A Summary Review on the Applications of Nanotechnology in the Manufacturing of Renewable Energy Production and Storage Devices

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Abstract—This paper presents a summary review on the applications of nanotechnology in the manufacturing of renewable energy production and storage devices. The use of carbon nanotubes (CNTs) and graphene nanosheets (GNSs) to improve the performance and durability of wind turbine and wave rotor blades will be reviewed. While GNSs are primary used for the performance enhancement of the resin system to manufacture Nanoresins, CNT-Nanoforests and Nanofilms are used to improve the performance of fiber systems in high-performance Nanocomposites. Next, the use of CNTs and GNSs in the manufacturing of other renewable energy production devices; such as, proton exchange membrane fuel cells (PEMFCs) and polymer solar cells as well as renewable energy storage devices; such as, batteries and supercapacitors to improve their performances, efficiencies, and durability while reducing their costs, weights, and sizes will be reviewed.

Keywords—Manufacturing, Nanotechnology, Renewable Energy Production Devices, Renewable Energy Storage Devices

I. INTRODUCTION

This paper presents a summary review on the applications of nanotechnology in the development of renewable energy production and storage devices. First, the use of carbon nanotubes (CNTs) and graphene nanosheets (GNSs) to improve the performance and durability of composites with applications to wind turbine and wave rotor blades will be reviewed. While GNSs are primary used for the performance enhancement of the resin system called Nanoresin [1]-[3], CNT Nanoforests and nanofilms [4]-[9] are used to improve the performance of fiber systems in high-performance Nanocomposites. Next, the use of CNTs as gas diffusion layers and CNTs combined with in-situ generated platinum nanoparticles as catalyst layers to improve the performance, efficiency, and durability of proton exchange membrane fuel cells while reducing their costs, weight, and size will be reviewed [9]-[13]. In addition, the use of CNTs and GNSs to improve the efficiency and performance of polymer solar cells will be reviewed [14], [15]. Finally, the use of CNTs and GNSs to enhance the performance, efficiency, and durability of batteries and supercapacitors while reducing their costs, weight, and size will be reviewed [15].

II. NANOCOMPOSITES FOR WIND TURBINE AND WAVE ROTOR BLADES

A. Wind Turbine Rotor Blades

Due to high specific strength and stiffness of composites, it is advantageous to fabricate the blades of Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) out of composite materials. It should be noted while the maximum theoretical efficiency of HAWTs is about 59%, that for VAWT is about 16%, based on the velocity of the wind entering and leaving the turbine blades [16]. Due to design, dynamics, and structural stability issues as well as efficiency, large output power wind turbines are HAWTs. In a HAWT, the produced power is related to the blade length (R) as the following [16], [17]:

\[ P = C_p \frac{1}{2} \rho A V^3 \]  

\[ A = \pi R^2 \]  \hspace{1cm} (1)

where, \( P \) is the harnessed wind energy, \( C_p \) is the efficiency of HAWT (i.e., 0.593 which is the Belts limit [16]), \( \rho \) is the air density, \( A \) is the swept area (i.e., the area of the circle generated by the rotating blades), \( V \) is the incoming wind velocity, and \( R \) is length of the turbine blade (i.e., the radius of the swept area). In addition, the following relationship also exists between various 3-blade HAWT parameters and the blade radius [16]-[18]:

\[ \text{Blade Swept Area} \sim R^2 \]  \hspace{1cm} (2)

\[ \text{HAWT Power} \sim R^2 \]  \hspace{1cm} (3)

Also, for a cantilever beam the moment, \( M \), on the beam is proportional to the “dead” and “live” loads applied on the beam, where the “dead load, \( W_D \)” is the blade distributed load due to the self-weight and “live load, \( W_L \)” is the windblade
distributed “lift” load due to the airfoil profile of the blade. Also, in a cantilever beam, the stress, \( \sigma \), distribution can be written as [19]-[21]:

\[ \sigma = M z / I \]  
(5)

where, \( z \) is the blade height coordinate system from the central line of the blade in the blade thickness, \( h \), direction (where, the \( z \)-maximum is \( h/2 \)), and \( I \) is the area moment of inertia for the beam, where:

\[ I = b h^3 / 12 \]  
(6)

where, \( b \) is the blade width. Also [16]-[18]:

\[ M \sim W_D + W_L \]  
(7)

\[ \text{Blade Weight} = W_D \sim R^3 \]  
(8)

Therefore, for a given, \( b, h, I \), and \( W_L \) and employing (6) to (8):

\[ \sigma \sim M \sim W_D \sim R^3 \]  
(9)

Therefore, (4) and (9) show that while an increase in \( R \) (i.e., blade length) increases the harnessing wind power by \( R^2 \), it increases the stress on the blades by \( R^3 \), respectively (Square-Cube Law) [22], [23]. As a result, in addition to the manufacturing limitations encountered to fabricate very large blades, there is also materials properties limitations that will not allow the lengths of the blades exceed certain sizes due to static and dynamic strength limitations of the external and internal structures of the blades (it should be noted that wind turbine blades are often made of composite materials with similar airfoil as well as external and internal structures as airplane wings [16]-[18]). Since 1980, the rotor diameter of the HAWT blade is doubled every 10 years from 15 meters in 1980 (producing 50 KW), to 40 meters in 1990 (producing 500 KW), to 80 meters (the same wing span of Airbus A380) in 2000 (producing 2 MW), to 180 meters in 2010 (producing 10 MW), shown schematically in Fig. 1 [22], [23]. The growth beyond 180 meters rotor diameter producing powers in the order of 20 MW (requiring a rotor diameter of about 250 meters) and beyond requires technological advances in various aspects of the HAWTs, including transmission and conversion, electrical/smart grids, support structures, non-linear behavior of electronics and electromechanical systems, aerodynamics and aero-elastics, flow and condition monitoring (using sensors such as LIDAR), distributed smart control strategies for blades operations and health monitoring as smart rotor blades (including the use of smart materials such as piezoelectrics and shape memory alloys as actuators as well as fiber optics as acceleration, strain, and temperature sensors with remote controls and wireless communications), and innovative blade structures and materials with higher strength, fracture toughness, damage tolerance, fatigue resistance, flexibilities, and damping properties [23].

**Nanoresin Technology**: Nanoresin (NR) technology employs sonication of hardener with additions of highly conductive Graphene Nanosheets (GNSs), CNTs, or nanoparticles (NPs), and then combining it with resin to produce the nanoresin system. Agglomeration of the GNSs, CNTs, or NPs can be precluded by employing Nanoresin Technology [1]-[3]. This technique gives structural and physical (including thermal and electrical conductivities) properties improvements isotropically [1]-[3] to produce NR technology. Such Nanoresins can be combined with fibers to give composites with improved properties (see Fig. 2).

**Nanoforest Technology**: Nanoforest (NF) technology grows a forest of carbon nanotubes (CNTs) onto the surface of microfibers or fabric in a CVD furnace with controlled environment allowing neighboring plies to interlock with each other like Velcro® producing hierarchical multiscale multifunctional nanocomposites macrostructures. This results in a 3-dimensional composite with dramatically improved interlaminar fracture toughness, hardness, delamination
resistance, in-plane mechanical properties, damping, thermoelastic behavior, and thermal and electrical conductivities, making the structure multifunctional (see Fig. 3) [4]-[7]. Alternatively, CNTs can be grown on a substrate and subsequently separated and interleaved in between the composite layers (see Fig. 4) [8]-[9] to produce multifunctional properties similar to those reported in [6]. These composites will also have improved EMI shielding properties.

B. Wave Air Turbine Rotor Blades

Oscillating Water Column (OWC) technology is one of the most successful and widely studied technology for harnessing energy from ocean waves. OWCs can be located on the shoreline, nearshore or offshore [26]. Incoming surface waves induce an oscillating flow of air within the chamber which, in turn, flows backwards and forwards through an air turbine installed in a duct connecting the chamber to the atmosphere. The turbine converts this air movement into electrical energy. Variable Radius Turbine (VRT) is one of the common air turbine used for the OWC application [26]. The turbine should be constructed to withstand the rigors of the marine environment and employs a combination of stainless steel, aluminum, and reinforced composites to resist corrosion [26]. Once again, to improve the performance of the wave rotor blades, Nanoresin and Nanoforest technologies, explained earlier here, can be employed to improve the performance, durability, and efficiency of the wave turbines while reducing the weight.

III. USE OF CNTS IN PROTON EXCHANGE MEMBRANE FUEL CELLS

Ghasemi-Nejhad et al. [27], [28] demonstrated that the use of CNTs can improve the performance, durability, efficiency of Proton Exchange Membrane (PEM) fuel cells while reducing their weight, size and costs.

A. Catalyst Layers

Ghasemi Nejhad et al [10]-[12] showed that it is possible to develop Catalyst Layers with a bed of MWCNT over which the Platinum (Pt) nanoparticles can be generated using an in-situ wet chemistry route employing chloroplatinic acid (1 wt % in deionized water) and sodium formate (1 M in deionized water) reducing agent were simultaneously added drop-wise into the MWCNT dispersion to deposit Pt (20 wt %, based on the amount of chloroplatinic acid added) on MWCNTs. This technique produced a well dispersed Pt nanoparticle on the MWCNT bed (see Fig. 5) leading to performance improvement (power density) by 10%, using oxygen or air on the cathode side (at ambient pressure and 70 °C), while reducing the use of Pt by 50-60% as compared with a conventional technique [10]-[12]. The performance enhancement was contributed to a better electrical conductivity and large surface area of MWCNTs as well as efficient dispersion of the Pt nanoparticles.

B. Gas Diffusion Layers

Ghasemi Nejhad et al [28] showed that it is possible to develop Gas Diffusion Layers (GDLs) employing the Nanoforest technology [4]-[7] where MWCNTs are grown in-situ on a teflonized carbon paper as a porous base inside a CVD furnace to develop Nanoforest GDLs (see Fig. 6) leading to performance improvement (power density) by 10%, using oxygen or air on the cathode side (at ambient pressure and 70 °C) due to a better electrical conductivity and large surface area of the MWCNTs. The authors [13] also showed that due to hydrophobic nature of the MWCNTs the Nanoforest-based GDLs can operate in lower humidity up to 30% producing up to 70% improvement in the operation of the PEM fuel cells at lower humidity employing conventional GDLs. Also, since the GDLs do not absorb moisture, they will have extended lifetime. This approach reduces the need for humidity and hence the size of the humidifiers can be reduced leading to lower
weights, sizes, and costs for PEM fuel cells made of Nanoforest GDL.

![Fig. 6 SEM Image of a) teflonized carbon paper, and b) in-situ Nanoforest-based GDL [13]](image)

IV. USE OF CNTS AND GNSs IN POLYMER SOLAR CELLS

Researchers have investigated the use of CNTs in Polymer Solar Cells [14], [15]. The idea is that by dispersing CNTs in Polymer Solar Cells the conversion and transport of the energy due to the exceptional properties of the CNTs will be improved. The polymer are either P3HT or P3OT. SWCNTs work better for the Polymer Solar Cell application as compared to their MWCNTs counterparts [14], [15]. Also, the high surface to volume ratio of the CNTs as well as a better electrical conductivity contribute to enhanced performance. It is expected that GNSs, similar to SWCNTs, improve the performance of the Polymer Solar Cells, with a difference that GNSs are easier to produce and are less expensive.

V. USE OF CNTS AND GNSs IN BATTERIES AND SUPERCAPACITORS

Researchers have also investigated the use of CNTs in energy storage devices such as batteries and supercapacitors as electrodes [15]. Also, the high surface to volume ratio of the CNTs as well as a better electrical conductivity contribute to enhanced performance. It is expected that GNSs, similar to CNTs, improve the performance of the batteries and supercapacitors, with a difference that GNSs are easier to produce and are less expensive.

MWCNTs are widely used in lithium ion batteries for notebook computers and mobile phones commercially [15]. For battery applications, small amounts MWNT powder are blended with active materials and a polymer binder, such as 1 wt % CNT loading in LiCoO2 cathodes and graphite anodes. CNTs provide increased electrical connectivity and mechanical integrity, which enhances rate capability and cycle life [15]. Similar approaches are reported for supercapacitors [15].

VI. CONCLUSION

Nanomaterials such carbon nanotubes, graphene nanosheets, and nanoparticles can improve the performance, efficiency, and durability of renewable energy production (such as wind turbine and wave rotor blades, proton exchange membrane fuel cells, and polymer solar cells) and storages (such as batteries and supercapacitors) devices, while reducing their weight, size, and costs.

REFERENCES


