Nanotechnology – Disruptive Technologies for Electric Utility Systems. Challenges and Opportunities.

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ABSTRACT

Within the next 25 years, the electric power utility system in the U.S. will face a number of serious challenges. These will include issues related to diminishing supplies and increased costs of fossil fuels, the demands for a reduction in the emissions of greenhouse gases, an increasing requirement for distributed generation and its integration into the grid system; and an increased demand for "digital quality power". Digital devices are highly sensitive to the slightest fluctuations in power supplies, and it is expected that 30% or more of the demand in 2025 will be for power capable of meeting this requirement. Nanotechnology offers possible solutions to these challenges; and some of these are discussed here. While some of these developments are evolutionary in character, based on the improvement of technologies that are currently in research and early development, the magnitude of the problems suggest a need for what have been called "disruptive technologies" and these are also discussed here.

1 INTRODUCTION

The U.S. electricity enterprise is one of the largest industries in the U.S.; it is approximately twice the size of telecommunications and nearly 30% larger than the automobile industry in terms of annual sales. Demand for electricity is projected to more than triple by 2050. Coincident with (and related to) the need for increased generating capacity is a number of serious challenges that face the power industry:

- Diminishing supplies and increasing cost of fossil fuels;
- Mandatory reduction of greenhouse gases released to the environment;
- Need for distributed generation and its seamless integration with the electricity grid;
- Demand for "digital quality" power.

This last challenge represents a major change in the demand pattern for electricity. Digital devices are highly sensitive to even the slightest interruption in power: an outage of even a fraction of a single cycle can compromise performance. Likewise, variations of power quality caused by transients, harmonics, and voltage surges must be avoided. Power with sufficient quality and reliability to serve digital loads now constitutes about 10% of total electrical load in the U.S.; it is expected to reach 30% by 2020.

The immense size of the electricity enterprise would appear at first to be incompatible with nanotechnologies; several studies, however, have identified numerous possible directions [1,2]. Some of these nanotechnologies are evolutionary; that is they are extensions and improvements of conventional technologies. However, others fall into another class where they represent a radical change from the existing practice: this is called 'Disruptive Technology'.

The term 'disruptive technology' is generally credited to Clayton M. Christensen, in his 1995 article *Disruptive Technologies: Catching the Wave*, co-authored with Joseph Bower [3]. He further developed the concept in his book *The Innovator's Dilemma* [4] (Harvard Business School Press, 1997). He remarked "Disruptive technologies typically enable new markets to emerge." It is interesting that even in the 2002 edition of his book, he makes no mention of nanotechnologies. The concept met with considerable criticism; for example in 2004 John C. Dvorak in *The Myth of Disruptive Technology* [5] wrote "There is no such thing as a disruptive technology. There are inventions and new ideas, many of which fail while others succeed. That's it." At almost the same time Christensen, with Michael E. Raynor, wrote a sequel to his earlier book entitled *The Innovator's Solution: Creating and Sustaining Successful Growth* [6] (2003; Harvard Business School Publishing Corporation). In this, he replaced the term 'disruptive technology' with 'disruptive innovation' because they recognized that few technologies are intrinsically disruptive: it is strategy that creates the disruptive impact. The general idea is that a new technology first targets customers at the low end of the market who do not need the full performance capability. The performance of the product is lower than the incumbent, but exceeds the requirements of certain segments at a lower cost, thereby gaining a foothold in the market.

This is called 'low-end disruption'. To go further, the disruptor has to innovate, and the effect is to squeeze the incumbent into the higher-end markets. There is also the situation where the new product is inferior by most measures of performance, but fits a new or emerging market segment: Christensen calls this 'New Market Disruption'. There comes a point where the new technology outperforms the older technology, but the existing player may be unable to afford to move into the new area, for example because of the level of the investment in the older technology:

Joab Jackson, in *WashingtonTechnology,*[7] (1/27/2003) identified nanotechnology as a "coming disruptor", noting the president's FY 2003 budget request for $710 million for nanoscale science, engineering and technology. John Taylor, Director-General of the Research Councils in the UK, in a report entitled "New Dimensions for Manufacturing: A UK Strategy for Nanotechnology" [8] discusses the implications of nanotechnology under the heading "Nanotechnology is Disruptive – What this Means for Manufacturing Sectors with Reference to the UK". Specifically, he writes "A key issue therefore that could disadvantage the UK, compared to other advanced industrial nations, would be a failure of its companies to appreciate that nanotechnology is really disruptive – that it will generate major paradigm shifts in how things are manufactured. Nanotechnology could lead to changes that equal the revolutions ushered in by semiconductor technology and biotechnology."

In this paper, we will discuss four technologies of importance to the future of the electric power industry that may be regarded as 'disruptive nanotechnologies'.

2 PHOTOVOLTAIC SOLAR CELLS

A prime example of non-polluting distributed generation is the use of solar cells to supply electricity. In fact, if solar cells were price-competitive with grid electricity, the way that utility customers obtain power would be changed radically. Several possible routes to inexpensive solar cells are outlined next.

A promising approach is the dye-sensitized solar cell (DSSC), also called the Grätzel cell [9]. This consists of a nanocrystalline mesoporous network of a wide band gap semiconductor (usually TiO_2) that is covered a monolayer of dye molecules (usually a Ru dye). The semiconductor is deposited onto a transparent conductive oxide, through which the cell is illuminated. The TiO_2 pores are filled with a redox electrolyte that acts as a conductor to a platinum electrode.

A different approach to nanostructured PV uses a "bulk heterojunction" design; the idea is to develop a structure of two interpenetrating continuous polymer phases, one of which is composed of donor molecules, the other of acceptor molecules, with each phase attached to a different electrode [10]. The structure evolves because the selected polymers have a low entropy of mixing and separate on the nanoscale. At this time, structures produced by this strategy are not sufficiently regular to achieve good performance. However, the introduction of time-resolved electrostatic force microscopy [11] should be a powerful tool for attacking this problem.

An embodiment of a quantum dot solar cell is a nanocomposite consisting of a porous oxide and a conjugated polymer. SnO_2 films with pore diameters of ~100 nm have been fabricated. Intercalation of polymers into the pores by absorption from solution yields structures with ~75% of the free volume filled with polymer [12].

Another route to nanostructured solar cells is the Hybrid Nanorod–Polymer Solar Cell [13] in which the bandgap is tuned by altering the nanorod diameter. A device has been fabricated, by solution processing, that consists of 7 nm x 60 nm CdSe nanorods in a conjugated polymer [poly-3(hexylthiophene)]. A power-conversion efficiency of 6.9% was obtained under 0.1 mW/cm^2 illumination at 515 nm.

One of the approaches currently being investigated might enable the disruptive technology needed to make solar cells a primary power source.

3 SENSORS

Integration of widespread distributed generation with an electricity grid that delivers digital-quality power will require current and voltage information on a continuous basis from many locations simultaneously. Although conventional sensors cannot provide that capability because they are not miniaturized [14], nanosensors based on magnetoresistance effects can [15]. For example, giant magnetoresistance devices (also called spin valves) consist of two or more layers of ferromagnetic metal separated by nonferromagnetic spacer layers. With a total thickness of 30 nm or less providing magnetoresistance ratios of 10-15%, they are the basis for 250 million magnetic read heads manufactured each year for the hard-disk industry. Tunneling magnetoresistance sensors are similar to spin valves, except that an ultra-thin insulting layer separates two ferromagnetic layers. Only when the magnetization directions are aligned in the magnetic layers is there a high probability of electrons tunneling quantum-mechanically through the insulator. Magnetoresistance ratios of >100% have been measured in prototype devices. Spintronic nanosensors with sensitivities of 1nT (1 nanoTesla) or better could be deployed to the grid in just a few years.

4 THERMOELECTRICS

Thermoelectric systems convert thermal gradients to electricity or electricity to thermal gradients. Although they are quiet, rugged, stable, and reliable, thermoelectrics have been regulated to niche applications because they are inefficient (≤5%). Efficiency improvements by factors of seven or eight are needed to make thermoelectrics competitive for distributed generation or for refrigeration [16]. In conventional materials the parameters of thermoelectric efficiency cannot be separately optimized because they are not independent: changing one parameter also changes the others. However, reducing dimensions to the nanometer scale can uncouple the efficiency parameters. 2-D quantum wells [17], short-period superlattices [18], and quantum dots [19] all show significantly higher efficiencies than their bulk counterparts.

Multilayer heterostructures probably cannot be made large enough for grid-connected electricity generation. Two approaches for developing the requisite high-efficiency bulk materials are being studied: (1) formulation of alloys in which nanoscale composition modulations can be induced in the solid state [20]; (2) self-assembling nanocrystal superlattices in which separately optimized nanoparticles interact synergistically [21]. Although truly high-efficiency thermoelectrics are still in the future, early results are very promising.

5 CATALYSIS

Catalysts touch directly several aspects of the electricity enterprise, among them the Polymer Electrolyte Membrane Fuel Cell (PEMFC) and photochemical splitting of water. Both applications could become disruptive technologies. PEMFC's low operating temperature (~80°C), and consequent quick start-up time, make it an obvious candidate for distributed generation. Platinum-alloy catalysts are used at both the cathodes and the anodes of PEMFCs. At the cathode, the oxygen-reduction reaction is still too sluggish. At the anode, Pt-based catalysts are susceptible to poisoning by CO and sulfur species remnant in the hydrogen produced from hydrocarbon feedstocks. Nanoscale strategies have offered some improvement: submonolayer clusters of Pt atoms on Ru nanoparticles are more effective catalysts than current Pt-Ru alloys and they are more resistant to CO poisoning [20]. Mitigation of sulfur poisoning remains to be addressed.

Photocatalytic splitting of water by sunlight is an appealing route to a "green" hydrogen economy, because carbon dioxide is not produced. It has been known since 1972 that n-type TiO_2 is a photocatalyst that can split water [21]. However, the 3.0 eV bandgap of TiO_2 allows absorption of only the UV portion of the solar spectrum, which is but 2-4% of the available energy. There has been some progress in reducing the bandgap by doping TiO_2 with carbon [22]: the absorption threshold is shifted from 414 nm to 535 nm, that is, into the visible range, but much of the spectrum is still not utilized.

An increase in our capability to create and manipulate nanoscale structures might lead to new, more potent catalysts for low-temperature reactions. The discovery that nanoparticulate gold is an excellent catalyst for some reactions, whereas bulk gold is not [23], encapsulates that hope.

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