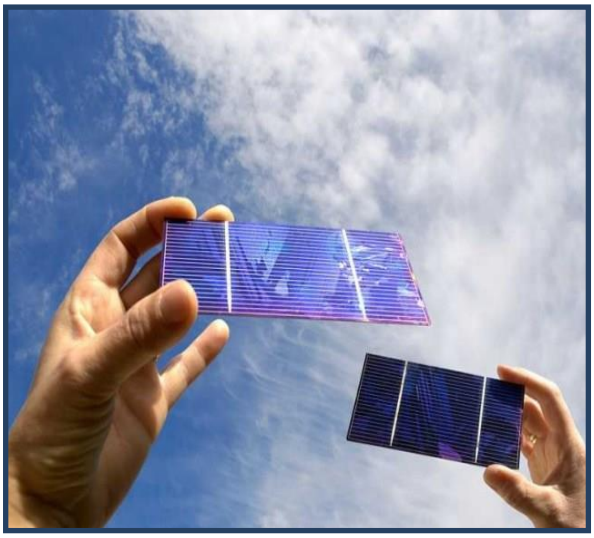
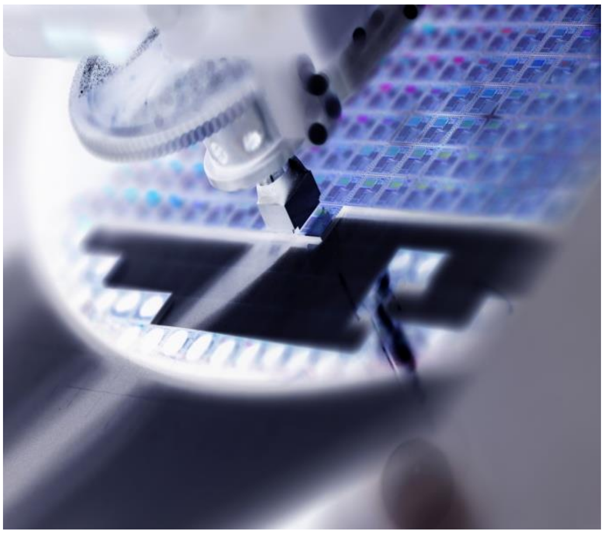
Application of Nanotechnology in Solar Energy





Prepared by

TERI ENVIS Resource Partner on Renewable Energy and Climate Change

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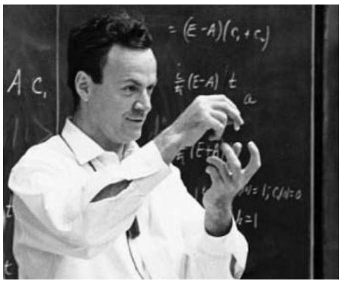
Nanotechnology means material on an atomic and molecular scale <100 nm which affects materials' mechanical and electrical characteristics. In general, nanotechnology comes with a change in the material's behavior, for instance quantum mechanical behavior, enhanced surface, or self-healing mechanisms.

Nanoscience and nanotechnology are the study and application of extremely small things and can be used across all the other science fields, such as chemistry, biology, physics, materials science, and engineering.

History of Nanotechnology



The ideas and concepts behind nanoscience and nanotechnology started with a talk entitled "There's Plenty of Room at the Bottom" by physicist Richard Feynman at the California Institute of Technology (CalTech) on December 29, 1959. In his talk, Feynman described a process in which scientists would be able to manipulate and control individual atoms and molecules. Over a decade later, in his explorations of ultraprecision machining, Professor Norio Taniguchi coined the term nanotechnology. It wasn't until 1981, with the development of the scanning tunnelling microscope that could "see" individual atoms that modern nanotechnology began.

Nanotechnology application in renewable energy

Nanotechnologies have potential to improve development of both conventional and renewable energy sources like geothermal energy, sun, wind, water, tides or biomass. It has a high impact on the energy sector with special reference to the influence of nanotechnology on the energy sectors solar energy and energy storage. Nanotechnology innovations could impact each part of the value-added chain in the energy sector. The expectations of nanotechnologies related to energy storage and the application of solar energy concern improvements in power and efficiency and the reduction of costs. The most relevant examples are low-cost manufacturing of solar cells, improvements in battery storage density, increased storage capacity, higher performance (e.g. in terms of lifetime, power), and enhanced efficiency in solar power generation(1).

For example in the renewable the energy sector, nanotechnology based micro- and nano-structured surfaces of solar cells are expected to increase efficiency of known solar cells, reduce costs due to less material needed, and hence contribute to a sustainable environment and operations. Following points shows application of nano-based cells for efficient renewable sources of power generation.

- ✓ Photovoltaics: Nano-optimized cells (polymeric, dye, quantum dot, thin film, multiple junction), antireflective coatings
- ✓ Wind Energy: Nano-composites for lighter and stronger rotor blades, wear and corrosion protection nano-coatings for bearings and power trains etc.
- ✓ Geothermal: Nano-coatings and -composites for wear resistant drilling equipment
- ✓ Biomass Energy: Yield optimization by nano-based precision farming (nano-sensors, controlled release and storage of pesticides and nutrients)

In the past years, nanotechnology based applications in solar cells development, energy storage etc. have been seen technology facelift.

Table – 1: Merits and demerits of using nanotechnology based solar cells

Merits	Demerits
• It will make solar power more economical by reducing the cost of constructing solar panels and related equipment.	• At present, solar cells are arranged in arrays and converts photons from sunlight into electricity. However, most of the time incoming photons are of low band energy, and can't be used for energy absorption for electricity, rather wasted in heat form.
• Cheap solar use for lighting, medical devices and cooking	• High manufacturing cost low in efficiency.
• Reduce manufacturing cost (from $3 per watt to 30 cents)	
• Capable of supplying low power devices	
• Preserve the environment by reducing fossil fuel use	
• The development of more effective energy-producing, energy-absorbing, and energy storage products in smaller and more efficient devices is possible with this technology, items like batteries, fuel cells, and solar cells can be built smaller but can be made to be more effective with this technology.	

Chapter 2: Application of Nanotechnology in Solar Energy

Photovoltaic technology has been categorized into three distinct generations, which mark step shifts in the materials and manufacturing techniques used to make the cells.

- The first generation of solar cells uses very high quality crystalline silicon. These are expensive to manufacture, and have a fairly low theoretical efficiency limit of around 33%.
- Second generation solar PV cells use thin film technologies with other semiconducting materials such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). These materials can significantly reduce processing costs, and promise much higher theoretical efficiencies than silicon-based PV materials.
- Third generation solar PV is a much broader group of technologies, all of which are emerging or in the development phases. Technologies often considered part of this third generation include quantum dots, nanostructured semiconductors, and amorphous silicon.

2.1 Rationale of nanotechnology use in solar energy

As far as the application of Nanotechnology in solar energy is concerned, it can be used to design and manufacture second generation, thin film PV cells, nano-elctrodes, nano-composites, nano-fluids, etc. However, nanomaterials will truly come into their own in the third generation of solar cell technologies, where novel technologies like nanowires, quantum dots and radial junctions will begin to push the upper limits of PV efficiency. Implications of application of nanotechnology in solar energy sector are as follows:

Inexpensive solar cells, which would utilize nanotechnology, would help preserve the environment.

Coating existing roofing materials with plastic photovoltaic cells which are inexpensive enough to cover a home's entire roof with solar cells, then enough energy could be captured to power almost the entire house. If many houses did this then the dependence on the electric grid (fossil fuels) would decrease and help to reduce pollution.

Inexpensive solar cells would also help provide electricity for rural areas or third world countries. Since the electricity demand in these areas is not high, and the areas are so distantly spaced out, it is not practical to connect them to an electrical grid. However, this is an ideal situation for solar energy.

Cheap solar cell could be used for lighting, hot water, medical devices, and even cooking. It would greatly improve the standard of living for millions, possibly even billions of people.

Flexible, roller-processed solar cells have the potential to turn the sun's power into a clean, green, convenient source of energy Even though the efficiency of Plastic photovoltaic solar cell is not very great, but covering cars with Plastic photovoltaic solar cells or making solar cell windows can generate the power and save the fuels and also help to reduce the emission of carbon gases.

Nanotechnology in solar cells would also have military implications. For instance, a regular field soldier carries 1.5 pounds of batteries now. A special operation has a longer time out, has to carry 140 pounds of weight. If nanotechnology could be used in cells to create inexpensive and reasonably efficient solar equipment, it would greatly improve soldiers' mobility.

2.2 Efficiency of thin-film solar cell

A thin-film solar cell is a second generation solar cell that is made by depositing one or more thin layers, or thin film (TF) of photovoltaic material on a substrate, such as glass, plastic or metal. Thin-film solar cells are commercially used in several technologies, including cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous thin-film silicon (a-Si, TF-Si). Thin films offer more absorption of photons, the benefits of thin film solar cell over solar cell is given below:

- ✓ Conventional solar cells convert only bluish light of sunlight not the red light.
- ✓ Solar cells coated with thin films of 1 nm are most efficient.
- ✓ Thin films boost absorption performance over 60%.
- ✓ Nanotechnology use quantum dots to enhance efficiency of solar cells. In conventional solar cells, one photon generates one electrons; however, in quantum dots possibility of generating multiple electrons in solar cells. Use of quantum dots helps more numbers of electrons to flow through the conduction band, generating more efficiency in solar cells. Moreover, single wall nanotubes are found to be more efficient than the nanoparticles alone.

Table – 2: Comparison of different Photovoltaic Cell

Sub-types	Monocrystalline	Polycrystalline	CdTe	CIGS
	Purity 99.99999%	Purity 99.99999%	low temperature sensitivity	captures large spectrum
Description	Crystalline silicon wafers		Semiconductor is deposited directly on glass	
Module Efficiency	High		Low	
Performance under heat	Performance degrades with higher temperatures		Up to 60% lower heat coefficient than crystalline silicon modules, making it a good choice in hot climates.	
Space required per kWp	Polycrystalline: 10m² - 30m² depending on cell spacing Mono crystalline : > 8m²		Glass-glass laminate ~ 25m²	
Amount of photovoltaic material needed	Poly silicon: 8g/W		CdTe : 0.22g/W	
Efficiency (production)	15-20%	13-15%	10%	12%

2.3 Nano-electrodes

Apart from the thin film, nanotechnology is also used in several other components and products which are in use today, the details are as follows:

- ✓ Metal oxide nanoparticles for transparent electrodes (other than ITO, e.g. based on ZnO, MoO3, SnO2): Metal oxide nanoparticles for transparent electrodes are already in use today (different metal oxides in different solar cell types). They are expected to substitute for ITO in the medium to long term.
- ✓ Nanoparticles for recombination layers (metal oxides): Nanoparticles for recombination layers are already used today and expected to firm up their use in solar cells in 2015
- ✓ CNT for transparent electrodes in PV cells (ITO replacement): In addition to other organic or inorganic transparent conductors, carbon nanotubes are seen as the future successors to transparent films for PV cells.
- ✓ Graphene for transparent electrodes in PV cells (ITO replacement): Graphene is considered a good replacement for ITO films acting as electrodes, due to its characteristics including low

sheet resistance, high optical transparency and excellent mechanical properties. The application of graphene in PV cells is not expected before 2020.

2.4 Nano-carbon materials

- ✓ Fullerenes (C60, C70) for OPV: Fullerenes are already extensively used as electron acceptors in OPV (III Generation). In the coming years (2013-2017), novel fullerene acceptors (including others in addition to C60) as well as other organic acceptor materials are expected to be used to reach higher efficiencies.
- ✓ Nano-carbon materials for counter electrodes in Dye-synthesized solar cell (DSSC): In the coming years (2013- 2017), nano-carbon materials (e.g. graphene, carbon nanotubes) are expected to be used to improve the counter electrodes in DSSC by replacing platinum (III Generation).

2.5 Nano-composites

- ✓ III-V semiconductor QD for intermediate band solar cells: The efficiency of PV cells can be improved radically by the use of an intermediate band between the valence band and the conduction band in the semiconductor. Through this, energy levels which don’t fi t in the band gap can still be absorbed and converted into current. These energy levels of the semiconductor may be manipulated by quantum dots after 2018 to achieve the desired characteristics.
- ✓ Gold nanoparticles as “hot spots” in PV cells: By using gold nanoparticles, the efficiency of PV cells can be increased. The estimated time of implementation is the future after 2020 in emerging photovoltaic applications (III Generation).
- ✓ Core-shell composite materials for PV (QD Solar) are materials with a core of an inorganic material and a shell of another material in order to achieve certain characteristics in the material. These materials are expected to be applied between 2013 and 2016 to emerging photovoltaic applications (III Generation).
- ✓ III-V semiconductor QDs for tandem solar cells For III-V semiconductor PV cells, the band gap may be tailored by creating quantum dots for use in tandem solar cells.

2.6 Nano-coatings

- ✓ Improved H2O and air protection coatings for organic PV: These coatings are expected to increase the protection of solar cells. Material performance inside solar cells is not expected to be improved by novel coatings.
- ✓ Improved UV-resistant coatings for increased life time: These coatings are expected to increase the protection of solar cells. Material performance inside solar cells is not expected to be improved by novel coatings.

2.7 Printed electronics

- ✓ Printed inorganic nano-particulate PV (e.g. Copper indium gallium selenide (CIGS), CuZnSnSSe): Besides organic PV, nanoparticles are also expected to play an important role in the technology of printed inorganic PV from today to 2030. Nanoparticles are already used in roll-to-roll printing of thin film CIGS (II Generation).
- ✓ Nano-Silver as ink for printed electronics: This technology refers to suspended metal nanoparticles (NP), which are already used today in printed electronics.
- ✓ Dendritic polymers for organic photovoltaics (OPV) to improve morphology are polymers consisting of repetitively branched molecules, which are expected to be used in the foreseeable future in emerging photovoltaic applications (III Generation) to improve the morphology. Similar advances are to be expected with cross-linkable polymers and block copolymers.

Chapter 3: Recent developments and commercialization of nanotechnology application in solar sector

Nanotechnology innovations are making a revolution in design and manufacturing, creating new materials and products through novel processes for commercial applications. New products based on nanotechnology with novel characteristics are continued to grow and benefit the society. Being general purpose technology, nanotechnology is expected to support all fields of the society, but some fields like medicine, energy, environmental remediation, robotics, manufacturing, commerce, and space exploration are expected to undergo explosive developments. Many business organizations are monitoring such developments to encash business opportunities of nanotechnology developments by commercializing these products successfully.

3.1 Recent developments

Nanotechnology is solar energy might be able to increase the efficiency of solar cells, but the most promising application of nanotechnology is the reduction of manufacturing cost. Chemists at the University of California, Berkeley, have discovered a way to make cheap plastic solar cells that could be painted on almost any surface. These new plastic solar cells achieve efficiencies of only 1.7 percent; however, this technology has the potential to do a lot better. These plastic solar cells utilizes nanorods to convert light into electricity, tiny nanorods are dispersed within in a polymer. The nanorods behave as wires because when they absorb light of a specific wave-length they generate electrons. These electrons flow through the nanorods until they reach the aluminum electrode where they are combined to form a current and are used as electricity.

Present available nanotechnology solar cells are not as efficient as traditional ones, however, their lower cost offsets this. In the long term nanotechnology versions should both be lower in cost and using quantum dots, should be able to reach higher efficiency levels than conventional ones. This type of cell is cheaper to manufacture than conventional ones for two main reasons.

- These plastic cells are not made from silicon, which can be very expensive.
- Manufacturing of these cells does not require expensive equipment such as clean rooms or vacuum chambers like conventional silicon based solar cells. Instead, these plastic cells can be manufactured in a beaker.

These days scientists have done a decent advancements in nanotechnology in solar energy. They have been working on increasing the efficiency and durability material that work for solar. Few examples are given below:

3.1.1 Nano-particle-based material

A team of engineer at the University of California, San Diego developed a new nanoparticle-based material for concentrating solar power plants designed to absorb and convert to heat more than 90 percent of the sunlight it captures. The new material can also withstand temperatures greater than 700 degrees Celsius and survive many years outdoors in spite of exposure to air and humidity.

- The novel nanotechnology material features a "multiscale" surface created by using particles of many sizes ranging from 10 nanometers to 10 micrometers.
- The multiscale structures can trap and absorb light which contributes to the material's high efficiency when operated at higher temperatures.

The team of researchers decided to use this material with one of the common types of Concentrating Solar Power (CSP) plant. This types of CSP systems uses more than 100,000 reflective mirrors to aim sunlight at a tower that has been spray painted with a light absorbing black paint material. The material is designed to maximize sun light absorption and minimize the loss of light that would naturally emit from the surface in the form of infrared radiation.

- The expertise of researchers was used to develop, optimize and characterize a new material for the system.
- The synthesized nanoshell material is spray-painted in the lab onto a metal substrate for thermal and mechanical testing.
- The material's ability to absorb sunlight is measured in optics laboratory using a unique set of instruments that takes spectral measurements from visible light to infrared.

Current CSP plants are shut down about once a year to chip off the degraded sunlight absorbing material and reapply a new coating, which means no power generation while a replacement coating is applied and cured. This is the reason why Department of Energy's SunShot program challenged and supported UC San Diego research teams to come up with a material with a substantially longer life cycle, in addition to the higher operating temperature for enhanced energy conversion efficiency. The UC San Diego research team is aiming for many years of usage life, a feat they believe they are close to achieving.

<https://www.nanowerk.com/nanotechnology-news/newsid=37903.php, accessed on July 17, 2019
https://www.energy.gov/sites/prod/files/styles/borealis_photo_gallery_large_respondxl/public/2017/09/f36/LCOE-bar-Chart-2030-Goals-2017--forppt.png?itok=5ObINKBq, accessed on July 17, 2019

3.1.2 Single walled carbon nano-tubes

The semiconducting single-walled carbon nanotubes (SWNTs) are potentially an attractive material with many unique structural and electrical properties. Semiconducting SWNTs bear a wide range of direct bandgaps matching the solar spectrum, and show strong photo-absorption and photo-response from ultraviolet to infrared, and exhibit high carrier mobility and reduced carrier transport scattering. In addition, like semiconductor NCs, SWNTs exhibit a strong coulomb interaction between electrons and holes, which suggests that SWNTs could also exhibit MEG. They can use the incident photon that other solar cells cannot absorb to generate more electrons. Therefore, Semiconducting SWNTs are nearly ideal materials for PV applications. The development in the research of SWNT PV solar cell is given in the following table.

Table – 3: Development in the research of SWNT PV solar cell

2008	2009	2010
The research group of Zhang at Shanghai Jiaotong University fabricated SWNT PV solar microcells • **In this cell, a directed array of monolayer SWNTs was nanowelded onto two asymmetrical metal electrodes with high and low work functions** • **This lead to a strong built-in electric field in SWNTs for efficient separation of photo generated electron–hole pairs.** • **Under solar illumination, the power conversion efficiency can reach 12.6%.**	The researchers at Cornell University fabricated photovoltaic cells with CNTs instead of the traditional silicon tube • The carbon nanotube p-n junction photodiode consist of individual SWNTs in split-gate field-effect geometry. • The results clearly confirm that multiple e-h pairs can be generated and collected in a nanotube p-n junction. • The e-h pair creation process observed can increase the power conversion efficiency and enhance photocurrent largely.	Zhang group, Shangai University • The network of SWNTs was directly assembled onto the surface of n-p junction silicon solar cells • The SWNTs network not only has high transparency, but also can significantly reduce the electrode resistance of the surface. • This lead to the improved collection efficiency of the hole and enhancement of 3.92% in energy conversion efficiency

3.1.3 Plasmonic nanostructure-based solar cells

Inspired by optoelectronics, plasmonic nanostructures have recently attracted attention for light trapping in solar cells due to their large resonant scattering cross sections.

- ✓ Metallic nanostructures supporting surface plasmons that excitations of the conduction electrons at the interface between a metal and a dielectric can also achieve light trapping.
- ✓ Metal nanoparticles deposited onto a substrate can increase the coupling of light into a substrate. By proper engineering of these metalloid-electric structures, light can be concentrated and 'folded' into a thin semiconductor layer, thereby increasing the absorption.
- ✓ Both localized surface plasmons excited in metal nanoparticles and surface plasmon polaritons (SPPs) propagating at the metal/semiconductor interface are of interest. Plasmonic structures can offer at least three ways of reducing the physical thickness of the photovoltaic absorber layers while keeping their optical thickness constant.
- ✓ Light trapping schemes are essential to capture the red and near-infrared portion of the solar spectrum. The metal island films, such as silver-, gold-, copper island layer, can couple incident light into the waveguide modes of the detector, resulting in increased absorption.

The observation and results by different team of researchers and scientists, in the development of Plasmonic nanostructure-based solar cells is as follows:

- ✓ The light trapping geometries using plasmonic metal nanostructures integrated into coupling of light.
- ✓ An enhancement of optical absorption and photocurrent in a semiconductor via the excitation of surface plasmon resonances in spherical Au nanoparticles deposited on the semiconductor surface. The surface plasmon resonance wavelength depends on the nanoparticle's size, shape, and local dielectric environment. Localized surface plasmons on metallic nanoparticles can be surprisingly efficient at coupling light into or out of a silicon waveguide.
- ✓ A team has demonstrated a factor of 8 times enhancement in the electroluminescence from a siliconon-insulator light-emitting diode at 900 nm using silver nanoparticles.
- ✓ The primary photocurrent enhancement occurs in the spectral range from 550 nm to 800 nm in the ultrathin film a-Si:H solar cell with nanostructured plasmonic back contacts.
- ✓ The surface plasmon polariton modes in Au nanoparticles deposited on the amorphous silicon film, and an 8.1% increase in short-circuit current density and an 8.3% increase in energy conversion efficiency are observed.

3.1.4 Nanostructure-based Thin-film Photovoltaic Cell

Compared with the traditional monocrystalline silicon solar cell, the important difference of Thin-film Photovoltaic Cell is that the electrode is transparent conductive film instead of conductive metal mesh. The p-type and n-type doping layer, called “dead zone” in Thin-film Silicon Photovoltaic Cell, make no contribution to the photocurrent.

- ✓ In order to increase the conversion efficiency of solar cell, the optical absorption in the doped layer should be reduced as low as possible. Therefore, in addition to reducing the doped layer as low as possible; the wide band gap material is also used as window layer to reduce the optical absorption.

Amorphous silicon solar cell has been especially popular due to its low cost; however, the low photoelectric conversion efficiency has seriously hampered their wider application. The actual conversion efficiency of amorphous silicon solar modules is only 4.8%-5.0% in industrial production. A series of methods are adopted to improve the conversion efficiency of amorphous silicon solar cell by using new wide optical band gap and low-resistivity p-type materials as window layer.

Above mentioned different types of solar cells are the advancement in the nano technology sector specifically in solar energy area. Apart from the above cells, there are two other inorganic solar cell type where nanotechnology is being utilized and regular research is going on such as Hot carrier solar cell and light trapping nanostructured silicon solar cells.

Chapter 4: Market for nanotechnology based solar energy applications

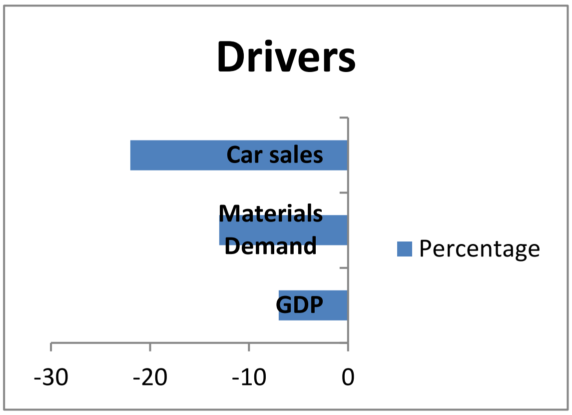
The Government is making a concerted effort to enhance the pace of innovation and scale of transformation in support of a clean energy revolution to meet the requirements and goals for India's economic and energy security in a timely manner.

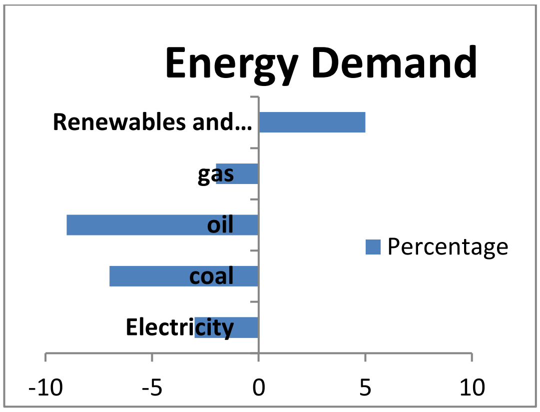
India has brought electricity connections to hundreds of millions of its citizens in urban and rural sectors; promoted the adoption of highly-efficient LED lighting by most households; and prompted a massive expansion in renewable sources of energy, led by solar power. The gains for Indian citizens and their quality of life have been tangible. However, the Covid-19 crisis has complicated efforts to resolve other pressing problems. These include a lack of reliable electricity supply for many consumers; a continued reliance on solid biomass, mainly firewood, as a cooking fuel for some 660 million people; financially ailing electricity distribution companies, and air quality that have made Indian cities among the most polluted in the world.

This will be achieved by:

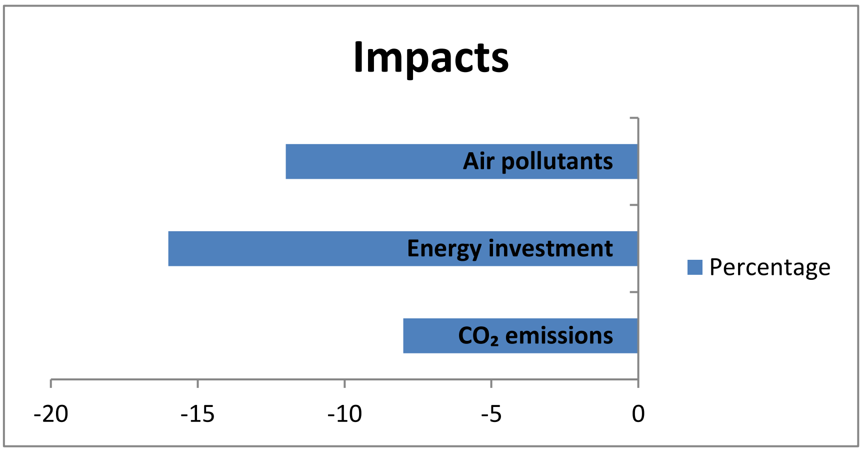
- ✓ Strengthening and scaling up research in existing programmes
- ✓ Enhancing international cooperation in priority areas
- ✓ Utilizing public-private partnerships and private sector investment
- ✓ Strengthening capacity building for specific skill requirements.

A lot has changed in India's energy sector through transition in energy mix and innovative technology adoption, while there has been progress on many fronts over these years. The extraordinary disruption caused by the Covid-19 pandemic in 2020-21 has cast a cloud over the future in terms of enhanced economic activities, business development, and job creation. To avoid the spread of the virus, the Indian government put in place a series of lockdowns starting in late March 2020, with varying levels of stringency, with the latest estimates showing a contraction in GDP of about 8% in 2020.





There was inevitably a considerable impact on energy demand. Full-year estimates see India's primary energy demand falling 5% from 2019 levels, with coal and oil expected to take the largest hit due to far-reaching restrictions on mobility, reduction in economic activity and investment. Natural gas demand has been resilient, as low prices have offset some of the forces driving down demand. Renewables have also fared relatively well, with generation from wind and solar growing by 15%.



Covid-19 has caused a significant break in India's development trajectory; a key uncertainty is the extent to which changes lead to structural shifts or temporary disruption
Source: India Energy Outlook, 2021[27]

The Government focus has changed into green energy solutions, as that would create climate resilience, transition towards net-zero carbon footprints and livelihood generation. While the pandemic is not over and its full implications are not yet visible, in the coming decade, India might see some durable, structural changes along-side temporary adjustments and breaks in trend.

The world market being influenced by nanotechnology (more concretely, by nano-enabled products) has been estimated to be in the range of 100 billion to 1000 billion US$ between 2005 and 2015 (pessimistic scenario). Market estimates for 2015 even approach 3000 billion US$ in a more optimistic scenario , being a significant percentage (about 5 %) of the world's gross domestic product (GDP) or about 15 % of the global production of goods. The forecasts differ significantly from each other, but have in common that they predict a substantial increase of the market for nanotechnology products, which took off in the early 2010s. A common feature of all forecasts is that they expect a strong increase in market size for nanotechnology products. The most conservative forecasts for specific product groups based on nanotechnology applications estimate an average annual growth rate (at current prices) of about 5 %, which is still above the average growth rate for global total manufacturing. The most optimistic forecasts assume an expansion of nanotechnology markets at annual rates of 50 % or even more.

The key drivers of the spread of solar cells in the energy market are improvements in efficiency, energy yield, stability and lifetime due to nanocomposite architectures. The environmental sustainability of the new technologies is also much improved when compared to previously used applications. Low manufacturing costs enable broad use of these technologies, since less material and cheaper material is used (avoidance of hyper-pure semiconductors). The new technologies allow efficient manufacturing processes for photovoltaic systems: the material can be applied directly onto flexible plastic foil (roll-to-roll), which decreases costs and improves manufacturing times. Thus broad use in PV and extensive market penetration is expected. For energy storage nanocomposite units provide high, long-term stability, higher energy density and mechanical flexibility. In addition, the new technologies require minimum space, adapt to shape requirements and are environmentally friendly. These improvements result in more efficient energy storage, which leads to a higher return on investment for the companies involved. Due to scale effects, mass roll-out is expected in the near future, which also includes the formation of new markets. This development is also accelerated by the global funding for nanotechnology ventures.

4.1 Nanotechnology Research, Development and Innovation in India: Major Actors

The government has played a pioneering role in promoting nanotechnology R&D in India. It has taken many initiatives to foster and promote R&D in India through several of its departments. Many schemes/programmes have been launched for infrastructure and human resource development. The government has also undertaken many bilateral/multilateral/regional initiatives with many countries to promote nanotechnology research, development and innovation (RDI). It has also encouraged PPP model to encourage nano-based product development. The main departments which have been involved in nanotechnology RDI in India are discussed below.

Department of Science and Technology (DST): DST is the nodal agency in the Indian nanotechnology innovation system. It has since 1980s launched may programmes/schemes to foster R&D on miniature-scale and on nano-scale. Some such major programmes/schemes are as follows:

1.	**Intensification of Research in High Priority Areas (IRHPAS)**	**A programme launched by the DST during the sixth Five Year Plan (1980-1985)**
2.	Science and Engineering Research Council (SERC)	Initiated a programme on nano-crystalline material.
3.	The National Programme on Smart Materials (NPSM)	A five year programme funded for Rs. 90 crore, was launched jointly by the five government departments, viz. Defence Research and Development Organisation (DRDO), Council of Scientific and Industrial Research (CSIR), Department of Space DOS, DST and Ministry of Information Technology (MIT) in the year 2000.
4.	Nano Science and Technology Initiative (NSTI)	Launched by the DST, in 2001, focused on various issues relating to infrastructure development, basic research and application oriented programmes in nanomaterial including drugs/drug delivery/gene targeting and DNA chips. It gave way to Nano Mission in 2007.
5.	The Nano Science and Technology Mission (NSTM)	An umbrella programme – was launched in the year 2007 to promote R&D in this emerging area of research in a comprehensive fashion. An allocation of Rs. 1000 crore for five years was made. The main objectives of the Nano Mission are: basic research promotion, infrastructure development for carrying out front-ranking research, development of nano technologies and their applications, human resource development and international collaborations. Through the NSTI and later Nano Mission, the DST has sponsored many nanoscience and nanotechnology projects across the country in various universities and research centres/laboratories. However, on analysing the budget of DST in the period 2001-2013, it is found that theDST has invested around Rs. 965 crore in the Nano Mission since its inception in 2007.
For nurturing the Public-Private-Partnership (PPP) activities, the DST had sanctioned a few nanotechnology projects (DST 2008).		
6.	Nano Functional Materials Technology Centre (NFMTC) at the Institute of Technology Madras, Chennai	The Centre is working on cost effective method for the production of oxide ceramic powders of nano size; consolidation and sintering of nanocrystalline oxide powders for the production of bulk ceramics; nanocrystalline diamond (NCD) films/coatings on die-inserts and plugs to increase wear-resistance and durability; cost effective production of large scale and highly pure random and aligned carbon nanotubes (CNT); and nanostructured multi-drug-delivery system for hard tissue applications and CNTs for laser based treatment of cancer by photodynamic therapy. The participating industries are Murugappa Chettiar Group and Orchid Chemicals and Pharmaceuticals.
7.	Development of high performance rubber	This project being implemented at Mahatma Gandhi University, Kottayam envisages the development of novel

	nanocomposites for tyre engineering	technologies in tyre engineering band on nanosize fillers in collaboration with Apollo Tyres.
8.	Research programme on Smart and Innovative Textiles (SMITA) at the Indian Institute of Technology, Delhi	Smart textile is an emerging area. The programme aims at fundamental understanding of generation of novel materials such as nanofibres, nanofinishes, and encapsulated phase change materials with desired characteristics; investigation of novel methods that are suitable for integrating above materials to textile substrates; fundamental understanding of the effect of the above materials and methods on functionalisation of textile structures for developing smart textile; development of technology for upscaling the above processes for industrial benefit and creating new products for high value addition in the textile sector and creating comprehensive expertise and competence within the country by man-power training and enhancement of technical knowledge base. The participating industries are Resil Chemicals, Bangalore; Purolator India Limited, Gurgaon; and Pluss Polymers Private Limited, Delhi.
9.	Support to Nanotechnology Business Incubator (NBI) at NCL	The NBI has nurtured activities by seven start-up companies on items like – computational modelling of flow and chemical processes, therapeutic potential of biotechnologically engineered antibodies, ocular and maxillofacial implants, and 12 start-up companies are under incubation presently as Resident Incubates on items like maxillo-facial surgery, organic chemical synthesis, etc., (DST 2013).

As far as the international collaborations in the field on nanoscience and nanotechnology research, development and innovation are concerned, the DST has launched bilateral joint-research projects with more than 25 countries and multilateral research projects with regional/multilateral bodies such as EU, BRICS and IBSA. The DST has been actively promoting international collaborations through bilateral joint research-projects over a period of time.

Department of Biotechnology (DBT): The DBT is basically active in the area of nano biotechnology R&D. It has been engaged in promoting interdisciplinary research, fostering innovations and promoting development of translational research in various areas of nano biotechnologies including developing new therapeutics, diagnostics for early disease detection and imaging, design and development of tissue specific drug delivery, medical devices, and fabricating sensors for detection of chemicals and pathogens in food and crop. The DBT is basically active in the area of nano biotechnology R&D. It has been engaged in promoting interdisciplinary research, fostering innovations and promoting development of translational research in various areas of nano biotechnologies including developing new therapeutics, diagnostics for early disease detection and imaging, design and development of tissue specific drug delivery, medical devices, and fabricating sensors for detection of chemicals and pathogens in food and crop. DBT promoted basic R&D in the following areas:

- ✓ Nanotechnology for food/agriculture: weed utility, nanosensor for crop protection, pesticide delivery vehicles, nanocides, smart packaging, sensors for detecting pathogens and chemicals in food and crop, etc.
- ✓ Nanotechnology for animal husbandry: biodegradable nanoparticles for drug delivery, etc.
- ✓ Nanotechnology for environment management: biosynthesis of nanoparticles, treatment of industrial effluent, waste management, etc.
- ✓ Nanotechnology for healthcare/medicine/drug delivery: Drug delivery system, disease diagnosis, cancer and TB therapy, scaffolds, medical devices, implants and

4.2 Opportunities (market perspective)

Throughout all the sectors considered where nanocomposite technologies can be applied, the current improvements result in a fast-growing market and extended usage of nanocomposite systems. For example, photovoltaic's are expected to contribute 9 % of worldwide electricity demand by 2030. Since nanocomposites are so versatile, market relevance of the technology is expected to be high for both the solar energy and energy storage sectors on a medium to long term horizon. Due to the fast growing markets, the annual growth rate of nanocomposite applications is estimated to reach 29 % in the period from 2005 to 2020. Developments to watch

The application of nanocomposite technologies is highly influenced by global developments in the energy sector. For example, the introduction of a smart grid with a high proportion of renewable energies strongly depends on efficient energy storage solutions and is therefore directly linked to the use of nanocomposite systems. At the same time, further incentive campaigns in favour of nanotechnology are expected to be introduced in several countries in the near future. While the US and Europe lead the world in market share of nanocomposites with 80 %, rapidly expanding Asian market is developing. Not only general energy market developments but also specific technology improvements will shape the future use of nanocomposites. For example, DSSC and QDSSC are constantly increasing in efficiency, and they are reported as approaching the efficiency levels required for market competitiveness. The recent improvements in nanocomposites also open new markets for these technologies, such as high-speed machining, optical applications, magnetic storage devices, smart cards and displays.

Key players- Research and development activities in nanocomposites can be found worldwide. One of the major research associations is the COST Action, merging the nanocomposite research activities of 31 countries. The table below gives a brief survey of regional research institutes that address nanocomposite technologies.

R & D	
USA	Nanocomposites COST Action, 31 countries
	Advanced Materials Research Center (AMRC), Sheffield
	Texas A&M University (Polymer Nanocomposite Lab)
	Nebraska Center for Materials and Nanoscience, University Nebraska
	California Institute of Technology
Europe	European Technology Platform, European Commission
	Helmholtz Zentrum Berlin for materials and energy (HZB): thin film solar cells via ion layer gas reaction (ILGAR-technique)
	Netherlands Organisation for Applied Research (TNO): R&D on integration of new energy systems
	Christian Doppler Laboratory for Nanocomposite Solar Cells, TU Graz
	PV- MIPS Project, 10 European countries
	Robert Bosch, Behr, Continental, Manz, BASF Suppliers for the automotive industry in Germany
Rest of World	Swiss Federal Institute for Technology (EPFL): Solar energy conversion
	Asian Institute of Technology (Thailand)
	Beijing National Laboratory for Molecular Science (China)
Others	Nanobattery “Nexelion” by Sony Corp. with tin-based nanoalloy anode commercialised in 2009 (consumer batteries, camcorder)
	Nanobattery “SCiB” by Toshiba Corp. with titanate anode and cobalt cathode developed in 2008 (consumer batteries, laptop)
	Altair Nanotechnologies Inc. with similar nanobattery to Toshiba’s, incorporated into the Lightning GT electric vehicle in 2008
	LIB-manufacturing companies: Panasonic Sanyo, ENAX, Mitsubishi Chemicals, NEC (JP), Samsung SDI, SK Innovation, LG Chem (KR), Johnson Controls (USA), Lishen, BAK, BYD (CN), Evonik Degussa, Li- Tec Battery, Varta Microbattery (GER), Leclanché (CH), Saft (FRA) (among others)

Companies that are already active in the research and development of nanotechnology have a natural head start. Innovative small and middle-sized enterprises may break this barrier, and mergers and acquisitions may occur. Joint ventures play a vital role when it comes to getting new technologies applicable for products ready for market introduction (e.g. for electric mobility, tier-one supplier and battery manufacturers). End user acceptance is key to market development and may take time to develop. The challenges lie in performance and cost, which together are very difficult to satisfy. Competition is harsh, and market concentration yet to take place. Technological challenges have to be overcome repeatedly through more investment in research and development or more expensive materials, thus increasing cost. Competitive factors are low cost, high performance, quality and reliability, and a rapid innovation cycle (time from research and development to market introduction). The competitive situation is the following:

- ✓ Power of suppliers (low),

- ✓ Power of customers (high),
- ✓ Threat of substitutes (low),
- ✓ Difficulty for new entrants (high),
- ✓ Intensity of rivalry (high).

The market relevance is expected to reach a high level, for both solar energy and storage.

Chapter 5: Case Studies

Case 1- Improving Solar Thermal Energy Generation and Conversion with Nanotechnology

In a program called Nanoparticle-Enhanced Ionic Liquids (NEILs) under the *Department of Energy* (DOE) SunShot Initiative, the Savannah River National Laboratory performed research to better understand the thermal stability of ionic liquids (ILs). The approach of this project is to determine thermal stability for both the neat ILs and the nanoparticle-enhanced ionic liquids, evaluate binary mixtures of ILs, and identify best candidates to investigate with the addition of nanoparticles. NEILs are a distinct subset of organic compounds that are fundamentally different from traditional molecular solvents and inorganic molten salts because of their low melting temperature and ionic nature. At the end of this project, Savannah River intends to have developed a fluid capable of operation at 500 °C in a parabolic trough system. This is approximately 100 °C higher than most commercially available systems.

Case 2- Development of a nanoparticle-based material for solar thermal energy applications designed to absorb and convert to heat more than 90% of the sunlight that it captures.

The University of California at San Diego, under the SunShot-supported High-Performance Nanostructured Coating program, developed a new low-cost and scalable process for fabricating spectrally selective coatings (SSCs) to be used in solar absorbers for high-temperature concentrated solar power systems. These refractory, nanoparticle-based coatings achieved an effective solar absorbance greater than 94% and an effective infrared emission lower than 7% at 750 °C. This could enable high thermal conversion efficiencies (≥ 90%) and increased temperature ranges for heat-transfer fluids (≥ 650 °C). The research being pursued under this project employs surface-protected semiconductor nanoparticles, which are fabricated by a highly scalable particle synthesis method with desired size distributions. By engineering the material properties and morphologies of the nanoparticle coating, the proposed SSCs simultaneously possess the attributes of high performance, low cost, and high-temperature durability.

Case 3- Ceramic Thermal Barrier Coating Systems for Turbine Blades

Thermal barrier coating systems consist of base material, adhesion promoting layer and thermal barrier coating (TE Due to start-up and shut-down processes as well as capacity changes of gas turbines and the related temperature gradients and transients, the thermal barrier coating system is exposed to thermo mechanical alternating stress. The base material of the blade bears the mechanical stress. The ceramic thermal barrier coating serves as thermal resistance and thus controls the heat flow into the base material. The adhesion promoting layer serves the connectio the thermal barrier coating, balances the different thermal expansion coefficients of thermal barrier coating and b material and serves as oxidation protection for the base material. In today's systems, this occurs through the format of an Al2O3-rich top layer (TGO, Thermally Grown Oxide), which develops to a third layer between thermal barr coating and metal. Here, an aluminum- rich phase in the adhesion promoting layer serves as aluminum reservoir whi helps maintain the aluminum activity in the layer matrix required for the top-layer formation over a long operation period. While the blade base material allows application of the metal adhesion promoting layer by LLPS (Low Pressure Plasma Spraying), the thermal barrier coating is applied through atmospheric plasma spraying (APS-proc or through electron beam physical vapor deposition (EB-PVD). The influence of the surface structure of the adhesion promoting layer on the lifespan of ceramic thermal barrier coatings is the subject of current surveys on crack forma up to delamination, accompanied by the development of suitable test methods and life assessment concepts. The research work is boosted by the Federal Institute for Materials Research and Testing (MPA), Darmstadt, and the Institute for Materials Technology (IfW) of the TU Darmstadt, which together, form a powerful technical-scientific ce with internationally proven capacity in materials testing and research.

Case 4- Silicon PV devices

In present days, Si PV technology is of more importance and amorphous silicon alloys are demanding for large area low-cost PV. Si is a promising candidate in photovoltaics not only for space related applications but also in terrestrial technology and they offer an energy source even in remote areas. Recently, Si PV industry is blooming to meet the energy requirements of people in both developed and developing countries . The higher conversion efficiency poses a major problem in Si PV and can be controlled by lowering the impurities, stress and defects in the Si crystals. The indirect band gap semiconductor such as silicon in the form of thick layers are applied in solar cells and inversely in the case of thin film solar cells, strongly absorbing direct band gap semiconductors can be used. The minority carrier diffusion length plays a major role in the transport properties of a semiconductor. Nowadays, Hybrid solar cells, a thin film solar cell c-Si solar cell seems to be a good material for the fabrication of high efficiency and low-cost solar cells.Si single crystals or multi crystals are commonly used in solar cells . The conventional solar cells together with the focussed solar cell system through the lens constitute the focused mirror solar cell system which is able to attain high efficiency by efficiently making use of the photons reflected from the cell. The development of the first Si p/n solar cells at Bell Labs, USA occurred in 1954 with 6% efficiency. In 1958, the Soviet satellite Sputnik 3 and the US Vanguard successfully initiated the first solar cells application where n-type Si with p type boron as dopant having efficiency of 8% was used.

Case 5- Nanocatalysts

An important nanotechnology which is already in the mature phase of the technology lifecycle is that of nanocatalysts. The following technology profile describes the characteristics of nanocatalysts as well as possible applications, technical challenges and the position in the lifecycle. In the oil and gas industry nanocatalysts are used for catalytic cracking, heavy-oil up-gradation, cleaning up oil spills, desulphurization, reformation, coal liquefaction and biodiesel/ethanol production (involving the removal of impurities such as sulphur, nitrogen and metals to reduce the emission of toxic gases; the improvement of the frictional properties and thermal stability of the oil and gas; the reduction of the octane and sulphur content in the oil to reduce pollution levels; and increasing the fluidity of heavy oil) . Concerning fuel cells, nanocatalysts are used for the manufacture of compact fuel cells with enhanced durability. They are also able to induce high energy density and advantageous oxidation resistance and redox properties . Nanoscale platinum is used as a catalyst for producing hydrogen to be used in fuel cells. In the renewable energy sector, nanocatalysts enable the conversion of liquid fuels into energy resources to fuel automobiles. They also help reduce storage degradation and induce better cold flow properties and cleaner combustion (for bioethanol, biodiesel and various other biofuels). In the chemical and polymer manufacturing sector, nanocatalysts help to increase the efficiency, selectivity and yield of certain chemical production processes, and are used in polymer solar cells and fuel cells. Polymer semiconductors, agrochemicals, industrial chemicals, cosmetics and dyes/pigments are additional examples of applications of nanocatalysts.

Case 6- Nanocatalyst converts greenhouse gas into green fuel

Researchers from the Tata Institute of Fundamental Research (TIFR) in Mumbai have synthesised ‘nanosilica’, a silica-based, reusable metal-free nanocatalyst that can convert carbon dioxide into methane, a potential green fuel. In search of an efficient and cheaper method, the TIFR scientists, collaborating with researchers from the Indian Association for the Cultivation of Science in Kolkata, prepared the metal-free silica-based nanocatalyst using a specific process that creates structural defects on its surface. They then tested the nanocatalyst’s efficiency in converting carbon dioxide into methane. The researchers, found that the defects in the catalyst acted as catalytic sites and played vital roles in producing methane from carbon dioxide. The catalyst, found can be regenerated simply by heating it in the air. After every 24-hour reaction cycle, the regenerated catalyst’s catalytic activity increased significantly. The catalytic activity saturated after eight regeneration cycles, when the methane production rate was more than double that of the initial production rate. The nanosilica remained active and stable for more than 200 hours. Such activity and stability were much better than conventional metal catalysts.

Case 7-Natural Clay Catalyst for Fuel and Value Added Products

Natural clay supported metal nanocatalysts were prepared and explored in catalytic hydrogenation of squalene into squalane (widely used in cosmetic, nutraceutical and pharmaceutical formulators), where clay/Pd catalyst were most effective at 200-300 °C and 4-10 bar H2 pressure under solvent free conditions. The catalysts are highly recyclable without any significant drop in activity. In extension to this work, non-noble metal (Ni and Co)-based clay catalysts were prepared and utilized in selective deoxygenation of algae oil and non-edible oil (such as jatropha oil) to produce diesel-grade hydrocarbons at <300 °C and <40 bar H2 pressure. Ni/clay catalyst promotes decarboxylation/decarbonylation, whereas remarkable selectivity in hydrodeoxygenation (HDO) is achieved with Co/clay catalysts. The catalysts are stable and recyclable under given reaction conditions. Metal leaching is less than 1 ppm during hydrotreatment. This process is advantageous in terms of metal-to-substrate ratio, use of solvents and their concentration, and comparable HDO selectivity over the previously reported catalysts. A hydroprocessing reaction was also performed under solvent free conditions, which could be useful in industrial applications of this approach. This innovation involves the use of natural clay as catalysis, though relatively expensive Pd metal is incorporated in the catalytic system. The ease in hydroprocessing and purification of product is profitable. A green natural clay-based catalytic system is developed for efficient and selective conversion of algae oil, non-edible oil into diesel grade hydrocarbons. The complete hydrogenation and deoxygenation could be realized solvent free conditions. The use of non-noble metals such as Ni and Co is an important feature. The selectivity toward hydrodeoxygenation further increased with low metal loadings. Such deoxygenation selectivity has not been observed previously for Ni and Co catalysts. The catalysts prepared from natural clay are considered green due to good recyclability and low metal leaching (less than 1 ppm) during the hydroprocessing reaction.

Chapter 6: Environmental Impact of Nano-based Solar Energy Applications

Nanotechnological products, processes and applications are expected to contribute significantly to environmental and climate protection by saving raw materials, energy and water as well as by reducing greenhouse gases and hazardous wastes. Using nanomaterials therefore promises certain environmental benefits and sustainability effects, which are outlined in this dossier. Note, however, that nanotechnology currently plays a rather subordinate role in environmental protection, whether it is in research or in practical applications. Environmental engineering companies themselves attach only limited importance to nanotechnology in their respective fields.

6.1 Potential Benefits

Rising prices for raw materials and energy, coupled with the increasing environmental awareness of consumers, are responsible for a flood of products on the market that promise certain advantages for environmental and climate protection. Nanomaterials exhibit special physical and chemical properties that make them interesting for novel, environmentally friendly products. Examples include the increased durability of materials against mechanical stress or weathering, helping to increase the useful life of a product; nanotechnology-based dirt- and water-resistant coatings to reduce cleaning efforts; novel insulation materials to improve the energy efficiency of buildings; adding nanoparticles to a material to reduce weight and save energy during transport.

- ✓ In the chemical industry sector, nanomaterials are applied based on their special catalytic properties in order to boost energy and resource efficiency, and nanomaterials can replace environmentally problematic chemicals in certain fields of application.
- ✓ High hopes are being placed in nano-technologically optimized products and processes for energy production and storage; these are currently in the development phase and are slated to contribute significantly to climate protection and solving our energy problems in the future.

In most commercially available “nano-consumer products“, environmental protection is not the primary goal. Neither textiles with nanosilver to combat perspiration odor, nor especially stable golf clubs with CNTs, help protect the environment. Manufacturers often promise such advantages, typically without providing the relevant evidence. Examples include self-cleaning surface coatings or textiles with spot protection, with are advertized as reducing the cleaning effort and therefore saving energy, water and cleaning agents.

6.2 Life cycle assessment

A Life Cycle Assessment (LCA) is the appropriate approach to analyze and evaluate the sustainable benefits, ecological advantages or environmental impact of a product, a process or an application. Environmental impacts encompass all the environmentally relevant factors when extracting resources from the environment as well as the emissions (e.g. wastes and CO2). The term "life cycle assessment" is also used in a comparative sense, i.e. between several products.

- ✓ LCAs focus on products and processes that are either already on the market or that are market ready.
- ✓ This enables using solid data. LCAs help analyze and evaluate potential health effects – to the extent that these can be described using impact models and that the relevant data are available.

An additional difficulty in compiling an LCA for "nano-products" is that information on a product's properties and ingredients is often lacking. Manufacturers often point to the proprietary nature of such data. Accordingly, the few LCAs conducted on products with nanomaterials fail to encompass all stages of the life cycle, hindering a comprehensive analysis and evaluation of environmental impacts and health effects.

The available LCAs indicate that the environmental impacts of a "nano-product" lie mostly in the production phase or in the nanoscale raw materials used. In a long-term operation scenario, the life cycle assessment of two solar processes to purify water, for example, showed a distinctly higher environmental impact of the photocatalytic process with nano-TiO2 as opposed to the conventional approach. This was due to the high consumption of resources in producing the nanoscale titanium dioxide.

- ✓ Several available LCAs, however, do show – for certain products – clearly reduced environmental impacts or energy and resource savings based on nanomaterial use or nanotechnological processes.
- ✓ Precious metals in nanoform in automobile catalytic converters can reduce the use of such metals by 50-95%. Nano-coated anti-reflex glass increases the efficiency of solar collectors by up to 6%; nano-paints for automobiles can be applied in thinner coats and reduce the

emissions of volatile organic compounds by 65%. Organic Light Emitting Diodes (OLED) in displays have a higher energy efficiency and require less materials than conventional displays.

- ✓ Beyond an LCA, a prospective environmental balance can be conducted in order to predict the benefits of an application or a process that is only in the development stage. Nonetheless, a range of technical problems and challenges can appear before the specific application comes on the market: the actual environmental benefits often remain open.

6.3 Present Scenario

To date, no resounding successes of nanotechnology in solving our environmental and climate-related problems have been documented: not every "nano-product" is by definition environmentally friendly or sustainable. In particular, environmental organizations emphasize that the advantages and potentials touted by industry are often exaggerated and untested; in many cases it could take years, if ever, until any such benefits are realized. In fact, the fear is that nanotechnology will further increase energy and environmental costs.

- The hightech production of nanomaterials based on carbon, such as fullerenes, carbon nanotubes and carbon nanofibers, remains very energy intensive: any potential environmental advantages – such as those through fuel savings due to lighter vehicle bodies – are currently negated.
- High energy demand plays an important role especially when mass producing a product requires large amounts of a nanomaterial. In contrast, if only very small amounts are used, for example of CNTs to produce special plastic films, then environmental benefits exist.

Thus, in order to determine such benefits, any potential energy savings in using a nanomaterial-based product must be compared with the energy consumed during its production. This must be done on a case by case basis. Further advances and improvements in production processes raise hopes that energy consumption can be reduced in the future.

The efficiency of nano-solar panels currently still lies about 10% below that of conventional silica panels. Moreover, nanotechnology has contributed little to making vehicles and airplanes lighter and thus more fuel efficient. The prerequisites for an industrial mass production have not been fulfilled, and the high demands on the material (e.g. durability, strength, safety) cannot yet be met at competitive prices.

- The contribution of nanotechnology to reducing the greenhouse gas CO2 appears to be minimal: a 2007 estimate predicted savings of about 200,000 t CO2 up to the year 2010 by reducing motor vehicle weight and emissions as well as by building insulation. This would correspond to a mere 0.00027% of global CO_2 emissions.

Based on their special properties, nanomaterials have the potential to make products or production processes more environmentally friendly. The focus lies mostly on energy and resource efficiency. Several consumer products that promise environmental advantages are already available, and certain applications have already been implemented in the industrial sector. Much is currently in the research and development stage, especially in the sectors energy and environmental technology.

The high expectations for potential environmental benefits of nano-technologically optimized products are contrasted by fears that the high consumption of energy and resources in industrial-scale nanomaterial production will negate any potential advantages. But in most cases no comprehensive life cycle analyses are available to evaluate the actual environmental effects – both the potential advantages as well as the risks – during the entire lifespan of a product.

Manufacturers are therefore called upon to provide the necessary evidence to support claims of environmental advantages or to provide the data required for analyses and evaluations. As in other cases of technological innovation, the focus in nanotechnology is primarily on the intended functions of the respective nanomaterials. Positive environmental effects are rarely the reason for using a nanomaterial, but such an influence is clearly a welcome side effect. Depending on the actual conditions, negative effects or no effects at all can occur. This calls for actively creating conditions under which positive effects can be realized.

Potential Benefits overview

Energy and environmental technology

- Various nanomaterials can improve the efficiency of photovoltaic facilities;
- Novel dye solar cells ("Grätzel cells") with nanoscale semiconductor materials are currently under development; they mimic natural photosynthesis in green plants;
- Plastics with CNTs as coatings on the rotor blades of wind turbines make these lighter and increase the energy yield;
- Nano-technologically optimized lithium-ion batteries have an improved storage capacity as well as an increased lifespan and find use in electric vehicles for example;
    - Fuel cells with nanoscale ceramic materials for energy production are under development; their production requires less energy and resources;
    - The effectiveness of catalytic converters in vehicles can be increased by applying catalytically active precious metals in the nanoscale size range,
    - Nanoporous particle filters are being developed to reduce emissions in motor vehicles.

Environmental benefits are expected especially in the following areas:

- Reduced use of raw materials through miniaturization
- By reducing the thickness of coatings and decreasing the amounts of food additives or cosmetic ingredients.
- Energy savings through weight reduction or through optimized function
- Novel lighting materials (OLED: organic light-emitting diodes) with nanoscale layers of plastic and organic pigments are being developed; their conversion rate from energy to light can apparently reach 50 % (compared with traditional light bulbs = 5%)
- Nanoscale carbon black has been added to modern automobile tires for some time now to reinforce the material and reduce rolling resistance, which leads to fuel savings of up to 10%
- Self-cleaning or "easy-to-clean"-coatings, for example on glass, can help save energy and water in facility cleaning because such surfaces are easier to clean or need not be cleaned so often;
- Nanotribological wear protection products as fuel or motor oil additives could reduce fuel consumption of vehicles and extend engine life;
- Nanoparticles as flow agents allow plastics to be melted and cast at lower temperatures;
- Nanoporous insulating materials in the construction business can help reduce the energy needed to heat and cool buildings.

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