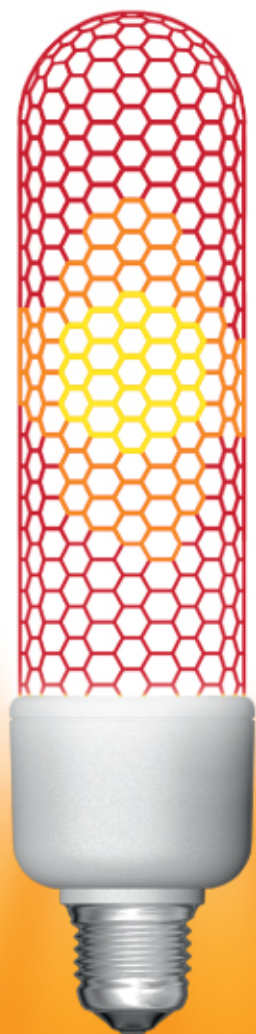


Edited by Javier García-Martínez

# Nanotechnology for the Energy Challenge

Second, Completely Revised and Enlarged Edition

With a Foreword by Zhong Lin Wang





*Edited by*  
*Javier García-Martínez*

**Nanotechnology for the  
Energy Challenge**

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# **Nanotechnology for the Energy Challenge**

*Second Edition*

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## Foreword

In the last two decades, worldwide research has been focused on three major fields: nanoscience, bioscience/medical science and energy science. Among these three areas, nanotechnology is the basis for the other two, developing the materials systems and basic engineering to be applied in bioscience and energy science. Bioscience will not only explore the structure of biosystems, but will also lead to huge advances in medical technology that will make us live healthier and better. Energy science will not only improve the quality of life, but also guarantee the sustainable development of our civilization. With the increasing world population, the presence of poverty in some areas, and the occurrence of natural disasters, a crisis in high energy demand is with us now! The development of new energy will be a huge challenge to the entire world for many decades to come. Energy is probably the only factor that can limit the development of mankind.

The world energy needs can be mainly classified into two categories. The most common category is for large-scale energy needs (measured in the giga- to terawatt range), in areas such as manufacturing, transportation, construction and lighting. Green energy technology is desperately needed to meet the challenge for large-scale energy production, but cost and environmental impact are the major concerns. The most active research in green energy is in solar, thermoelectric, biomass, hydraulic and wind energy. The key measures for green energy are efficiency, cost and environmental impact. Although these various technologies can contribute a substantial percentage of the energy needed by the world, fossil energy and nuclear energy are still the major contributors.

In the second category, with the increase of mobile and personal electronics, as the world enters into the era of sensing networks, powering micro- and nanosystems is becoming vitally important. Although the total amount of energy required for such applications is not huge, the energy required for such systems is characterized by availability and sustainability, while cost is not the most important issue. This is the era of *nanoenergy*, which means using nanomaterials and nanodevices to convert and store the available energy for powering micro- and nanosystems, such as personal/mobile electronics and sensor networks, with applications in bioscience, environmental/infrastructure monitoring, the internet, security and defense technology. Furthermore, with the development of low-power electronics, it is possible to use the energy harvested from our living environment to drive

these electronics, forming a self-powered system. This is a new area of energy research and it will impact largely the sensor network used for various purposes.

The book entitled *Nanotechnology for the Energy Challenge* edited by Dr. Javier García-Martínez is about the application of nanomaterials and nanotechnology in energy science. The book covers three sections: sustainable energy production, efficient energy storage and energy sustainability. In the section on sustainable energy production, starting from a basic introduction about nanotechnology for energy production, chapters are attributed to nanotechnology in areas such as dye-sensitized photoelectrochemical devices, thermal–electric energy conversion, nanogenerators for mechanical energy conversion, graphene for energy production, fuel cells and hydrogen production. This section is mainly about the effective conversion of energy from various sources using the largely improved properties provided by nanomaterials. In the second section, chapters are attributed to energy storage, such as hydrogen storage and electrochemical energy storage including the Li-ion battery and supercapacitors. The last section gives extensive coverage in the area of energy sustainability with a consideration of the environmental impact and materials sustainability. Chapters about green fabrication and carbon dioxide capture are included. Then two chapters are presented on catalysis for energy production. Finally, chapters are given on energy saving and efficient energy usage, such as light-emitting diodes and electrochromics.

This book is a comprehensive and up-to-date coverage on nanotechnology in effective energy conversion and storage, and energy sustainability and environmental impact. Each chapter is written by well-respected scientists in their fields. Such a book is of great value not only to the advanced graduate students who are engaged in energy research, but also to the researchers who are specialized in the applications of nanotechnology in energy. I strongly recommend this book to anyone who likes to know about nanotechnology for energy.

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## Preface to the 2nd Edition

After the successful first edition of this book *Nanotechnology for the Energy Challenge*, the second edition has been extensively updated to include the latest progress in this field. It includes three new chapters on graphene, piezoelectric nanomaterials, and nanocatalysts for Fischer–Tropsch synthesis. This book is now a collection of 18 chapters written by some of the world-leading experts in nanotechnologies and their applications in the broad field of energy. The book is, like the first edition, divided into three thematic parts that cover energy production, storage, and efficient usage.

*Part One: Sustainable Energy Production* is concerned with the use of nanotechnology for sustainable energy production. Following an updated introductory chapter on nanomaterials for energy production (Chapter 1), which is now expanded to also include piezoelectric nanomaterials, graphene, and metal–organic frameworks, world-leading scientists examine the impact of different nanotechnologies on the main energy production and transformation technologies, that is, dye-sensitized solar cells (Chapter 2), thermal–electrical energy conversion (Chapter 3), fuel cell technologies (Chapter 6, fully updated), and hydrogen production (Chapter 8). There are three new chapters in this part: Chapter 4 focusing on piezoelectric nanomaterials, Chapter 5 discussing graphene and Chapter 6 describing nanocatalysts for fuel cell synthesis.

*Part Two: Efficient Energy Storage* covers the potential use of nanomaterials for efficient energy storage systems. The first chapter in this part (Chapter 9) begins with an overview on how nanotechnology contributes to the increase in performance of hydrogen storage systems. The following two chapters (Chapters 10 and 11) focus on the use of nanomaterials in general, and more specifically carbon-based nanomaterials, for electrochemical energy storage. Finally, an updated Chapter 12 is included to describe how new types of nanostructures that are artificially introduced in superconducting films enhance the superconductors' performance.

The last part of the book, *Part Three: Energy Sustainability*, is oriented to the efforts on advancing the efficient usage of energy through the application of nanotechnology. This part begins with Chapter 13 on unconventional approaches for the conservative use of energy from the point of view of green nanofabrication. The subsequent two updated chapters (Chapters 14 and 15) overview recent

advances on nanocatalysts for fuel production and biofuel applications. Other areas where nanotechnology offers breakthrough opportunities are carbon dioxide capture by using nanoporous materials (Chapter 16), as well as nanostructured light-emitting diodes (LEDs) and organic LEDs (OLEDs) for higher energy conversion from electricity to light (Chapter 17). Finally, recent advances in the nanotechnologies that are applied to energy-efficient buildings are collected in an updated chapter on electrochromics (Chapter 18).

## Preface to the 1st Edition

Mankind faces daunting energy challenges in the twenty-first century, i.e., its over-reliance on the quickly diminishing fossil fuel-based energy sources and the consequent negative impacts to the global environment and climate. Although evolutionary improvements in existing technologies will continue to play important roles in addressing some of the challenges, revolutionary new technology will be the key to a clean, secure and sustainable energy future. Nanotechnology, by manipulating matter at the nanoscale with unprecedented accuracy, holds the promise of providing new materials with distinctly different properties. In recent years, breakthroughs in nanotechnology, especially in their applications in the energy sector, have opened up the possibility of moving beyond our current alternatives by introducing technologies that are more efficient, environmentally sound and cost effective.

This book, *Nanotechnology for the Energy Challenge*, is a collection of 15 chapters contributed by some of the world's leading experts in nanotechnology and its applications in the energy sector, each covering a specific subject that falls within three general aspects: production, storage and use of energy, correspondingly the three parts of the book.

*Part I Sustainable Energy Production* covers the main developments of nanotechnology in clean energy production and conversion. Following a general overview on the contributions of nanomaterials in selected specific areas of energy production, such as photovoltaics, hydrogen production, fuel cells and thermoelectricity, the remaining individual chapters within this part take these topics, i.e. dye-sensitized photoelectrochemical devices, nanostructured thermoelectric materials, nano-sized electrodes and electrolytes for fuel cells, and nanomaterials-based photoelectrochemical water splitting, into in-depth discussions.

*Part II Efficient Energy Storage* is concerned with the potential use of nanomaterials in more efficient energy storage systems. Batteries, superconductors, hydrogen storage for fuel cell applications are the main foci, which exemplify the three main families of energy storage systems in which "going-nano" is found to be especially beneficial. Firstly, hydrogen storage by physical and chemical adsorption is reviewed with an emphasis on how the use of nanomaterials helps improve its performance. Then the subsequent two chapters, with different focal points, discuss the impacts of nanostructuring on the performance of batteries and

supercapacitors. The final chapter in this part describes the use of extrinsic nano-sized defects to produce advanced superconducting materials with minimal dissipation.

The last part of the book, *Part III Energy Sustainability* discusses how nanotechnology helps to use energy more efficiently, and mitigate its impact to the environment. While energy-efficient, or “green,” nanofabrication of the nanomaterials themselves constitutes an important component of energy sustainability, nanocatalysis in petroleum refining and biofuel production also contribute significantly to the conservation of energy. Carbon dioxide capture by nanoporous materials is another area where nanotechnology may offer breakthrough opportunity. Nanostructured light-emitting diodes (LED) and organic LEDs (OLEDs) provide higher efficiency in energy conversion from electricity to light. Lastly, electrochromic materials with nanostructures and their use in energy-efficient buildings are discussed.

This book is intended to provide a balanced treatment of the various topics of nanotechnologies in the energy and related areas with both general overviews and in-detail discussions to suit for a broader audience. I sincerely hope it will attract your attention to nanotechnology and its applications in energy related areas.

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**Part One**  
**Sustainable Energy Production**



# 1

## Nanotechnology for Energy Production

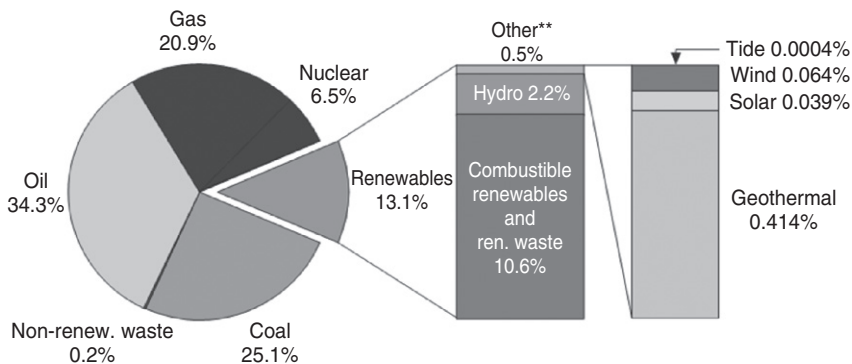
*Elena Serrano, Kunhao Li, Guillermo Rus, and Javier García-Martínez*

### 1.1

#### Energy Challenges in the Twenty-first Century and Nanotechnology

One of the greatest challenges for mankind in the twenty-first century is its over-reliance on the diminishing fossil fuels (coal, oil, natural gas) as primary energy sources (Figure 1.1). Fossil fuels are nonrenewable resources that take millions of years to form. Consequently their reserves are depleted much faster than new ones are formed and/or discovered. While concerns over fossil fuel supplies are often the direct or indirect causes of regional and global conflicts, the production, transmission and use of fossil fuels also lead to environmental degradation. Combustion of carbon-based fossil fuels generates not only air pollutants, for example, sulfur oxides and heavy metals, but also CO<sub>2</sub>, the infamous greenhouse gas widely believed to be the culprit of global climate change. One of the solutions to this energy challenge, on the one hand, relies upon increasing the efficiency in production, transmission and utilization of the remaining fossil fuels while reducing their negative impacts on the environment. On the other hand, technologies and infrastructures have to be developed or improved in preparation for the smooth transition to the alternative and renewable energy sources, that is, nuclear power, solar energy, wind power, geothermal energy, biomass and biofuels, hydropower and so on.

Technological advancement, as shown by history, will play a pivotal role in this path to a more sustainable energy future. As defined by the International Energy Agency (IEA) [1], there are three generations of renewable energy technologies. The first generation technologies (including hydropower, biomass combustion, geothermal power and heat) emerged from the industrial revolution at the end of the nineteenth century. The second generation technologies include solar heating and cooling, wind power, bioenergy and solar photovoltaics. These technologies are now entering markets as a result of continuous investments in their research and development since the 1980s, which were largely driven by energy security concerns linked to the oil crisis in the 1970s. The third generation technologies currently under development include advanced biomass gasification, biorefinery technologies, concentrating solar thermal power, geothermal power, ocean tide and wave energy and so on.



**Figure 1.1** Fuel shares of world total primary energy supply. Reprinted with permission from [1].

The rapid evolution of nanoscience and nanotechnology (the study and control of materials and phenomena at length scales between 1 and 100nm) during the past two decades has demonstrated that nanotechnology holds the keys to many of the technological advancements in the energy sector, which relies, at least in part, on having novel materials with superior properties. According to the “Roadmap Report Concerning the Use of Nanomaterials in the Energy Sector” from the Sixth Framework Program [2], the most promising application fields of nanotechnology or nanomaterials for the energy production domain will be in photovoltaics, hydrogen conversion (hydrogen production, fuel cells) and thermo-electricity (see Table 1.1 for the timeframe of possible industrial applications of a few exemplary nanomaterials).

This book intends to present a comprehensive overview of the up-to-date progress in various important fields of nanotechnology research and development that are closely related to sustainable energy production, storage and usage. This chapter, in particular, mainly serves as an “overview” of the book, with an emphasis on sustainable energy production.

Nanotechnology intervenes at a number of stages in the energy flow that starts from the primary energy sources and finishes at the end user. The growing and diffuse limits of what can be considered as energy and the complex flows of energy in society and ecosystem make it impossible to draw an unequivocal definition of energy production. Herein, the term “energy production” encompasses all processes that convert energy from primary energy sources to secondary energy sources or forms. Energy production processes that are associated with nonrenewable energy sources, that is, fossil fuels (and nuclear power), and a few renewable sources, that is, ocean wave energy, wind energy and hydropower, will not be covered. However, we have included a chapter on the contributions of nanocatalysis in fuel production because of many recent advances in a more efficient production and transformation of various fuels thanks to catalysis with novel nanomaterials.