letter to the editor: a brief overview of nanotechnology applications in smart power grid

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Letter to the Editor: A Brief Overview of Nanotechnology Applications in Smart Power Grid

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Abstract—The smart power grid is the future conversion for the methods and strategies of production and consuming of electrical energy and the interaction between all the components of power grid. The smart power grid rate of achievement is accelerating with the fast growth of related technologies. Nanotechnology science is a trend in improvement and changing of material characteristics, behavior, and cost. Application of nanotechnology in electrical energy production and storage is in the early stages of development and research. This article presents a brief overview for recent and expected advancements in the smart power grid in the environment of nanotechnology discoveries, specifically describing applications and benefits of nanotechnology in photovoltaic cells, wind turbines, fuel cells, plug-in electric vehicles, energy storage batteries, and smart sensors. The use of nanotechnology in smart grid power electronics, computing, and communications is also introduced. This overview gives a promising outline for the future smart grid.

1. INTRODUCTION

Smart power grid is considered as the intelligent monitoring and control of each element of the existing electrical power system (generation, transmission, distribution, and end use) [1–5]. One of the main features of smart grid is the developing of renewable energy resources and distributed generations (DGs) in power grid. Basic functions of smart grid also include its self-healing capability and allowance for the incorporation of demand-response and energy-efficient resources. In addition, the smart grid allows consumers to dynamically participate in grid operations by providing timely information and control options. Moreover, the smart grid improves the electricity infrastructure’s reliability, power quality, and security. To achieve these functions, intelligent systems are required [5]. Intelligent systems have the ability to monitor, forecast, plan, learn, understand complexity, share understanding across different areas, schedule, make decisions, and take appropriate actions. This can ensure stability, reliability, and high efficiency of the electric power grid. In contrast, the smart grid requires not...
only knowledge in the field of electric energy but also of many other fields, such as information technology, communication, control and automation, education, and nanotechnology [6].

The science that concerns observing, measuring, manipulating, and manufacturing materials at the nanometer scale is called nanoscience. Field of nanotechnology has appeared with great opportunities in recent years [7–10]. Nanotechnology is the field attempting to control effects and functionality that takes place in materials and structures. In other words, nanotechnology has the huge ability to control and characterize materials and structures on the nanoscale with extraordinary sensitivity and accuracy. Nanotechnology ranges from modifying conventional device structures to completely developing new devices based on the nanoscale. Nanotechnology has benefited different disciplines, including environmental, medical, agriculture, space, aircraft, transportation, materials, manufacturing, electronics, computers, and energy. Even with the successes achieved by nanotechnology research, major challenges still lie ahead. These challenges include the fabrication techniques, devices, and sensitivity testing of nanostructures [7].

Increasing research in nanotechnology is expected to radically modernize materials, communications, and computing for the future [7, 8]. Also, nanotechnology promises to enable critical applications for the electric power industry [11]. Promising components and parts of the smart grid must be fast enough, small enough, and cheap enough to satisfy the purposes of the smart power grid. Nanotechnology will give the smart grid these features, as shown in Figure 1, which illustrates the update of the current existing power grid using the smart grid concept enhanced with nanotechnology applications.

This article focuses on the application of nanotechnology in smart grid components and infrastructure. Nine topics are highlighted in the following sections: photovoltaic (PV) cells, wind turbines (WTs), fuel cells, power storage batteries and plug-in electric vehicles (PEVs), smart sensors, power electronics, smart grid computing, and communication infrastructure.

2. NANOTECHNOLOGIES ENHANCING THE SMART GRID

Throughout the following sections, specific nanomaterials and nanostructures are introduced for the smart power grid. These include silicon nanoparticles, carbon nanotubes, nanobased membranes, nano-based Li batteries, nanowires, quantum dots, nano-RAM, and diamond nanowires. Some are described briefly in this section, and others are mentioned in the related sections.

Silicon nanoparticles are based on the deposition of multilayers in which excess silicon is aggregated into nanoparticles through high-temperature annealing. The control of size and bulk dispersion of nanoparticles is difficult. Moreover, only limited (silicon containing) host matrix materials can be considered. In contrast, the challenge is to develop nanomaterial with reliable and tailored characteristics by achieving accurate control over silicon nanoparticles and host matrix properties [12]. One application of silicon nanoparticles is PV cells.

Carbon nanotubes are fullerene-related structures that consist of graphene hollow cylinders closed at their ends by semi-fullerene-like structures [13]. Carbon nanotubes have different types of structures: long, short, single walled, multi walled, open, and closed. Carbon nanotubes are very small size and have superior strength, thermal conductivity, and electrical conductivity. Carbon nanotubes are some of the most common nanostructures. Nanoelectronics, semiconductors, supercapacitors, batteries, data storage, solar storage, and hydrogen storage are the applications (related to the smart grid) of carbon nanotubes.

Quantum dots are nanoscaled semiconductor crystals [14]. These semiconductor nanocrystals shine at a specific wavelength depending on their design and excitation. These nanocrystals have the properties of quantum mechanical and semiconductors, so quantum dots are suitable for those applications, including LEDs, optical logic gates, and biological tags. Solar cells and PV cells are also use quantum dots.

Nanotechnology is expected to develop the performance of three parts of a lithium-ion battery: cathodes, anodes, and separators [15]. Cathodes and anodes are expected to be improved using carbon nanotubes. A nano-sized ceramic separator will also enhance the battery safety.

Nanowires are very long thin and short width structures formed with diameters of less than nanometers [16]. Nanowire
technology is being used for faster and smaller electronic components. Its applications also exist in solar and PV cells as well as electrochemical storage.

3. NANOTECHNOLOGY USE IN PV CELLS

PV energy is one of the distributed clean and renewable energy resources in the smart power grid. PV cells are used to generate the electrical power from sunlight.

Extensive studies have been carried out on different design aspects and performance characteristics of PV cells with a goal of producing fully integrated PV modules to compete with traditional energy sources. The aim of the development in PV technology is to improve the efficiency of the cells while reducing the production cost of the modules. There are three generations of industrial update on the development of PV technology: Crystalline, thin film, and nanotechnology. This variety of PV technologies is still under development to enhance the use of solar energy for a cleaner environment. The relatively new field of nanotechnology has opened up new and promising possibilities to improve environmental quality and economic prosperity [17–21].

The major trend of nano-based PV cells is oriented toward absorbing more sunlight with low cost using nanotechnology. Developments in nanotech PV cells via nanotubes, quantum dots, and hot carriers could reduce the cost of PV cells and modules for bulk power generation as well as improve the efficiency of cell conversion. However, implementation of these nanotechnologies in the design of PV cells is a real challenge [10, 12, 18, 21].

Numerous projects in [12] consider the use of nanotechnology for improvement and realize the nano-based PV cells characteristics. The aims of these projects are summarized as follows:

1) exploring new innovative concepts for thin film solar cells based on nanorods;
2) developing a novel PV nanomaterial with reliable and tailored characteristics by achieving accurate control over silicon nanoparticle,
3) developing new nanomaterials with new production technologies and fabricating silicon quantum dot materials for all-silicon tandem solar cells to achieve increased efficiencies,
4) combining advanced nano- and hetero-structures with silicon PV technology,
5) developing novel nanostructured surface layers in silicon solar cells for increasing light absorption in the cell while decreasing surface and interface recombination loss, and
6) developing radically new nanostructured materials for PV excitonic solar cells that are competitive with traditional energy sources.

4. NANOTECHNOLOGY FOR EFFICIENT WTS

Wind generation is the fastest growing source of renewable energy [22]. Capacity grew an average of 26% per year from 2000 to 2011. One-quarter of renewable electricity is expected to be obtained from wind by 2035 [22].

Energy is produced from wind by rotation of fiber glass or aluminum blades that rotate the turbine. The turbine operates as a prime over for generating electrical power. WTs are usually grouped to form wind farms [23].

This type of renewable energy source (wind energy) is also expected to be improved using nanotechnology advancements. In modern WT systems, nanotechnology plays a role in improving the maintenance, operation, and efficiency of windmills [24]. Nanomaterials are expected to impact the rotor blades of WTs, for example, using nanocoatings for corrosion protection. Table 1 summarizes WT problems and the efficient solutions that nanotechnology research has provided.

Many research and technology efforts have improved WTs using nanoscience. Carbon nanotubes are one of the

<table>
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<th>Problems of WT</th>
<th>Nanotechnology-based solution</th>
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<tr>
<td>Dirt build up on blades</td>
<td>Self-cleaning surfaces</td>
</tr>
<tr>
<td>Damage to blades</td>
<td>Use protective coatings, e.g., non-scratch surfaces</td>
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<tr>
<td>Strength and weight of composites</td>
<td>Nanocomposites to improve properties</td>
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<td>Reliability of rotating machines and replacing worn-out components.</td>
<td>Nanolubricant for improved wear resistance at all temperatures and pressures</td>
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<td>Carbon nanotubes as fuel storage</td>
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**TABLE 1.** Opportunities for nanotechnology in WTs
nanomaterials that have been the subject of much interest [23]. They are the stiffest and strongest fibers known and also have unique electrical properties. Carbon nanotubes have been bound with epoxy in windmill blades; it is found that the blades are approximately 50% lighter than glass fiber blades, and the windmill can start operation at low wind speeds of 2–2.5 m/s. The wing size is expected to double, providing 30% greater power production. The use of nanomaterials in commercial windmill applications does not appear to be widespread due to its high cost. Commercial possibilities will be known with the mandatory exercise of nanomaterials used in composites, coatings, and lubricants.

5. NANOTECHNOLOGY USE IN FUEL CELLS

A fuel cell is a small power generating system used for various applications, including mobile, stationary, and portable applications, as seen in Figure 2. A fuel cell is introduced in this overview as a distributed resource.

As a distributed resource, the fuel cell is a device used for electrical power generation. The fuel cell is composed of electrodes that convert the energy of a chemical reaction directly into electrical power. It is similar to a battery, except that it is designed for continuous replenishment of the reactants that become consumed, thereby requiring no recharging. Fuel cells produce electrical power from an external supply of fuel and oxygen rather than the limited internal energy storage capacity of the battery. Fuel cells are not new, but the cost of its materials and manufacturing complexity process has limited their development and usage.

Fuel cells operate by catalyzing the conversion of hydrogen (as a fuel) into electrical energy as the hydrogen passes through a catalytic medium. Advanced designs for fuel cells involve the use of a polymer membrane as the structure through which the hydrogen passes and on which the catalysis occurs. The use of nano-based membrane materials is expected to increase the amount of hydrogen conversion that increases electrical energy generation [19, 20]. Metal nanoparticles of various compositions have been optimized to act as effective electrocatalysts in polymer electrolyte fuel cells and direct methanol fuel cells at both the anode and cathode sides [25]. A design concept used to control and manipulate the structure of a new material on the nanoscale is expected to lead to more powerful fuel cells than currently available and to devices that enable more efficient energy extraction from fossil fuels and carbon-neutral fuels. Also, the new electrode material will allow more efficient direct utilization of natural gas or biogas (produced from waste) in fuel cells [25].

6. NANOTECHNOLOGY IN ENERGY STORAGE AND PEVS

Increasing the penetrations of renewable and distributed energy resources, such as PV arrays, wind farms, and fuel cells, requires the ability to store electrical energy for reuse on various times [10, 26–28]. The stored electrical energy can be reused for the public utility and small portable electronic devices. The Department of Energy (DOE) Grid2030 Vision Conference in April 2003 announced that electrical energy storage is a top concern for the future smart power grid. The DOE organized an electricity advisory committee to introduce recommendations for an energy plan, including energy storage. Types of electrical power storage devices include the flywheel, super capacitor, and battery, as illustrated in Figure 3 [29].

The main challenge in the development of the smart grid is the intermittent nature of renewable energy resources. This balance can be smoothly achieved with energy stored throughout the electrical power grid. An example of storage in a smart grid is the concept of placing small amounts of energy storage via PV cells on the feeders of residential areas [29].

Moving from bulk materials to the nanoscale can significantly change device performance for electrical energy storage and conversion [26]. Nanotechnology can increase the efficiency of storage devices and release of electrical energy, as well as stabilize of electrode materials against swelling-induced damage from ion uptake.

Nanotechnology carries great promise for advancement in energy storage technology; specifically, such technologies utilizing ion insertion processes, such as Li battery technology.
The development of high-performance Li-ion batteries can benefit from the different properties of nanomaterials, such as high surface areas, short diffusion paths, and a large quantity of active sites, as well as freedom for volume change during charging or discharging modes.

Using nanotechnology in the electrical energy storage devices is still in the stage of research and development. For implementation of industrial and practical applications, more work is required to achieve controlled and large-scale synthesis of nanostructures to understand mechanisms of Li battery storage in nanomaterials and to understand kinetic transport on the interface between electrode and electrolyte.

Effects of nanostructures in the battery performance are also very complicated consequences of a reduction in size. The interfacial properties are subtle and critical, considering space-charge effects at the interface between nano-sized electrode materials and charge transport between the electrode and electrolyte. This challenges the carrying out of systematic experimental studies and developing predictive theoretical tools for better understanding of relationships between nanostructures and electrochemical characteristics of electrode materials [31].

PEVs use batteries as an electric supply for the electric motor, which drives the vehicle without CO₂ emissions [32]. The electrical power grid is used to charge these batteries. Hybrid PEVs (PHEVs) use both the battery charged from power grid and the internal combustion engine to drive its motor according to the trip distance. If the running distance is in the range of the storage battery, the PHEV operates as a PEV.

One of the main tasks of the smart grid is the control of PEV battery charging [33]. A smart grid control strategy has to charge the PEV's batteries during the daily low-demand periods to avoid stressing the power grid during peak periods. Smart grid control can also charge the batteries during large penetration of renewable energy resources. The stored power in the PEVs can also be returned to the power grid when needed [34].

Recent and future storage batteries for PEVs are Li-ion batteries [35]. Integrating lithium metal oxides with different structures in nanoscale has been adopted to design and develop electrode materials for advanced high energy Li-ion batteries [36]. Argonne's nanocomposite cathode materials have recently been licensed to some battery companies [37].

7. NANOTECHNOLOGY FOR SMART GRID SENSORS

Installing smart sensors is one of the keystones of the direction toward the smart electrical power grid. Smart grid sensors enable remote monitoring of equipment conditions, such as transformers and power lines, and the demand-side management of resources on smartpowergrid [38–40].

Any smart grid sensor has four parts, as shown in Figure 4: a sensing element (measurement device), a microcomputer, a communication module, and a power supply. The electrical measurement devices sense certain measurements, such as phase voltage magnitude, voltage angle, currents, power flow through transmission lines, and frequency. The microcomputer processes and stores the measured data. The communication modules, which can serve hard wired or wireless, receive commands from a central computer and send data to that computer. The power for each sensor can be obtained from the power system or from a special battery.

Smart grid sensors can be used to monitor weather conditions and power line temperature, which can then be used to calculate the line's carrying capacity. This process is called dynamic line rating, and it enables power companies to increase or decrease the power flow of existing transmission lines. Smart grid sensors can also be used within homes and businesses to increase energy efficiency. Smart grid sensors can link the consumers' appliances with smartmeters, providing monitoring of real-time power consumption. Electrical power companies can use this information to develop real-time pricing, and consumers can use the information to reduce and manage their power consumption at peak times.

As an example, one of the smart grid intelligent sensors was introduced in [41]. Matrix of fault-tolerant distributed sensors, as proposed in [41], can sense and take local actions. These sensors are three-dimensional (3D) mixed systems on one chip. This 3D sensor can be applied for fault-distance estimation and the detection of the failures in such devices. This failure may be due to defects both within the chip and due to external stress. Use of the 3D mixed systems brings benefits relating to both the detection and accuracies of fault distance and arc voltage estimates. However, the proposed sensors in [41] still use multiple devices on a chip, and this can cause a problem during measurements, processing, or communication event.

Future sensors are expected to have transducers able to sense multiple measurements, sophisticated analysis
electronics, and wireless communication systems. Each of these components is vital to the system, and the nanotechnology offers new solutions for the technical challenges associated with realizing each of them [42, 43].

One-dimensional (1D) nanoscale materials, such as nanowires and nanoelectronics, are extremely attractive as main elements for the first action of the sensors [43]. These nanoscale materials offer significant advantage over bulk or thin-film planar devices. The size of these nanoscale materials makes it possible to develop high-density arrays of individually addressable units for simultaneous analysis of a range of different measurements. The ability to develop high-density arrays in a controlled manner allows for enormous replication to improve measurement accuracy and increase the signal-to-noise ratio, in turn increasing smart sensor reliability and accuracy.

8. POWER ELECTRONICS WITH NANOTECHNOLOGY

Power electronics technology as a part of the smart grid infrastructure enables a full utilization of existing (and future) distributed resources and storage devices in a power system, maintaining and improving the current state of the power source security and quality [44].

In general, power electronics’ converters are applied in

1) matching of distributed resources with power grid or local end users and controlling consumption of electrical power with these sources;
2) coupling of energy storage with the power grid and controlling the exchange of energy between storage systems and power grid;
3) improving the quality of the power system by compensation of sags and swells, asymmetry, and distortions of source voltage, as well as compensation for distortion, asymmetry, and phase shift in load current;
4) connecting far networks using high voltage direct current (HVDC) transmission systems; and
5) controlling power system using flexible alternating current transmission system (FACTS) devices.

Nanopower electronics utilize diodes and transistors in switching applications [45, 46]. Power diodes are frequently used in power converters and inverters as freewheeling and snubber components. In several applications, power diodes are required to meet such demands as short reverse recovery time, soft recovery, high breakdown voltage, and low forward voltage drop at the rated forward current. The carbon nanotube p-type semiconductor is a candidate material for power diodes because of the selective electron transport that can be used in hot carriers, ballistic transport, high-current density, mechanical stiffness, thermal stability, and chemical stability. In addition, the carbon nanotube-based power diode gives high breakdown voltage, high electrical conductivity in the forward mode, and high-current output capability [45]. A similar development is also expected for the power transistor for efficient reliability and low power consumption.

9. NANOTECHNOLOGY APPLICATIONS FOR SMART GRID COMPUTING

The amount of exchanged data will be increased greatly in the environment of smart grid, which will be far beyond the scope of the existing power grid condition monitoring. These data cover not only on-line real-time data but also system equipment’s basic information, test data, operating data, defect data, inspection records, and other off-line information. Conventional data storage and management will encounter great difficulties with these massive, distributed, mixed, and complex state data. The candidate computing model for the future smart grid is cloud computing [47–49].

Cloud computing is a general term for anything that involves delivering hosted services over the internet. Cloud computing is an emerging computing model by which users can gain access to their applications anytime they want, from anywhere, through any connected device. The major cloud providers such as Google, Microsoft, and Amazon have been built and are working on constructing the world’s largest data centers.

Nanotechnology can improve cloud computing in two ways. Nanotechnology usage in communication systems, (presented in Section 10) is related and affects cloud computing for the smart grid. The other field is computer architecture; application of nanomaterials in computer architecture (beyond the well-established complementary metal-oxide-semiconductor [CMOS] technology) makes it faster and reliable [50, 51]. Nanotechnology can affect the modern computer in the following ways.

1) Nanofabrication of integrated circuit (IC) is the technology used to produce nanodevices [52]. There are two types of these technologies. The first is the top-down method, which changes the behavior of a certain material or device; the other is the bottom-up, method which changes the molecules nanostructure to produce absolutely new materials or devices.
2) Carbon nanotubes material is used to create electronic components (of the computer), such as transistors, diodes, relays, and logic gates [52, 53].
3) Non-volatile RAM (NVRAM) is made up of tiny nano-engineered ferroelectric crystals. These crystals do not return naturally; in other words, NVRAM can keep data even with a power failure [52]. The researchers in [54] showed prototype memory cells operating between 10 and 100 times as fast as conventional RAM. This prototype has been achieved by creating nano-sized silicon dots that change their state when subject to a short pulse of green laser light.

4) Quantum dots material consists of crystals (that can emit only one waveform length of light) used as quantum bits forming the basis of quantum computers [52]. Quantum computers have the ability to hold both the 1 and 0 states simultaneously. This makes the computer faster than before. Real-time application of quantum computers is still facing a challenge: that the coherence of the two states (1 and 0) is missed as soon as the computer comes in contact with the outside world.

10. NANOTECHNOLOGY FOR SMART GRID COMMUNICATION INFRASTRUCTURE

Smart grid depends mainly on the exchange of the data and information between all parts of the power system (wide-area measurements and signals). Success or failure of the smart grid depends upon the communication infrastructure. Smart grid communication infrastructure is expected to be intelligent, secure, reliable, and effective [55]. Integrated nanocircuits are used in the silicon chips to reduce the size of the processors.

Cyber-security is also a major concern in the smart power system communication due to the following reasons [55]:

1) The smart grid has a large interconnection and integration,
2) the smart grid is a two-way system,
3) the smart grid has end-user interaction with the grid,
4) the smart grid has numerous third-party control systems,
5) the smart grid uses communication software and the public internet.

Recent developments offer solutions of nano-enabled technologies for secure exchange of information [56, 57]. Quantum dots, carbon nanotubes, and diamond nanowires are among the materials currently being exploited for developing robust light sources that emit one photon at a time. Recently, the single quantum dot has been considered one of the most promising materials to creating viable solutions for quantum information processing [56]. It has specific advantages, including stability, compatibility with chip technology, wide spectral range, and high repetition rate.

Communication systems are oriented toward the nanotechnology. Each of the transmitters, receivers, and communication links will use nanotechnology in the near future. Traditional communication protocols will not be suitable for nanonetworks. At this nanolevel, components and communication protocols will be achieved based on the biological or chemical point of view [57].

11. CONCLUSIONS

This article presented a brief overview for the recent direction of nanotechnology applications in the devices/components of the smart electrical power grid. Some nanomaterials and nanostructures were introduced. This letter described the promising use of these nanomaterials and nanostructures in some of the distributed resources, renewable energy resources, energy storage batteries, sensors, and power electronics. Some fields, such as the use of nanoscience in communication technology and data and information technology, are also related to the smart power grid and were mentioned in this overview. Increasing the discoveries in the field of nanotechnology and nanomaterials related to the smart power grid issues to solve the energy problems will be unlimited in the near future. Challenges faced by nanotechnology in the smart grid (including nanostructure development, fabrication devices, testing devices, and nanodesign software) still need more research and development. Cost analysis with respect to future applications of nanotechnology in the context of smart grids is important; however, this is left for further work.

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