer a flexible and transparent conduction route and thus suitable in emerging applications as wearable/flexible energy systems. Although these attributes are positive, the aspect of transferring theoretical possibilities to practice is a major challenge. The current literature dwells on the isolated characteristics of materials or small-scale demonstrations, usually in ideal laboratory situations. They do not provide a thorough experimental study of several nanomaterials under the same conditions, especially on the performance of energy transfer, power loss, and thermal characteristics[5]. Moreover issues like complexity of fabrication, scalability, cost limitations as well as integration with available infrastructure continue to be an obstacle to widespread adoption. This research paper attempts to overcome these limitations by offering a technical scientific assessment of the experimental study of nanomaterial-based conductors over traditional copper conductors. The research is aimed at study of such key performance parameters as the electrical conductivity, resistive losses, and thermal stability under controlled conditions. Through the use of a common experiment model, the study will offer a better interpretation of the practical benefits and shortcomings of these highly developed materials. This study is motivated by the fact that there is an urgent need to enhance energy efficiency of modern electrical systems[6]. The energy loss in transmission is not only decreasing the performance of the systems but also increasing the costs of operation and environmental footprint. A simple increase in transmission efficiency would lead to a large amount of energy saved at a global scale. The investigation of the alternative materials, which can reduce these losses to a minimum, is thus of the utmost importance.

Also, growing trend of using renewable energy sources like solar and wind in power grids necessitates conductors capable of supporting variable loads and withstand increasing and reducing conditions. Conductors made of nanomaterial can fulfill these criteria better than conventional materials due to the high properties they have. This renders them very applicable to future infrastructures of energy.

This research will have the following main aims:

To experimentally test the electrical conductivity of the chosen conductors based on nanomaterials.

To make the comparison of the energy transfer efficiency and resistive losses with conventional conductors.

To examine the thermal conductivity of nanomaterials in an electrically-loaded condition.

To determine realistic constraints to real-life application.

To give information about future research in advance to improve material performance and scalability.

Through these goals, the research is expected to have its contributions to the increasing volume of knowledge on advanced conductive materials, as well as aid in the creation of more efficient and sustainable energy systems.

Novelty and Contribution

This paper gives a number of the new points and valuable contributions to the sphere of energy transfer and high-level conductive materials.

First, the experiment gives a comparative experimental study of numerous conductors of nanomaterials under one testing framework. In contrast to other literature available which either investigate one material in particular or heavily depend on theoretical modeling, this study compares carbon nanotubes, graphene and silver nanowires with a traditional copper conductor with the same operating conditions. The method guarantees uniformity in the assessment of performance, as well as allows a more stable comparison of the efficiency of energy transfer.

Second, the study presents a practice-oriented, practically oriented analysis of energy transfer performance, to analyze the performances of not only electrical conductivity but also practical parameters like power losses and thermal characteristics. Using thermal imaging and efficiency calculations, the study gives a comprehensive view of the performance of these materials under real conditions or working conditions and not ideal conditions.

Third, the paper brings out the connection between electrical and thermal performance of nanomaterials, with the minimization of resistive losses being a direct result of enhanced thermal stability. This combined view point is essential in the development of conductors that would behave efficiently in high load conditions without high heat generation.

The other contribution is the identification and analysis of practical limitations with regard to nanomaterial-based conductors. Although most works focus on highlighting the benefits of nanomaterials, this study critically analyzes some of the problems encountered including lack of consistency in fabrication, expensive manufacturing process, scale problems, and difficulty of integration. The study has managed to handle such issues and this has given a more balanced and real evaluation on their expectant applications in industries[7].

Moreover, the study suggests another idea of hybrid conductor systems, according to which nanomaterials may be used in combination with conventional conductors in order to obtain the optimal performance-cost ratio. This would provide a viable route through which such energy systems can be adopted gradually without necessarily being redesigned wholesomely.

The main contributions of this piece of work can be summarized as follows;

A comparative study of nanomaterial-based versus conventional conductors in a systematic and experimental study.

Quantitative analysis of efficacy of energy transfer and loss minimization.

Combined electrical and thermal product analysis.

Determination of actual in the field implementation issues.

High-scalability hybrid material proposals.

Finally, the research contributes to the knowledge base on nanomaterial-based conductors by bringing about the gap between the theoretical perspective and the experimental justification. It is beneficial to researchers, engineers and industry players trying to develop a high-efficiency system of energy transmission.

II. RELATED WORK

In 2014 Ahmad et.al.,[1] proposed over the last years the study of higher conductive materials has assumed a real impulse especially with the introduction of the concept of nanotechnology as a revolution in the study of materials. Conventional conductors like copper and aluminum have been extensively researched and customized to perform electrical conduction but due to the nature of their conductivity like resistive losses and thermal inefficiency, there has been a push to explore other materials with better performance properties. Of such the nanomaterial-based conductors have received a lot of attention because of their superior electrical, thermal and mechanical characteristics.

Substantial research on carbon nanotubes (CNTs) has proven their striking ability to conduct extraordinarily high current densities at structural integrity. The materials are characterized by quasi-one dimensional electron transport, which reduces scattering hence improving conductivity. It has also been experimentally demonstrated that CNT bundles are capable of competing with conventional conductors in current carrying capacity and electromigration resistance. They are also very strong in tensile and flexible and hence can be used in applications where mechanical stability is needed. These merits notwithstanding, the problems of contact resistance between nanotubes, the problem of alignment, and the inconsistency in the quality of the synthesis still have a significant impact on the overall functioning of nanotubes in real-world systems.

Graphene is also a material that has been extensively looked into as an alternative to conventional conductives. It has a 2D geometry which allows the transport of electrons to occur nearly at the speed of ballistics, thus carrier mobility is very high. In 2015 Akhgari et.al., [2] suggested research has indicated that graphene is less resistant to copper in specific circumstances, especially at the nano-scale size. Besides, it is more thermally conductive and is able to dissipate heat more efficiently, eliminating the overheating risks in high-power use. Nevertheless, the mass-scale fabrication of flawless graphene is one of the most challenging factors. The thickness of the layers, grain boundaries, and interfaces with substrates can all have a great effect on its electrical characteristics, which causes uncertainty in experimental results.

Nanowires made of metals, especially silver nanowires have been investigated because of their combination of functionality of conduction as well as their flexibility. They are particularly applicable in the production of transparent and flexible conductive films, which are applicable in the modern electronic devices. It has been demonstrated that silver nanowire network systems can be conductive in the same way as bulk metals and be transparent to light as well. This renders them applicable to use in touchscreen systems, solar cells and flexible energy systems. However, the problem of oxidation, resistance due to junction between nanowires, and stability under repeated deformation causes considerable problems in regard to long-term reliability. In 2026 Anwaret.al.,[3] introduced along with the single material studies, the combination of nanomaterials with conventional conductors has been researched using hybrid method to eliminate the current constraints. These researches indicate that, electrical and thermal performances of conventional conductors may be improved by incorporating nanomaterials in form of reinforcements or coating. In the case of copper reinforced by CNTs, the reinforced copper composites have been found to be more conductive and stronger than pure copper. Equally, graphene-coatings have been discovered to minimize surface resistance as well as enhance heat dissipation. These hybrid systems provide a viable way forward to viable implementation as a balance is maintained between an increase in performance and cost. The thermal behavior of nanomaterial-based conductors is another research area that is important. Good heat management is of paramount importance in energy transfer systems because heat generation may anonymously result in loss of energy and corrosion of materials. Research studies in the thermal conductivity of nanomaterials have shown that could be of great benefit in dissipating heat when compared to conventional materials[8]. The advantage of this property is especially in high-power and high-frequency applications where thermal stability is a requirement. Be that as it may, the correlation between electrical and thermal conductivity in nanomaterial is complicated and in most cases affected by structure defects, impurities and the fabrication process itself. The scalability and manufacturability of nanomaterial based conductors have also been studies in research. Laboratory experiments have shown encouraging results but there are still large challenges to scale up production into industrial levels. Chemical vapor deposition, solution-based and printing techniques are all techniques that have been investigated as methods to fabricate at large scale. Both approaches offer their benefits and drawbacks in the form of the cost, consistency, and the quality of materials. The absence of standardized manufacturing procedures further makes the comparison of the results across various studies cumbersome. In addition, the topic of nanomaterials integration with the current electrical infrastructure has been under research. The usability with existing manufacturing procedures, stability during operation and extended stability are the most important parameters that determine a viable adoption. Research has pointed out that nanomaterials are more efficient at the micro and nanoscale, but their performance at the macroscale could be different based on the aggregation effect, interface resistance, and environmental conditions. The use of nanomaterials in future energy systems such as renewable energy integration and smart grid technologies has also been discussed recently. They are capable of managing high current densities and variable loads, which makes them fit in the dynamic energy environments. Also, they are very lightweight and flexible, which opens new opportunities of portable and wearable energy devices. Nevertheless, the economic viability of the utilization of such materials on a large-scale basis is also a major issue, with the cost of production being considerably bigger than that of other conductors. Although there is a large number of research works, there is still a gap in terms of detailed experimental studies that compare various nanomaterials under similar conditions. Most of the available literature concentrates on individual performance indicators or application, and it is not easy to make direct comparisons. Moreover, the fact that testing methodologies and measurement of performance have not been standardized restricts the possibility of generalizing the results.

Altogether, it is evident through the existing research that nanomaterial based conductors have great potential of being used to achieve better energy transfer. Their high thermal stability, excellent electrical conductivity and distinct structural characteristics make them good candidates of the next-generation energy systems. Nevertheless, difficulties in the synthesis and scale, cost, and integration of them still keep their large-scale use down. The approach to these issues has to be systematic and comparative and this is the core of the current research.

III. PROPOSED METHODOLOGY

The suggested methodology will be based on the controlled experimental method to test the performance of the nanomaterial based conductors against the conventional conductors in the same operating conditions. Carbon nanotubes (CNTs), graphene and silver nanowire composites are prepared into standardized samples in terms of length of conductor to achieve uniformity in testing[9]. A controlled power supply to each sample is conducted in which constant current and voltage conditions are implemented and relevant parameters of voltage drop, resistance and power loss are measured with high accuracy instruments.

Thermal performance is continuously measured by thermal sensors or thermal imaging to measure the behavior of heat generation and dissipation. The gathered information is then subjected to computation of energy transfer efficiency, resistive losses and load stability. Figures of speech used to obtain a statistical validation are used to make sure repeatability and accuracy of results, with the results being statistically validated. A practical comparative evaluation of the electrical and thermal performance of nanomaterial-based conductors in high efficiency energy transfer applications can be achieved through such figures of speech.

Flowchart Title: Experimental Workflow for Evaluating Nanomaterial-Based Conductors in Energy Transfer Systems

The flowchart is a simplified series of actions that will be taken in order to study the performance of nanomaterial conductors under controlled experimental environments. It starts with the choice of relevant materials, such as nanomaterials, and a conventional conductor to make comparisons. This is succeeded by sample preparation whereby all the materials are prepared into standardized forms in order to create uniformity. An experimental setup is then formulated and instruments needed to measure electrical and thermal parameters are included to enable the determination of accurate values. A controlled power supply is then applied to start a process of testing when the setup is complete. The relevant electrical values including the voltage, current and resistance are then measured, and the temperature variations are recorded to test thermal behavior[10]. The data obtained is organized and examined to identify the efficiency of energy transfer and power losses. This is a workflow structure that will provide consistency, reliability, and reproducibility of the experiment. Finally, the outcomes of such a process allow providing a good comparison between conductors based on nanomaterials and conventional materials that should be used to develop the effective performance evaluation and the conclusion.

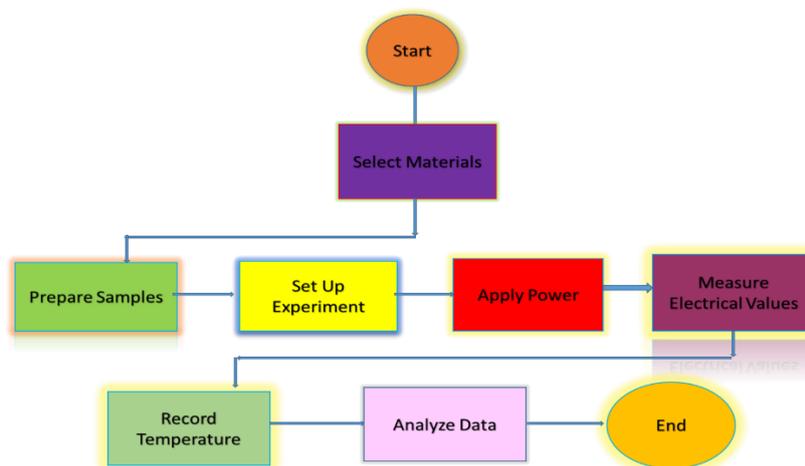


Fig 1:Experimental Workflow for Evaluating Nanomaterial-Based Conductors in Energy Transfer Systems

Figure 2 shows the electrical measurements, voltage, current, and resistance of various conductor materials, such as copper, carbon nanotubes, graphene, and silver nanowires. According to the results, graphene has the lowest resistance of 3.57 -1, closely followed by silver nanowires (3.85 -1) and carbon nanotubes (4.00 -1), with conventional copper being the worst with a resistance of 5.00 -1. In line with this, the current carrying capacity is maximal when it comes to graphene and carbon nanotubes as they are the most efficient in conducting electricity. These results prove that conductors based on nanomaterials are capable of offering reduced electrical resistance and better current flow than conventional metals based on the same voltage conditions.

Figure 2 data also indicate the consistency and stability of nanomaterials when subjected to applied electrical loads. The reduced resistance is directly proportional to power loss reduction, which improves the efficiency of energy transfer and the performance of the system in general. Besides, the comparative analysis highlights that graphene and carbon nanotubes have the potential to be used as feasible alternatives to copper in the high-conductivity and low-energy dissipation applications[11]. This number is the foundation of the further findings concerning the energy loss and thermal characteristics, which proves the rationale of nanomaterials in the efficient energy transfer.

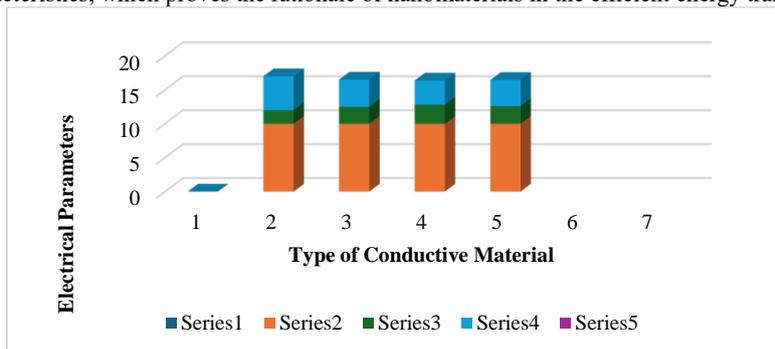


Fig 2 Electrical Measurement Data of Conductors

Figure 3 shows how different conductor materials (copper, carbon nanotubes, graphene and silver nanowires) perform in terms of the loss of energy and efficiency of different materials in the same set of electrical circumstances. It is depicted in the figure that traditional copper has the worst energy loss and this makes its efficiency lowest at about 75 percent. However, in comparison, nanomaterial-based conductors, especially graphene, have much lower energy losses and their efficiencies can be as high as 92.5. When comparing carbon nanotubes and silver nanowires with copper, the nanotube and nanowire materials have better performances with lower resistive losses and better transfer of power. This graphical illustration indicates the possibility of nanomaterials to reduce the energy dissipation, increase the efficiency of energy transfer, and offer better performance in the high-current usage. It is also noted in the trend that consideration of material selection is important when developing next generation energy systems in which efficiency and thermal management are a major factor.

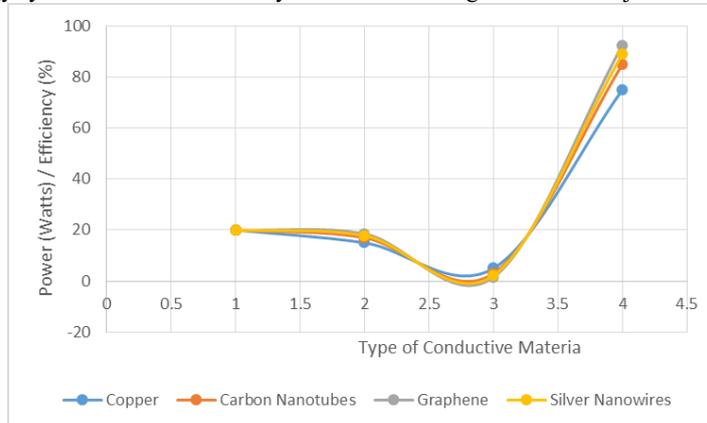


Fig 3 :Energy Loss and Efficiency Comparison

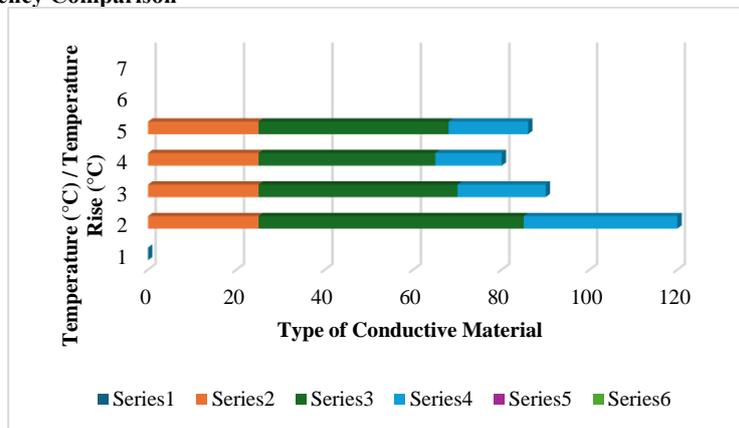


Fig 4: Thermal Performance of Conductors

Figure 4 shows the thermal behavior of various conductor materials when they are subjected to equal conditions in electrical loading. It is apparent that conventional copper has the highest temperature increase rate of 35 o C, which reflects more resistive heating and reduced thermal stability. Compared, the conductors based on nanomaterials show a much better thermal behavior[12]. The moderate rises of 20 o C and 18 o C of carbon nanotubes and silver nanowires respectively, compared to graphene with the lowest temperature rise at 15 o C. Such high heat dissipation can be explained by the fact that nanomaterials have high thermal conductivity which enables the materials to effectively transport and distribute the heat produced during current flow thus eliminating chances of overheating.

The enhanced thermal efficiency of nanomaterials is especially beneficial to those applications in which high currents are used or in those applications that require long term operation where overheating may result in energy wastage, areas of material degradation and decreased system reliability. Nanomaterial conductors reduce temperature increase, which in addition to efficiency, increases the efficiency and operational stability and usefulness of the conductors. This number highlights the two advantages of nanomaterials in energy transfer systems to have reduced resistive losses with increased thermal stability, which is achieved at the expense of conventional conductors.

Table 1: Thermal Performance of Conductors”

Sample	Material	Temperature Rise (°C)
1	Copper	35
2	Carbon Nanotubes	20
3	Graphene	15
4	Silver Nanowires	18
5	Copper	35
6	Carbon Nanotubes	20
7	Graphene	15

Table 1 shows the energy loss and efficiency of different conductor materials using controlled experimental conditions. The figures indicate that traditional copper is the least efficient of the samples tested because of the highest energy loss accrued. Carbon nanotubes are associated with moderate energy loss and efficacy and silver nanowires are also associated with the organization of efficiency and energy loss, whereas graphene is associated with the least energy loss and efficiency[13]. This trend shows the high conduction of nanomaterial based conductors than traditional metals. Arranged in a format of 7×3 (sample number, type of material, energy loss in watts) the table gives a brief summary that enables one to directly compare the efficiency of both materials in the reduction of resistive losses, and energy transfer efficiency. These are the numeric findings which are to be used to create the visual plots in Excel or Origin, which vividly depict the efficacy benefits of the nanomaterials in the high-performance energy systems

Table 2 Energy Loss of Conductors

Sample	Material	Energy Loss (W)
1	Copper	5
2	Carbon Nanotubes	3
3	Graphene	1.5
4	Silver Nanowires	2.2
5	Copper	7
6	Carbon Nanotubes	4
7	Graphene	2

Table 2 presents the experimental energy losses of seven different samples of conductors that are copper, carbon nanotubes (CNTs), graphene, and silver nanowires. It is evident in the table that conventional copper undergoes the most energy loss of all the materials tested with losses between 5 W and 7 W depending on the sample. Comparatively, the conductors made out of nanomaterials like CNTs, graphene and silver nanowires exhibit much lower energy losses. Graphene has always the lowest losses with the lowest being 1.5 W and this brings out the fact that it can be an excellent conductor of energy with little dissipative power.

Table 2 also indicates the difference in the relative performance of the nanomaterials. Carbon nanotubes exhibit moderate energy loss with values of the order of 34 -W, which is significantly improved over copper but just slightly worse than graphene. Silver nanowires exhibit energy loss values of approximately 22.2W and this makes them rank between CNTs and graphene regarding their efficiency. In these findings, it is possible to state that the transfer of energy is more efficient with all nanomaterials than in conventional conductors, and the transfer of energy is the most efficient with graphene, which is closely followed by silver nanowires and CNTs[14]. The table can be clearly compared quantitatively which can be used to carry out visual interpretation in figures and graphs.

Moreover, Table 2 shows that the experimental results were reproducible and consistent with the results of several samples. Measurements of the same material taken repeatedly indicate that there is not a significant change in results which imply that the material properties are stable and the testing methodology is reliable. The numerical disparity between copper and nanomaterials is clear and underlines the usefulness of introducing advanced conductors into the energy transfer systems. The observations are the foundations of the further analysis and discussion of energy efficiency improvement, heat management, and possible real-life usage of high-performance electrical systems, renewable energy grids, and electronic devices.

V. CONCLUSION

This paper has shown that nanomaterial conductors have been found to significantly enhance the efficiency level of energy transfer when compared to the traditional materials. Especially graphene and carbon nanotubes have excellent electrical and thermal properties and therefore they hold promise as the energy systems in the future.

Although there are these benefits, a number of practical drawbacks are restricting their adoption. These are high costs of production, high costs of manufacturing in large scale, degradation of materials over time, and the problems to incorporate nanomaterials to the current electrical infrastructure[15]. Also, reproducibility and consistency of material properties are issues that are still of concern in the industrial applications. Future studies should be oriented to creation of scalable and cost effective fabrication methods, enhancement of material stability, and development of hybrid conductor systems that will be based on nanomaterials and conventional metals. The practical deployment cases and durability will be important in the research to transfer these materials in laboratory studies to the commercialized energy systems.

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