

# Photochemical Conversion and Storage of Solar Energy

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Rising prices and sporadic shortages of fossil fuels in the 1970's provided the impetus for the present worldwide effort to develop alternative sources of energy. The exploitation of solar energy as an especially attractive option, since this resource is abundant, non-pollutantly drawn, and exchange provided by the difference in flow power per unit area<sup>1</sup> and international availability of solar radiation,<sup>2</sup> however, some method of storage must be provided in order that energy can be stored when it is plentiful for use when other times when demand exceeds supply.

Nature furnished a photochemical solution to the problem of energy storage with the process of photosynthesis in green plants. Through its complex series of steps, carbon dioxide and water are converted photochemically to oxygen and a combustible carbohydrate. The challenges facing the photochemist to be devise an artificial (e.g., non-molecular) cycle which accomplishes the same task, namely, the production of a storable fuel from readily available and inexpensive raw materials (3-11).



Figure 1. Scheme for conversion and storage of solar energy.

The essential components of such a cycle are outlined in Figure 1. Sunshine drives a photochemical reaction in which a portion of the incident photon energy is converted to and stored as the increased free energy of the photo-product(s). The reactant(s) need not be converted directly by the light absorption process if a photocatalyst is present. Restoration of the system to its original state occurs with the release of the stored energy in the form of either heat or electricity. Ideally, the reverse step is exothermic since at ambient temperature and pressure rapidly upon heating or the addition of a catalyst. This feature ensures that energy can be stored for extended periods and will be released only when desired.

In the present article I consider the use of inorganic photochemical reactions for the conversion and storage of solar energy.<sup>1</sup> The primary emphasis is on reactions occurring in homogeneous solution.<sup>2</sup> Rather than attempting to catalog all of the systems examined to date, I will focus upon the principles and general strategies that have emerged from this work. I begin with a brief description of the important characteristics of the sun as a radiation source and then summarize the practical criteria for a photochemical energy storage cycle. This is followed by an overview of the thermodynamic and kinetic limitations associated with the conversion of radiant energy into chemical storage. Several examples of energy-

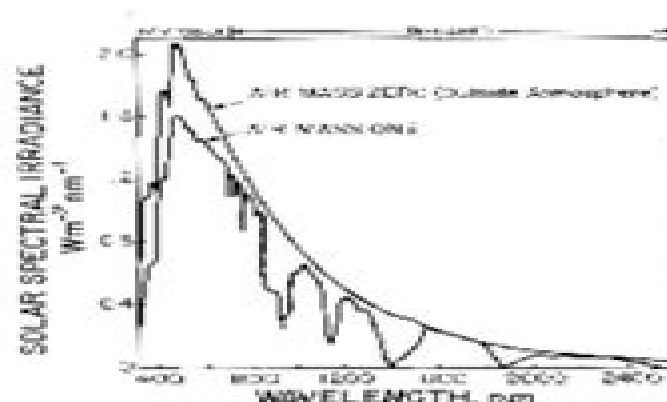


Figure 2. Solar spectral distribution outside the Earth's atmosphere for various values of air mass, as in the IAU standard cycle (ref. 1).

storage photochemical reactions are then presented. The final section summarizes comments concerning the progress and prospects in this frontier area.

## Characteristics of Solar Radiation

The sun is a sphere of intensely hot gaseous matter lying at an average distance of  $1.5 \times 10^8$  km from the Earth. Its temperature varies from approximately 6000°K at the surface to  $>10^8$ °K in the interior regions. These extremely high temperatures result from a series of nuclear reactions, the end result of which is the fusion of four protons to form an alpha particle (helium nucleus). This process liberates energy which ultimately is radiated into space (1).

Scientists approximate the Earth with the spectral distribution shown in Figure 2. This spectrum is modified in the atmosphere by scattering and absorption processes, the importance of which depends upon the pathlength of the light beam through the atmosphere, and  $\lambda$ . A standard specific pathlength in terms of the air mass,  $AM$ , is defined by the relation  $AM = 1/\sin \theta$ , where  $\theta$  denotes the angle between the incident beam and the Earth's surface (considered to be a plane).<sup>3</sup> As seen in Figure 3, the shortest path through the atmosphere occurs when the sun is directly overhead at the position,  $\theta = 0^\circ$ , and  $AM = 1$ . For  $\theta = 30^\circ$ ,  $AM = 2$  and the pathlength doubles.

The spectral distribution of solar radiation when  $AM = 1$  is shown in Figure 4 which is shown in Figure 2. Inasmuch as we are interested in practical applications of solar energy, only those photons having wavelengths in the range 200-2500 nm need be considered. The short wavelength cutoff results from absorption by  $O_3$ ,  $N_2$ ,  $O_2$ ,  $N_2$ , and  $O_2$ , while absorption by water vapor and carbon dioxide is vital when the long wave earth limit. About half of the solar spectrum lies in the ultraviolet and visible regions, while the remaining half falls in the infrared. The energy equivalent of an average mole of photon

<sup>1</sup> Discussions of photochemical energy storage in primarily organic systems can be found in references 1-35.

<sup>2</sup> The article by Whiggson in this issue provides a thorough discussion of heterogeneous photochemical processes.

<sup>3</sup> Because of the curvature of the earth's surface, this expression is less satisfactory at very small angles of  $\theta$ .

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## **Photochemical Conversion And Storage Of Solar Energy 198:**

*Solar Thermal Energy Storage* H.P. Garg, S.C. Mullick, Vijay K. Bhargava, 2012-12-06 Energy Storage not only plays an important role in conserving the energy but also improves the performance and reliability of a wide range of energy systems Energy storage leads to saving of premium fuels and makes the system more cost effective by reducing the wastage of energy In most systems there is a mismatch between the energy supply and energy demand The energy storage can even out this imbalance and thereby help in savings of capital costs Energy storage is all the more important where the energy source is intermittent such as Solar Energy The use of intermittent energy sources is likely to grow If more and more solar energy is to be used for domestic and industrial applications then energy storage is very crucial If no storage is used in solar energy systems then the major part of the energy demand will be met by the back up or auxiliary energy and therefore the so called annual solar load fraction will be very low In case of solar energy both short term and long term energy storage systems can be used which can adjust the phase difference between solar energy supply and energy demand and can match seasonal demands to the solar availability respectively Thermal energy storage can lead to capital cost savings fuel savings and fuel substitution in many application areas Developing an optimum thermal storage system is as important an area of research as developing an alternative source of energy

**Carbon Nanotubes and Related Structures** Dirk M. Guldi, Nazario Martín, 2010-01-26 Written by the most prominent experts and pioneers in the field this ready reference combines fundamental research recent breakthroughs and real life applications in one well organized treatise As such both newcomers and established researchers will find here a wide range of current methods for producing and characterizing carbon nanotubes using imaging as well as spectroscopic techniques One major part of this thorough overview is devoted to the controlled chemical functionalization of carbon nanotubes covering intriguing applications in photovoltaics organic electronics and materials design The latest research on novel carbon derived structures such as graphene nanoribbons and carbon nanotubes round off the book

**Energy for the Year 2000** Richard Wilson, 2012-12-06 The Third International School on Energetics was devoted to the subject of Energy for the Year 2000 By this title we hoped to avoid discussion of such matters as the role of OPEC in raising oil prices In one sense therefore our task was made easier we could merely look into our crystal balls The choice of lecturers was made with the idea that no reasonable source of energy can be overlooked We omitted detailed lectures on oil and natural gas because we took it as a given fact that we would continue to use as much of these fuels as we can get at a reasonable price To give us an overview we started the School by discussing U S energy policy and possible U S energy scenarios As might be expected there was some disagreement about the current energy program in the U S but little disagreement about the facts presented

**Solar Energy Update**, 1984 [Energy Research Abstracts](#), 1979

*Photochemistry* Derek Bryce-Smith, 1979 **Nanomaterials for CO<sub>2</sub> Capture, Storage, Conversion and Utilization** Phuong Nguyen Tri, Haobin Wu, Simon Barnabe, Pierre Benard, Tuan Anh Nguyen, 2021-04-10 The gradual

increase of population and the consequential rise in the energy demands in recent years have led to the widespread use of fossil fuels. CO<sub>2</sub> transformation by various processes is considered as a promising alternative technology. This book sets out the fundamentals of how nanomaterials are being used for this purpose. *Nanomaterials for CO<sub>2</sub> Capture, Storage, Conversion and Utilization* summarizes the research development and innovations in the capture, storage, transformation and utilization of CO<sub>2</sub> into useful products and raw chemicals for industry. This is achieved by using advanced processes such as CO<sub>2</sub> reforming, bi-reforming and tri-reforming of hydrocarbons or biomass derivatives, homogeneous and heterogeneous hydrogenation, photochemical reduction, photoelectrochemical reduction, electrochemical reduction, biochemical reduction, supercritical CO<sub>2</sub> technology, advanced catalyst synthesis for CO<sub>2</sub> conversion, organic carbonates for polymers synthesis from CO<sub>2</sub> and CO<sub>2</sub> capture and sequestration. The systematic and updated reviews on the mentioned sectors, especially on the use of nanotechnology for the transformation of CO<sub>2</sub>, is scarce in the literature. Thus, the book addresses the recent knowledge gaps and potential solutions of the storage, utilization and transformation of CO<sub>2</sub>, as well as its promising applications. This is an important reference source for materials scientists, engineers and energy scientists who want to understand how nanotechnology is helping us to solve some of the world's major energy problems. Shows how nanomaterials are being used to create more efficient CO<sub>2</sub> capture, storage and conversion systems. Outlines the major nanomaterials-based techniques to create such systems. Assesses the major challenges in using nanomaterials for energy capture, storage and conversion.

*Nanostructured and Photoelectrochemical Systems for Solar Photon Conversion* Mary D. Archer, Arthur J. Nozik, 2008. In this book, expert authors describe advanced solar photon conversion approaches that promise highly efficient photovoltaic and photoelectrochemical cells with sophisticated architectures on the one hand and plastic photovoltaic coatings that are inexpensive enough to be disposable on the other. Their leitmotifs include light-induced exciton generation, junction architectures that lead to efficient exciton dissociation and charge collection by percolation through mesoscale phases. Photocatalysis is closely related to photoelectrochemistry and the fundamentals of both disciplines are covered in this volume.

Photochemistry D. Bryce-Smith, 2007-10-31. The breadth of scientific and technological interests in the general topic of photochemistry is truly enormous and includes, for example, such diverse areas as microelectronics, atmospheric chemistry, organic synthesis, non-conventional photoimaging, photosynthesis, solar energy conversion, polymer technologies and spectroscopy. This Specialist Periodical Report on Photochemistry aims to provide an annual review of photo-induced processes that have relevance to the above wide-ranging academic and commercial disciplines and interests in chemistry, physics, biology and technology. In order to provide easy access to this vast and varied literature, each volume of *Photochemistry* comprises sections concerned with photophysical processes in condensed phases, organic aspects which are subdivided by chromophore type, polymer photochemistry and photochemical aspects of solar energy conversion. Volume 34 covers literature published from July 2001 to June 2002. Specialist Periodical Reports provide systematic and detailed review

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**CRC Handbook of Organic Photochemistry and Photobiology, Volumes 1 & 2** William M.

Horspool, Francesco Lenzi, 2003-09-29 The second edition of this best selling handbook is bigger more comprehensive and now completely current In addition to thorough updates to the discussions featured in the first edition this edition includes 66 new chapters that reflect recent developments new applications and emerging areas of interest Within the handbook's 145 critically reviewed articles

**Polymeric Materials Encyclopedia, Twelve Volume Set** Joseph C. Salamone, 2020-07-17 The Polymeric Materials Encyclopedia presents state of the art research and development on the synthesis properties and applications of polymeric materials This groundbreaking work includes the largest number of contributors in the world for a reference publication in polymer science and examines many fields not covered in any other reference With multiple articles on many subjects the encyclopedia offers you a broad based perspective on a multitude of topics as well as detailed research information figures tables illustrations and references Updates published as new research unfolds will continue to provide you with the latest advances in polymer science and will keep the encyclopedia at the forefront of the field well into the future From novices to experienced researchers in the field anyone and everyone working in polymer science today needs this complete assessment of the state of the art The entire 12 volume set will be available in your choice of printed or CD ROM format

**Aquatic and Surface Photochemistry** George R. Helz, 2018-01-10 Aquatic and Surface Photochemistry provides a broad overview of current research in the emerging field of environmental aquatic and surface photochemistry Selected reviews and current research articles are blended to provide an in depth treatment of various aspects of this

research area The first part of the text deals with photochemistry in the environment covering recent research on the following topics aquatic photochemistry of organic pollutants and agrochemicals photochemical cycling of carbon and transition metals especially iron photochemical formation of reactive oxygen species in natural waters photoreaction in cloud and rain droplets and photoreactions on environmental surfaces soil ash metal oxide The second part provides discussions and data on both heterogeneous photocatalytic and homogeneous processes with topics ranging from applications to mechanistic studies These chapters illustrate the wide diversity of pollutant classes that are degradable by photochemical techniques and the effects of various reaction conditions on the rates and efficiency of the techniques Current kinetic studies are presented which provide new information about the role of adsorption and the nature of the reactive oxidizing species that mediate these photoremediation processes This book will interest civil chemical and environmental engineers as well as chemists soil scientists geochemists and atmospheric chemists **Energy** ,1983 *Russian Chemical Reviews* ,1998

The Science of Photobiology Kendric C. Smith,2013-03-08 The first edition of The Science of Photobiology was published in 1977 and was the first textbook to cover all of the major areas of photobiology The science of photobiology is currently divided into 14 subspecialty areas by the American Society for Photobiology In this edition however the topics of phototechnology and spectroscopy have been combined in a new chapter entitled Photophysics The other subspecialty areas remain the same i e Photochemistry Photosensitization UV Radiation Effects Environmental Photobiology Photomedicine Circadian Rhythms Extraretinal Photoreception Vision Photomorphogenesis Photomovement Photosynthesis and Bioluminescence This book has been written as a textbook to introduce the science of photobiology to advanced undergraduate and graduate students The chapters are written to provide a broad overview of each topic They are designed to contain the amount of information that might be presented in a one to two hour general lecture The references are not meant to be exhaustive but key references are included to give students an entry into the literature Frequently a more recent reference that reviews the literature will be cited rather than the first paper by the author making the original discovery The chapters are not meant to be a repository of facts for research workers in the field but rather are concerned with demonstrating the importance of each specialty area of photobiology and documenting its relevance to current and or future problems of man *Index of Conference Proceedings* British Library. Document Supply Centre,2000 *Fullerenes* ,2005

*Organic, Physical, and Materials Photochemistry* V. Ramamurthy,Kirk S. Schanze,2000-08-22 This text examines organic physical and materials photochemistry It reports the first example of a TiO<sub>2</sub> sensitization with a fullerene based donor acceptor dyad and covers halophenols diflusalin photochemistry hydroxystyrenes acetylenes and other related compounds The volume also investigates whether  $\alpha,\beta$ -alkenes influence the efficiency and **Energy: a Continuing Bibliography with Indexes** ,1979

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