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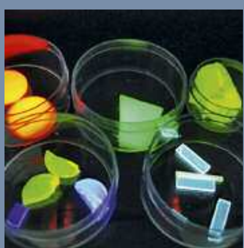
Application of Nanotechnologies in the Energy Sector



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Hessen Nanotech

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Volume 9 of the Technologielinie
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Application of Nanotechnologies in the Energy Sector

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Created by:
VDI Technologiezentrum GmbH,
Innovationsbegleitung und Innovationsberatung
VDI-Platz 1, 40468 Düsseldorf, Germany

Authors:
Dr. Wolfgang Luther, Dr. Heinz Eickenbusch, Oliver S. Kaiser, Dr. Leif Brand

Translated by:
A.C.T. Fachübersetzungen GmbH, Mönchengladbach

Editorial team:
Sebastian Hummel (Ministry of Economics, Energy, Transport and Regional Development – State of Hessen)
Dr. David Eckensberger (Hessen Trade & Invest GmbH, Hessen-Nanotech)

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Preface

The energy sector faces enormous challenges requiring innovative solutions: completing the nuclear power phase-out, substituting fossil fuels, reducing carbon dioxide emissions. All this affects the generation of energy as well as its efficient use. Gradually, fossil fuels are being replaced by new technologies – not least due to nanotechnological innovations. Here, companies and research institutions in Hessen are at the forefront.

For example, the Marburg-based NAsP III/V GmbH has developed concentrators that double the efficiency of silicon or gallium arsenide based solar cells. This enables highly efficient and miniaturised solar cells. The Hanau operation of the technology group Umicore provides nanostructured catalysts for efficient membrane fuel cells. And scientists of the RheinMain University of Applied Sciences in Rüsselsheim investigate the hydrogen storage and its detection in nanoporous powder materials – fundamental research to develop safer hydrogen storage systems for fuel cell vehicles.

Obviously, nanotechnological innovations have already found their way into the energy sector. And lots more wait to be developed. The completely revised edition of our brochure provides an up-to-date overview of success stories and development potentials. I wish you enjoyable and stimulating reading.

Tarek Al-Wazir

Tarek Al-Wazir
Minister of Economics, Energy, Transport
and Regional Development – State of Hessen

1. Energy Supply Perspectives in the 21st Century

1.1 Energy Supply and Global Energy Demand

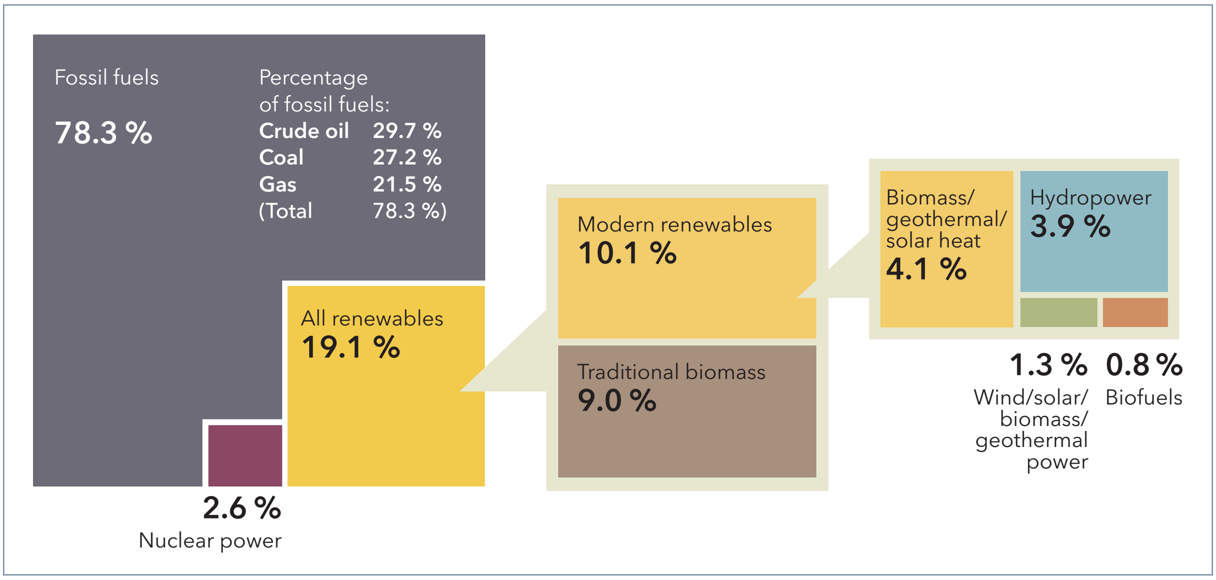
Energy drives our lives. It guarantees pleasant temperatures and ensures our living and working environments are sufficiently bright; it feeds production facilities, urban infrastructure and the army of routine electronic assistants, and allows almost unlimited mobility around the globe. Global energy demand continues to grow and, according to International Energy Agency forecasts, will increase from approximately 13 billion tonnes crude oil equivalent at the moment to probably 15 to 17 billion tonnes crude oil equivalent by 2030 (IEA 2014). The primary driver for this large increase in energy consumption, and with it the associated global carbon dioxide emissions, is the backlog demand of emerging economies such as China and India, whose energy consumption is increasingly approaching that of the industrialised nations, generally utilising fossil fuels. The largest proportion of global energy consumption is used by the industrial sector, followed by the transport sector, households and other commercial operations (services, retailing, etc.). However, there are pronounced regional differences in terms of energy consumption and developments in the individual sectors. For example, in advanced industrial nations such as Germany, energy consumption is highest in the transport sector and also displays the greatest growth rates there, while energy consumption in the industrial sector has been falling in recent years.

At a global level, however, an increase in energy consumption is forecast for all sectors, with the greatest rates of increase being anticipated in non-OECD countries such as China and India. It is obvious that in order to meet this growing energy demand in the long term a fundamental renewal of the energy sector is necessary, away from the previously dominating fossil fuels and towards the increased use of renewable energy sources. Climate change, which forces us to reduce carbon dioxide emissions, and the foreseeable scarcity of fossil fuels leave us with no other choice than to continue to drive forward the urgently required innovations in the energy sector. This not only applies to the increased development of renewable energy sources but to the entire value chain, from the production of energy carriers from primary energy sources to the conversion, storage, distribution and utilisation of energy.

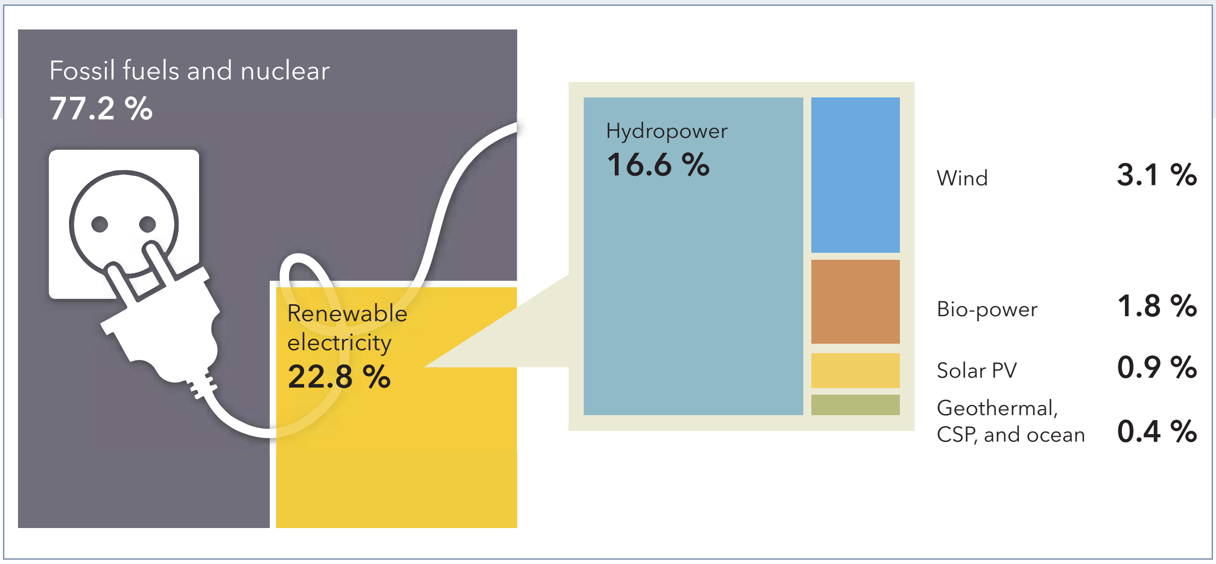
1.2 Available Primary Energy Source Potentials

The fossil fuels coal, crude oil and natural gas cover the largest proportion of today's global energy demand at around 80 percent. Current scenarios for the development of future energy demand assume that the proportion of fossil fuels in global supplies will remain at the same high level until 2035 (BP 2015). This trend can only be countered by massive global efforts and investments in the fields of renewable energy and energy-saving measures. The European Union assumes a pioneering role here and has committed to some ambitious targets, for example with a mandatory proportion of 20 percent renewable energy sources in overall EU energy consumption by 2020, a 20-percent reduction in EU-wide greenhouse gases and a 20-percent increase in energy efficiency.

The global proportion of renewable energy forms in energy consumption is currently less than 20 percent. Energy recovery from biomass contributes half of this, followed by hydropower and geothermal energy, while wind and solar energy together contribute just over one percent. In terms of the generation of electrical energy, renewable energy forms, including hydropower, produce around 22 percent globally.



Percentages of energy sources in global energy consumption in 2013. (Source: REN21 2015)



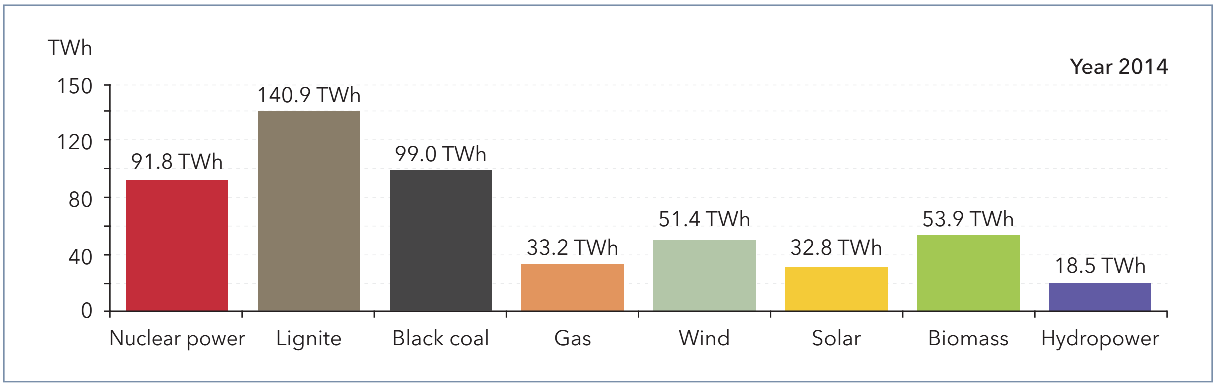
Estimated percentages of renewable energy sources in global electricity generation in 2014. (Source: REN21 2015)

Today's proven reserves of technically recoverable fossil fuels are sufficient to meet global energy demand for a few more decades. Availability estimates are greater than 50 years for crude oil and natural gas and greater than 100 years for coal (WEC 2013). These figures are constantly changing in line with developments in global consumption and advances in exploration and production technologies. With regard to crude oil, non-conventional sources such as heavy oil or oil shale, the use of which is associated with major environmental pollution, are being increasingly exploited.

1.3 Using Renewable Energy Sources

Large regional differences exist in the use of renewable energy sources. In Germany, the proportion of renewable energy sources relative to total energy consumption is currently around ten percent and thus below the global average. This is primarily due to the lesser use of biomass in the energy supply compared to less industrialised nations. However, the trend to use renewable energy sources has greatly increased in Germany in recent years, in particular in electricity supplies. Due to highly dynamic developments the wind energy sector's share of the total electricity supply in Germany is now over 14 percent (FHG ISE 2015). In photovoltaics, too, very high growth rates are achieved, so that this technology now accounts for approximately seven percent of total electricity generation.

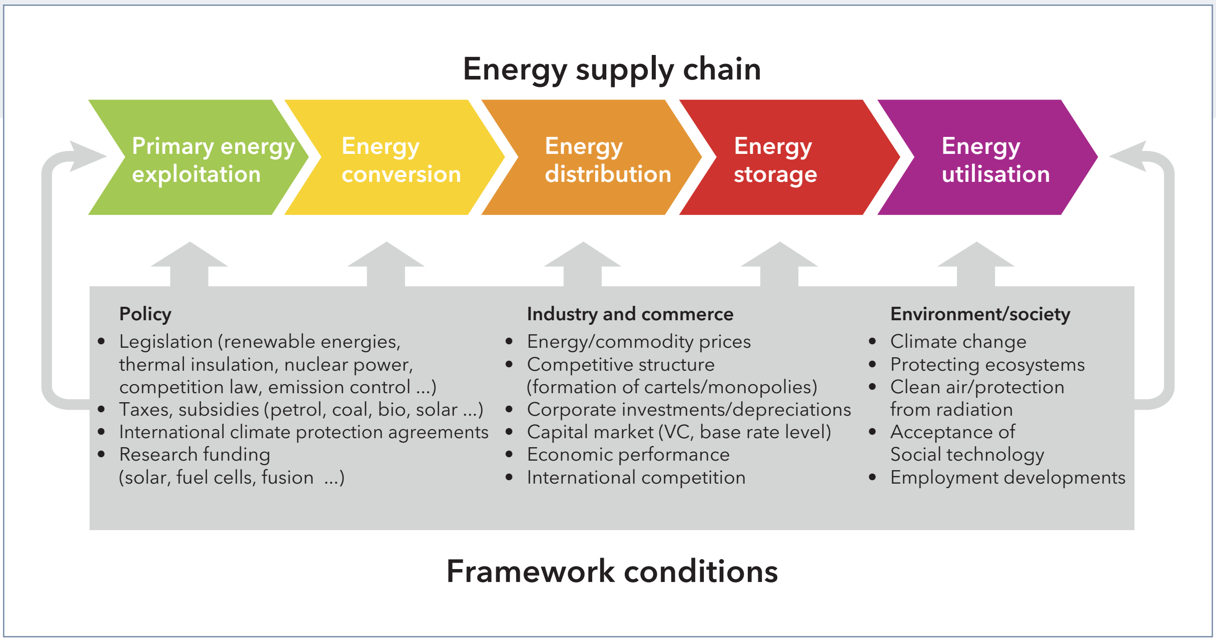
Together with electricity from biomass and hydropower, one third of electricity is produced from renewable energy sources. The aim of the Federal Government is to increase the proportion of renewable energy sources in total energy consumption to 60 percent by 2050. It is intended to increase the proportion of renewable energy sources in the electricity supply to 80 percent by 2050. Objectives such as these will only be achievable through the use of new approaches and technological breakthroughs, which will further increase the cost-effectiveness of providing renewable energy sources and contribute to developing significant efficiency potentials along the entire energy sector value chain.



Net electricity generation in the public power supply in Germany in 2014 (TWh: terawatt hours). (Source: FHG ISE 2015)

The global potential of renewable energy sources is currently barely developed. Global energy demand could be met many times over by direct utilisation of the radiation energy of the sun. Wind and tidal energy also offer considerable potentials. However, from today's perspective, the technically and economically exploitable percentage is extremely small, in particular due to the low energy density and the limited number of economically exploitable sites. For example, the energy input of the solar radiation impinging on the surface of the Earth in central Europe is limited to a maximum of approximately 1,000 watts per square metre. Other barriers to the use of renewable energy sources include the discontinuous energy input as a function of environmental influences, low energy conversion efficiencies and the cost-intensive manufacturing methods and materials.

A prerequisite for significant growth in energy supplies from renewable energy sources is the substantial reductions of costs, for example through economies of scale in the further development of renewable energy sources, the development of more cost-effective manufacturing methods and efficiency improvements through technological innovations. In the long term, there will be no alternative but to optimise the development of renewable energy source potentials. The utilisation of solar energy using solar cells and solar thermal power plants, in particular, will play a key role here. Long-term scenarios forecast that the utilisation of solar energy will cover more than 50 percent of the global energy demand by the year 2100. Whether or not additional options will be available, for example, the technically and economically achievable use of nuclear fusion, remains conjecture at the present time.



Value chain and framework conditions in the energy sector. (Source: VDI TZ)

1.4 The Energy Value Chain

In order to safeguard global energy supplies in the long term, it is not enough to merely develop the available energy source as efficiently and environmentally compatible as possible. The energy losses en route from the source to the end consumer must also be minimised, the provision and distribution of energy must be made as flexible and efficient as possible for the respective purpose, and the energy demand in industry, infrastructure and private households must be reduced.

Optimisation potentials, which can also be exploited with the use of nanotechnologies, exist in every section of the value chain. As enabling technologies, nanotechnologies generally take hold relatively early in the value chain, because they optimise components and intermediate products. However, the implementation of nanotechnological innovations not only depends on technical and economic criteria, but also heavily on the political and socio-economic environment and framework conditions, especially in the energy sector. Which technological development will ultimately prevail is therefore primarily determined by economic constraints, as well as by political and social aspects, in addition to technological feasibility.

2. Nanotechnology Innovation Potentials in the Energy Sector

2.1 Importance and Definition of Nanotechnologies

The term nanotechnologies has been established for more than two decades as a keyword in the research and innovation strategies of leading industrial nations. Around the world, nanotechnologies are viewed as key technologies for innovation and growth in modern industrial societies. By virtue of their innovative properties, from a technical perspective, nanotechnologies primarily mean nanostructured materials, the properties of which differ from the properties of individual atoms, molecules and bulk materials, and which can be used for enhanced materials, applications and systems.

The term nanotechnologies bundles a multitude of different technology and application fields, dealing with the technical utilisation of structures and material components in the nano-size range. It is therefore difficult to conclusively define nanotechnologies and to clearly distinguish them from other fields of technology. In practice, nanotechnologies are often addressed as subsectors of traditional technological disciplines such as materials engineering, electronics, optics or biotechnologies, and doubtlessly the interdisciplinary interactions have an important role to play. Nanotechnological methods are not even always entirely new but often rather developments of tried-and-tested production and analysis techniques. Nanoeffects were even sporadically used during the middle ages, for example in colouring church windows red due to finely distributed gold colloids or in hardening the Damascene steel of sword blades using carbon nanotubes, without even being conscious of the physicochemical principles. The essence of nanotechnologies is therefore the controlled use of nano-scale structures, an understanding of the laws governing them at the molecular level and targeted technological improvements in both materials and components derived from this.

In recent years, the international standardisation organisation ISO has compiled a basis for definitions and standards relating to nanotechnologies. In it, nanotechnology denotes the application of scientific insights for controlling and utilising material components in the nano size range (approximately one to 100 nanometres; one nanometre equals 10-9 metres), where special properties and phenomena relative to the size or structure may occur (ISO 2010).

However, the subject of nanotechnologies is best approached less by formal definitions than by a description of principles and research approaches, which play a considerable role in this context. There are two fundamental approaches for technical utilisation of the nanocosmos. One is the principle of construction using the elementary units of animate and inanimate nature, atoms and molecules, comparable to building with a Lego set (bottom-up approach). The aim here is to manufacture complex components and products, based on nature's model, through the self-organisation of material components and without the use of energy- and resource-intensive technical processes. In addition to these approaches, predominantly still in the realm of basic research, the nanocosmos is exploited by the miniaturisation of structures down to sizes of only a few nanometres. This top-down approach allows an increasing number of structures and functions to be implemented in as small a space as possible and thus to further increase the performance of technical components. A classic example of this approach is the five decades of advancing miniaturisation of semiconductor structures in electronics, which have now shrunk to as little as ten nanometres. Such nanotechnologies drive the development of ever smaller and more powerful electronic chips as motors for the progressing digital revolution in industry and society.

2.2 Application of Nanotechnologies in the Energy Value Chain

In power engineering, a whole range of products only made possible by nanotechnologies is already in the prototype stage or available on the market. The following products are offered, for example: nanoporous antireflection coated solar glass, nanostructured LEDs, nano-additives for engine lubricants, nanoelectrodes for lithium-ion batteries, nanocrystalline magnetic materials for power electronics and nanoporous hydrogen storage materials, as well as nanocatalysts in fuel cells and industrial chemical production processes. The success stories from Hessen given in Section 7 also demonstrate that nanotechnology is already being implemented by companies in their products. But this nowhere near exhausts the potential applications of nanotechnology in power engineering.

Chemical

- More efficient catalysts in fuel cells and for the chemical conversion of fuels facilitated by enlarged surfaces and specific catalyst designs.
- More powerful batteries, accumulators and supercapacitors facilitated by enlarged specific electrode surfaces.
- Optimised polymer electrolyte membranes with enhanced temperature and corrosion resistance for applications in fuel cells or separators in lithium-ion batteries.
- Nanoporous materials for storing hydrogen, for example metal hydrides or metal-organic compounds.
- Optimised separation efficiency of gas membranes for separating carbon dioxide from coal-fired power plants.

Mechanical

- Improved stiffness of construction materials for wind turbine rotor blades.
- Wear-resistant nanolayers for drill heads, transmissions and motor components.
- Nanostructured silicate compounds as lubricant additives for improving wear protection and lowering energy consumption in motors and transmissions.

Optical

- Optimised light absorption properties of solar cells facilitated by quantum dots and nanolayers in stacked cells.
- Antireflection properties for solar cells to increase the energy yield in photovoltaics and solar thermal applications.
- Light-emitting polymers for manufacturing more energy-efficient organic light-emitting diodes.

Electronic

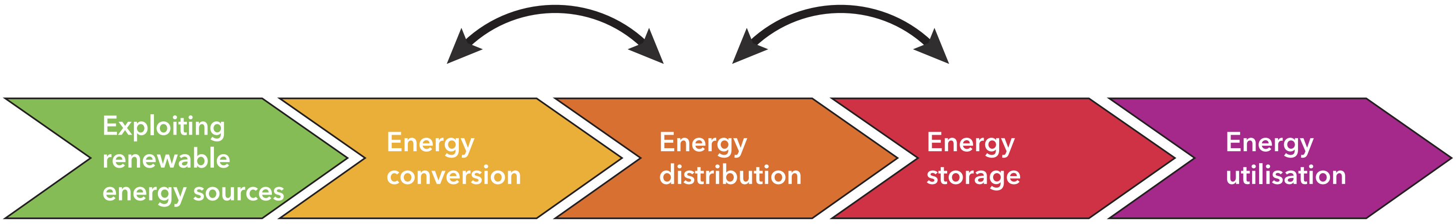
- Optimised electrical conductivity facilitated by nanostructured superconductors.
- Electrical isolators facilitated by nanostructured fillers in high-voltage line components.
- Improved thermoelectric materials facilitated by nanostructured layer systems for efficient electricity generation from heat.

Thermal

- Nanostructured thermal protection layers for turbine blades in gas and aircraft turbines.
- Improved thermal conductivity thanks to the use of nanomaterials for optimised heat exchangers.
- Optimised heat storage based on nanoporous materials (zeolites) or microencapsulated phase change storage.
- Nanofoams as superinsulating systems for industrial and building technology applications.

Examples of nanobased property changes and their potential applications in the energy sector. (Source: VDI TZ)

This is because nanotechnologies present numerous additional opportunities for innovative, intelligent material design, in which the desired material properties can be combined and specifically adapted to meet the needs of the respective technical application. Here, a broad spectrum of chemical, optical, electronic and thermal material properties that are of interest for applications in the energy sector are addressed.



Photovoltaics
Nanomaterials for solar cells (fullerenes, quantum dots, titanium dioxide nanoparticles, organic semiconductors), nanocoatings (for example, antireflection)

Solar heat
Nanocoatings for enhanced energy input (antireflection, light absorption, nanooptimised heat exchangers)

Wind energy
Nanomaterials for lighter and more stable rotor blades, wear and corrosion protection for bearings and transmissions

Geothermal energy
Nanocoatings and materials for wear resistant drill heads

Marine energy
Nanocoatings as corrosion protection, nanomaterials for wave power and reverse osmotic power plants (nanomembranes, electroactive polymers)

Biomass
Creation of biofuels from renewable resources facilitated by nanooptimised catalysts and methods

Gas turbines
Heat and corrosion protection for turbine blades (e.g., ceramic, intermetallic coatings) for more efficient power plants and propulsion units

Thermoelectrics
Nanostructured semiconductor materials (boundary layer design, nanowires) for more efficient thermoelectric electricity generation (among others, utilisation of waste heat from vehicles and bodies for mobile electronics)

Fuel cell
Nanooptimised membranes and electrodes for more efficient fuel cells (vehicle and mobile electronics applications)

Chemical transformation
Nanocatalysts for optimised production of chemical energy sources (hydrogen, biofuels, crude oil processing, coal liquefaction)

Combustion engines
Wear/corrosion protection of engine components, diesel injectors (composites, coatings, particle additives)

Electric motors
Nanocomposites for superconductors and magnetic materials

Conducting electricity
High-voltage transmission: Nanofillers for electrical insulation systems and transformers, power semiconductors for low-loss voltage conversion

Supraconducting: Optimised superconductors facilitated by nanostructuring and boundary layer design for loss-free power conductors

CNT cables: Superconducting cables based on carbon nanotubes envisaged in the long term

Cordless transmission: Power transmission by laser, microwaves, electromagnetic resonance possible in the long term with partial solutions from nanooptimised components

Intelligent power grids
Nanosensors and power electronics for controllable grids with load and fault management for heavily decentralised energy input

Heat transmission
Heat input and output facilitated by nanooptimised heat exchangers/pipes (for example based on nanocarbons) in industry and private households

Electrical energy
Batteries/rechargeable batteries: Optimised lithium ion batteries facilitated by nanostructured electrodes and flexible, ceramic separators, used in electronics, in the mid term, in automobiles or for load regulation in power grids

Supercapacitors: Nanomaterials for electrodes (carbon aerogels, graphenes, metal (oxides) and electrolytes for higher energy densities

Chemical energy
Hydrogen storage: Nanoporous materials (organometals, metal hydrides) for applications in mobile electronics, in the long term in automobiles

Fuel tanks: Gas-tight polymer nanocomposites for reducing emissions from automobile fuel tanks

Thermal energy
Phase change storage: Microencapsulated PCMs for air conditioning in buildings and more efficient solar heat energy.

Nanoporous materials (e.g. zeolites) for thermal adsorption storage units in heaters

Thermal insulation
Nanoporous foams and gels for thermal insulation in buildings (aerogels, polymer foams) or thermostatically controlling technical processes

Air conditioning
Light and heat flow control in buildings facilitated by switchable windows (electrochemistry), micromirror systems or infrared reflectors

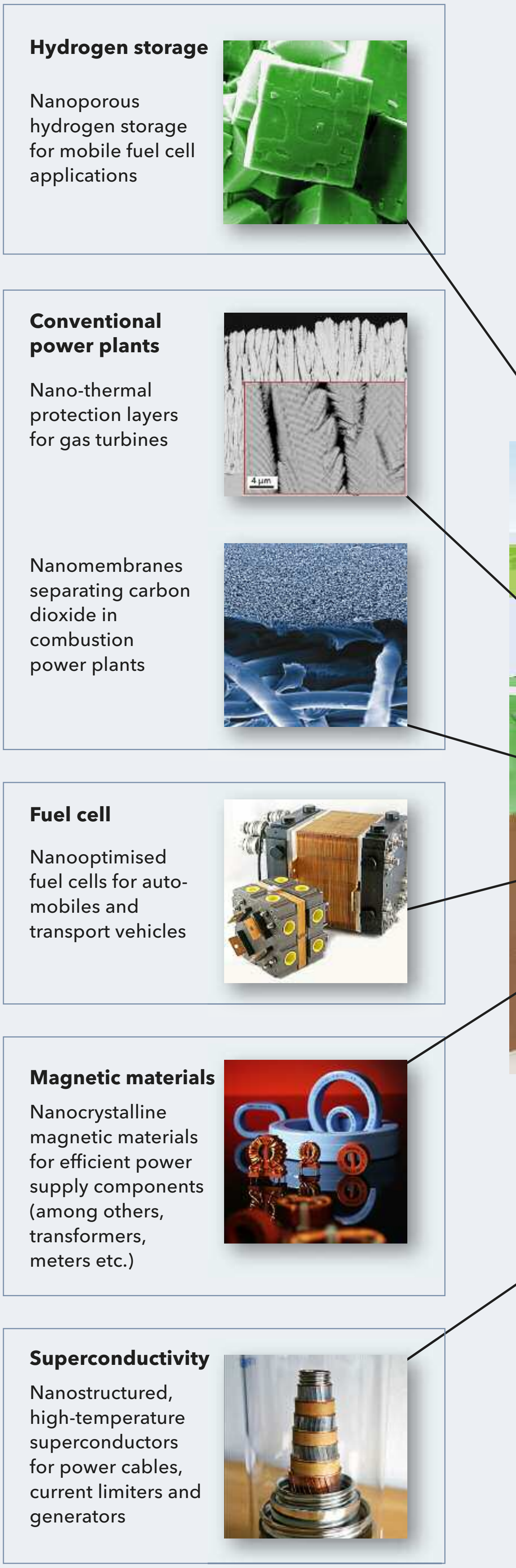
Lightweight construction
Lightweight construction materials based on nanomaterials and composites (carbon nanotubes, metal-matrix composites, nanocoated lightweight metals, polymer composites, ultra-high strength concrete)

Industrial production
Replacement of energy-intensive processes utilising nanotechnological process innovations (among others, optimised catalysts), self-organising processes

Lighting
Energy-saving lighting thanks to inorganic and organic light-emitting diodes (use of nanomaterials and nanocoatings, e.g. quantum dots)

Examples of potential nanotechnology applications along the energy sector value chain (Source: VDI TZ)

Thanks to improved materials and methods, nanotechnologies can contribute to utilising renewable energy sources in a considerably more cost-efficient way and thus help smooth the way to a broad-based economic breakthrough. Here, nanotechnological innovations play a role in all sections of the energy sector value chain, from the development of renewable energy sources to the conversion and storage of energy and on to its utilisation in industry and in private households. Nanotechnological solutions offer substantial energy-saving potentials across all branches of industry thanks to more efficient energy utilisation and optimised production technologies. In the long term, they raise hope for of important contributions to sustainable energy supplies and the success of global climate protection policies.



Scenario with examples of future application options for nanotechnologies in the energy sector.

Image: VDI TZ

Image sources (clockwise from top left): BASF; Skeleton Technologies; Fraunhofer IWS; Fraunhofer IPA; Heliatek/Tim Deussen, Berlin; Fraunhofer ISE; Universität Duisburg-Essen; Novaled; REWITEC; BINE Informationsdienst/Anna Durst; MAGNETEC; ZBT GmbH – Zentrum für BrennstoffzellenTechnik; Helmholtz-Zentrum Geesthacht; TU Darmstadt, Institut für Werkstoffkunde

Electricity storage

Graphene-based supercapacitors for electromobility applications

Nanocomposites as electrode material for high-performance batteries in stationary and mobile applications

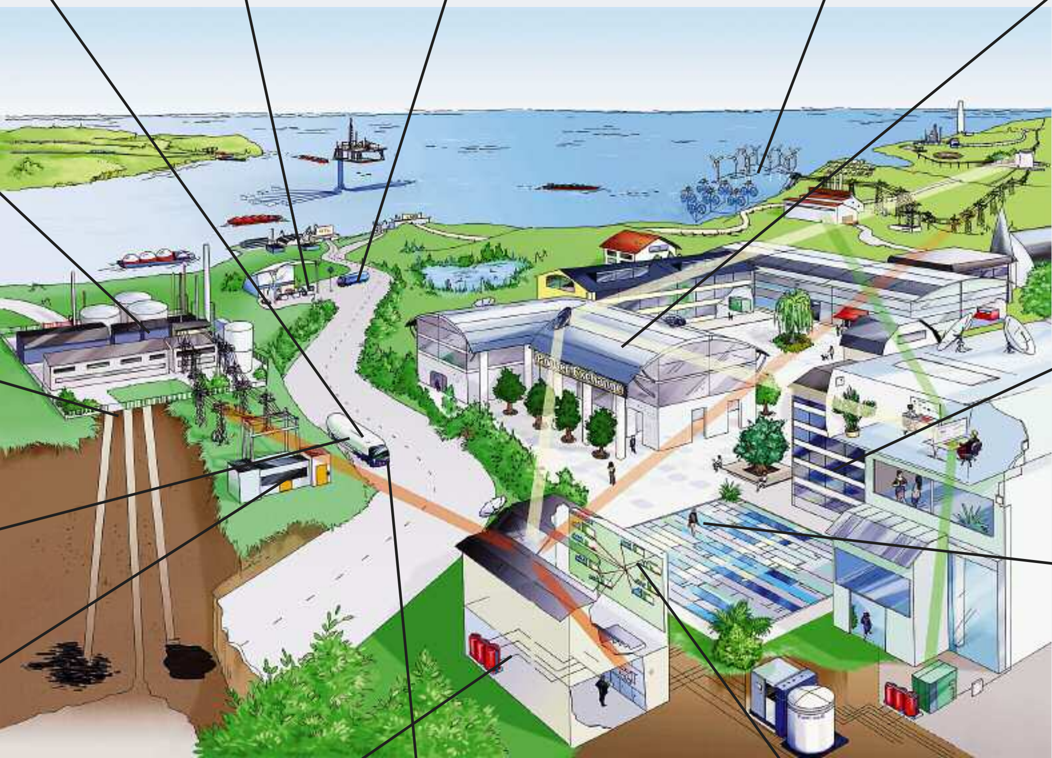
Wind energy

Carbon nanotube-based, heatable coatings for ice-free wind turbine rotor blades

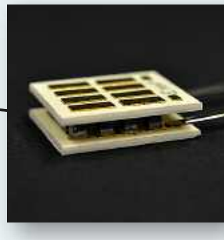
Photovoltaics

Nanooptimised polymer solar cells for large scale solar facades and integration in everyday items

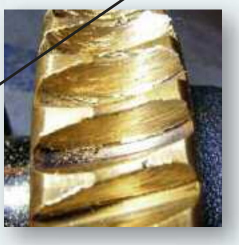
Nanomaterial-based, dye-sensitised solar cells as decorative facade elements for electricity generation

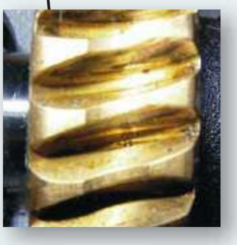


Thermoelectrics



Nanomaterials improve the efficiency of thermoelectric generators for wearable electronics and waste heat utilisation in industry and automotive engineering





Wear protection

Nanoparticles as lubricant additives improve energy efficiency and reduce wear in mechanical components (for example, motors, transmissions, vehicle and machine bearings)

Lighting

Organic light-emitting diodes for large-scale displays and lighting objects

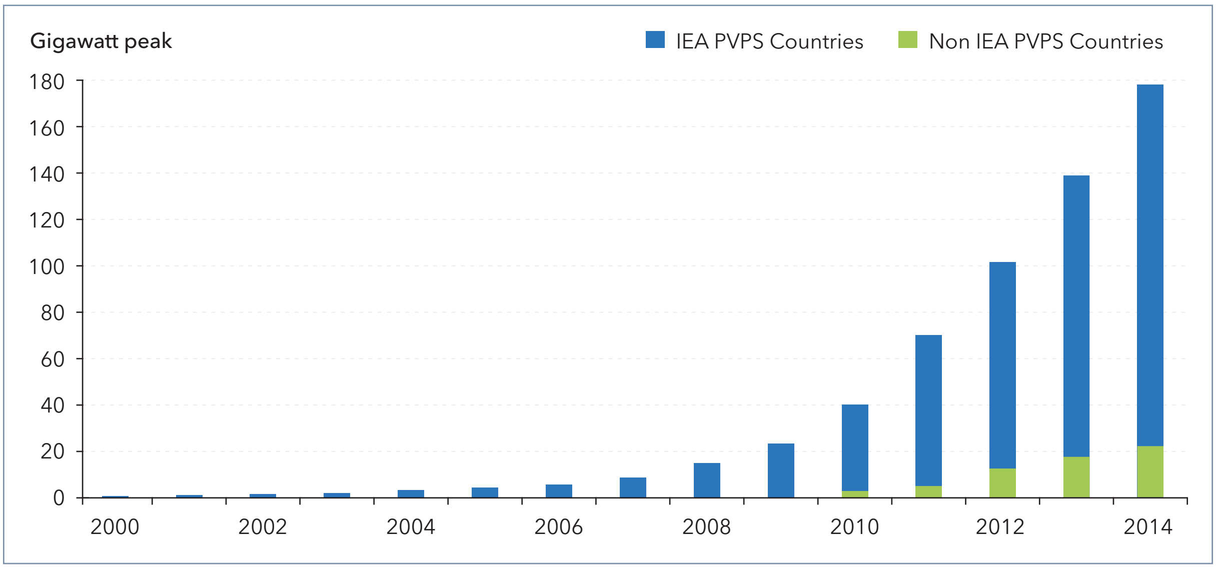
3. Utilising Renewable Energy Sources and Energy Conversion

3.1 Photovoltaics

Photovoltaics market and economic relevance

The global photovoltaics market has displayed double-digit growth rates in recent years, in particular in Japan, China and the USA. According to the 'Global Solar Power Market' report by the market research company Frost & Sullivan, the global market for solar energy will more than double from its current approximately 60 billion US dollars by 2020 (to approximately 137 billion US dollars). A European Photovoltaic Industry Association study predicts that photovoltaics may cover up to 15 percent of the European Union's electrical energy demand in 2030 (EPIA 2015). Around 177 gigawatts of PV capacity were installed globally at the end of 2014. Of this, Germany produces the largest proportion at 38.2 gigawatts, followed by China (28.2 gigawatts), Japan (23.3 gigawatts), Italy (18.5 gigawatts) and the USA (18.3 gigawatts). In addition to these five largest photovoltaic electricity producing countries, France, Spain, the United Kingdom, Australia and Belgium also belong in the top ten.

Despite the global growth in the photovoltaics industry, a noticeable decline has been registered in Germany in recent years, especially in cell and module production. The cause of this is, on the one hand, the erosion of prices for solar modules, in particular as a result of Chinese competition, and, on the other hand, a substantial drop in newly installed photovoltaic capacity as a consequence of the altered feed-in conditions brought about by the revised Renewable Energy Sources Act (German: Erneuerbare-Energien-Gesetz) in force since 2014. Despite the declining number of solar cell and solar module manufacturers the industry continues to be very important economically in Germany. According to the German Solar Association (German: Bundesverband Solarwirtschaft) data, there are currently around 50,000 people employed in approximately 10,000 German solar companies, including suppliers, distributors and installers providing installation and servicing, in addition to cell, module and inverter manufacturers (BSW Solar 2015).

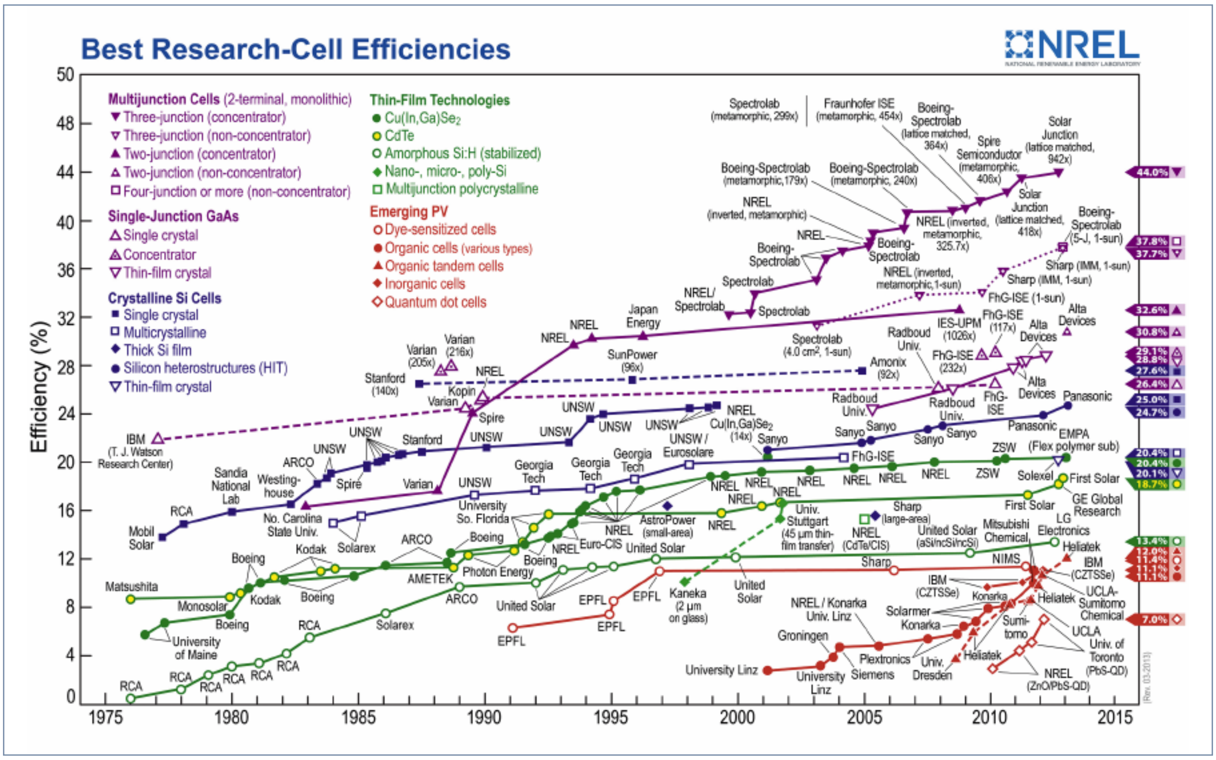


Development of global photovoltaic installations with time. Gigawatt peak: electrical capacity in gigawatt at standardized test conditions. (Source: International Energy Agency – Photovoltaic Power Systems (IEA PVPS))

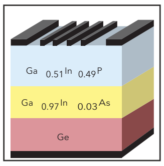
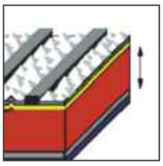
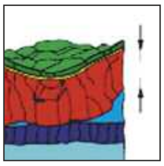
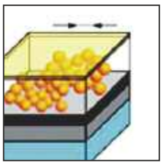
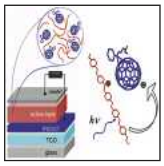
Additional efficiency improvements and especially lower prices will be decisive for the future course of photovoltaics. The broad commercial breakthrough of photovoltaics is to be expected only as soon as it becomes possible to cover large areas with solar cells without recourse to state subsidies. What is needed here, among other things, is further efficiency improvements and, even more importantly, more cost-effective materials and manufacturing methods, with development activities focusing on a variety of solar cell types.

Development status and applications of a variety of solar cell types

Wafer-based mono and multicrystalline silicon solar technology continues to dominate the market with a share of around 90 percent in photovoltaics. However, further cost reductions in this field resulting from technical improvements and mass production are limited. Alternative cell types, offering material savings potentials and substantially more cost-effective manufacturing methods, appear more promising here. They include thin-film solar cells and organic solar cells (dye-sensitised solar cells or polymer solar cells).



Different solar cell types and efficiencies achieved to date. (Source: NREL 2013)

Solar cell type	Wafer-based solar cells		Thin-film solar cells	Dye-sensitised solar cells	Polymer solar cells
Structure					
Materials	Multi-stacked cells III/V compound semiconductors	Crystalline silicon	Silicon (amporphous or crystalline), CIGS, cadmium telluride, III/V compound semi-conductors, perovskite	Nanoporous titanium dioxide, organic dye complexes	Fullerenes (C60), conjugated polymers
Efficiency	46 % with concentrator 38 % without concentrator	25 %	21 %	14 %	11 %

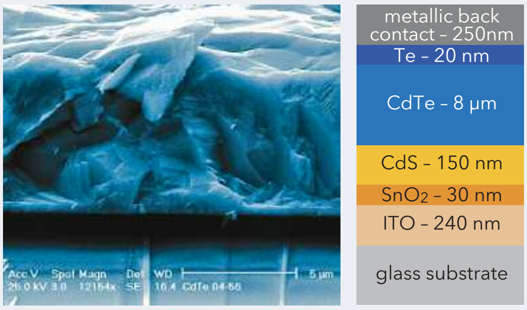
Structure and materials of different solar cell types as well as efficiency based on current state of the art.
(Source: altered after Hahn-Meitner-Institut, Helmholtz-Zentrum Berlin, HMI 2007)

Compared to conventional silicon wafer technology, inorganic and organic thin-film solar cells offer substantial cost reduction potentials in terms of solar cell production as a result of material savings, low temperature processes, integrated cell circuitry and a high degree of automation in series production. An additional advantage is that flexible substrates are adopted as carrier materials, allowing a new range of energy supply applications to be developed, for example, by integrating solar cells in textiles and everyday items. Thin-film solar cells, for instance, can be used as a mobile power supply for entertainment electronics and small devices, allowing mobile telephones and notebooks to be charged even in remote and rural regions without electricity grids. Even the decentralised power supply for electrical plants and devices is possible, independent of a main power supply. Solar modules integrated in solar vehicle roofs may provide not only the on-board power supply, but also support battery charging in hybrid vehicles. In buildings, for example in house roofs and walls, glass facades, skylights, sunroofs or display boards, transparent organic solar cells can be used to generate and use energy and to feed into the grid.

Nanotechnology application opportunities

Nanotechnologies have a key role to play in further advancing the development of photovoltaics through cost savings and efficiency improvements based on new materials, nanolayers and solar cell types, as well as by adopting simpler production processes.

Info box: III/V compound semiconductors



Electron microscope image (left) and diagram (right) of a cadmium telluride thin-film solar cell. (Source: TU Darmstadt)

III/V compound semiconductors are semiconductors consisting of material combinations of chemical elements in the main groups III and V. Compared to silicon, III/V compound semiconductors have the advantage that their electronic properties can be optimised to meet specific application requirements (for example, solar cells or light-emitting diodes) by altering the composition of the material.

Inorganic thin-film solar cells

With regard to inorganic thin-film solar cells, nanotechnological expertise is primarily required in terms of coating technology for optimised cell design. In addition to the photoactive layer, only a few micrometres thick, a typical thin-film solar cell design also comprises nanoscaled layers, which act as adhesion promoters and buffer zones for contact to the substrate, the metallic back contact and the transparent front electrode. In addition to crystalline and amorphous silicon, other material combinations such as copper, indium, gallium, sulphur and selenium (CIGS cells), cadmium telluride/selenide, perovskite or III/V compound semiconductors (for example, gallium nitride, gallium arsenide, gallium indium phosphide) are also used for inorganic thin-film solar cells. Moderate efficiencies of more than 20 percent can be achieved using thin-film solar cells.

In addition to the already established thin-film solar cell nanotechnologies, by utilising nanocrystals, offer potentials for replacing complex vacuum coating processes with more cost-effective liquid phase processes or for substituting environment-polluting materials such as the lead in perovskite solar cells with alternative substances such as tin, for example.

Currently the world's largest dye-sensitised solar cell (60 x 100 centimetres), manufactured by Fraunhofer ISE in Freiburg. (Source: Fraunhofer ISE)

Dye-sensitised solar cells

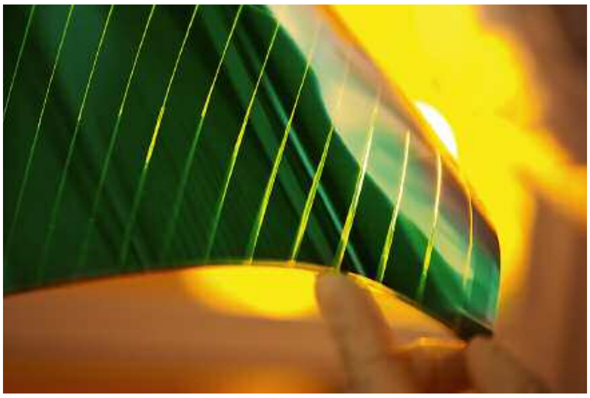
Dye-sensitised solar cells utilise dye molecule-doped titanium oxide nanoparticles (for example, various ruthenium complexes) for charge separation. Light absorption in the dye molecules leads to the release of electrons, which are then accepted by titanium dioxide particles and transferred to the electrode via a redox electrolyte. The advantages of dye-sensitised solar cells include cost-effective manufacturing methods using screen printing, applications using even diffuse incident light (for example, in interior applications), and the transparency and colour design options of the cells, opening up interesting architectural application opportunities. Disadvantages include the chemically reactive liquid electrolytes used, which may leak into the environment, the still relatively low efficiencies up to twelve percent and the limited long-term stability. Initial prototype applications have been implemented by Fraunhofer Institute for Solar Energy Systems ISE.

Polymer solar cells

Polymer solar cells use organic semiconductors for energy conversion. Conjugated polymers are used as light absorbing electron donors and fullerene derivatives as electron acceptors. Both components are integrated as 100 to 300 nanometre thick composite layers between charge transfer layers and electrodes in the sandwich-like cell structure. Merck, based in Darmstadt, is a leading manufacturer of materials for organic photovoltaics and is running numerous projects in order to participate in the new growth market. In cooperative research with the American start-up Nano-C, Merck has developed new fullerene derivatives for the organic photovoltaics (OPV) field, which display substantial improvements in service lifetime and thermal durability compared to traditional substances. Formulations comprising these fullerene compounds can be processed as the active layer using a variety of industrial coating technologies (Merck 2015).

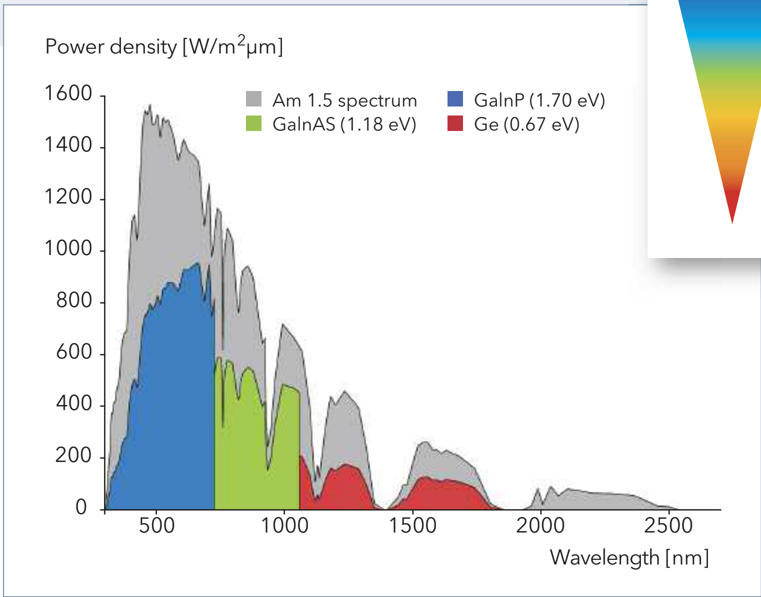
The advantages of organic solar cells include cost-effective materials and manufacturing methods, and the flexibility of the modules, which can adapt to almost any object and product shapes and contours. The objective is to achieve the mass production of large-scale modules in a traditional roll-to-roll printing process. In the mid term, efficiencies of approximately ten percent and durabilities extending to several years are aimed for with the aid of material and cell design optimisation. In Germany, research into polymer solar cells is driven by numerous Federal Ministry for Education and Research funding programmes.

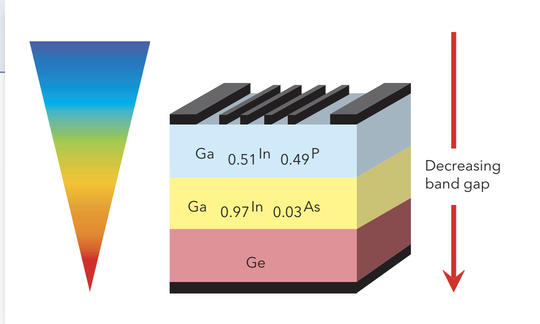
For example, Merck coordinates the funded collaborative project 'Development of new materials and device structures for competitive mass production methods and applications in organic photovoltaics' (German: 'Entwicklung neuer Materialien und Devicestrukturen für konkurrenzfähige Massenproduktionsverfahren und Anwendungen der organischen Photovoltaik' ('POPUP'). The collaboration partners have set themselves the target of developing cost-effective industrial solar modules using more efficient materials and coating methods.



Left: Thin and mechanically flexible organic solar foils for novel applications. (Source: Heliatek / Tim Deussen, Berlin)
Right: Printed solar cells as reels. (Source: pmTUC / Bystrek Trenovec)

Left: The German pavilion's 'solar tree', based on polymer solar cells, at the 2015 Milan Expo. (Source: U.I. Lapp)
Right: Special inks for printing the solar cells are produced by Merck. (Source: U.I. Lapp)





Absorption spectra of semiconductor materials used in stacked solar cells to optimise the quantum efficiency. Stacked cells consist of a series of layers of compound semiconductors with different band gaps. (Source: Fraunhofer ISE)

Band gap optimisation for highest conversion efficiencies

In traditional photovoltaics, non-conducting electrons in a semiconductor are excited into movement by the absorption of sunlight and can be used as a source of electricity. Light that exactly corresponds to the energy difference between the non-conducting and the conducting electrons is required to excite the electrons. This energy difference, referred to as the band gap, is a specific material property for every semiconductor. One photovoltaics development objective is to optimise the band gap of a semiconductor by combining various materials such that as large a fraction of the sunlight as possible is used to excite the free electrons and thus the efficiency of the solar cells is increased. The world record, at up to 46 percent conversion efficiency, is held by wafer-based stacked cells made of III-V semiconductor systems. In these solar cells, nano to micrometre thin, semiconductor material layer systems with differing band gaps are combined such that the solar spectrum is exploited as efficiently as possible to convert light to electricity (see the NAsP III/V success story, Section 7.2). However, due to the complex manufacturing process these cells are often still too cost-intensive. Their use is more economical if the sunlight is concentrated through relatively cost-effective optics and thus the cell efficiency increased. Such concentrator modules are commercially available and there are realistic chances of substantially reducing costs by further system optimisation and by economic effects of scale in production. Another approach for reducing the cost of these solar cells is to use them in combination with cheaper silicon substrates.

Approaches for utilising quantum dots to increase the efficiency of solar cells are still in the basic research stage. Quantum dots are nanoscaled clusters of semiconductor compounds with unusual optoelectronic properties which can be modified using quantum physics effects as a function of the size of the cluster. Applications in solar cells are of interest because, on the one hand, several electron-hole pairs can be generated for each photon by using quantum dots and, on the other hand, the absorption bands can be optimally adapted to the wavelengths of the incident light. At the laboratory scale, three-dimensional quantum dot meshes or other structures, which may be interesting for solar cell applications, can be produced using nanowires. Cells such as these make theoretical conversion efficiencies of more than 60 percent possible. However, current research is still a long way from this objective and no functioning, experimental model of a quantum dot solar cell has yet been demonstrated.

Nanostructures for optimising energy yield

Regardless of the type of material used and the cell type, nanotechnological approaches to solutions are adopted in order to further optimise solar cell efficiency. For example, efficiency increases can be achieved using nanostructured antireflection layers, which allow better light exploitation. One development that is ready to market is antireflection layers for plate glass, based on a nanoporous coating of silicon dioxide. The layers are generated based on a sol-gel process and subsequent immersion coating. The porosity allows the effective refractive index of the glass to approach that of the surrounding air, thereby reducing the reflective losses of the glass plates from the usual eight percent to two percent. Such antireflection glasses for solar modules have been commercially marketed by the Darmstadt company Merck for several years and display good growth rates in photovoltaics and in solar thermal applications.

An alternative approach is based on nanotextured, transparent, conductive oxide layers, used as front electrodes to minimise light scatter and reflection losses. In organic solar cells, the large-scale periodic surface structures created with the aid of holographic exposure methods can be transferred to the solar cell polymer layer using a cost-effective embossing method. In addition to this, work is being carried out on improving the back reflectors in order to further increase light exploitation in the substrate. To achieve this, photonic crystals or non-metallic nanolayer systems, offering the potential for additional efficiency improvements, are used instead of conventional metal layers such as, for example, silver.

Research is also being carried out into coating structures with which solar spectrum frequencies are converted into light quanta with higher (up-conversion) or lower energy (down-conversion), in order to optimise them for the absorption properties of the adopted solar cell material. A promising option seems to be available in rare earth metal nanoclusters embedded in glass ceramics, with which infrared and ultraviolet light can be converted into visible light that is utilisable in photovoltaics.

Glass ceramics doped with rare earth metals for up and down-conversion. (Source: Fraunhofer IWM)

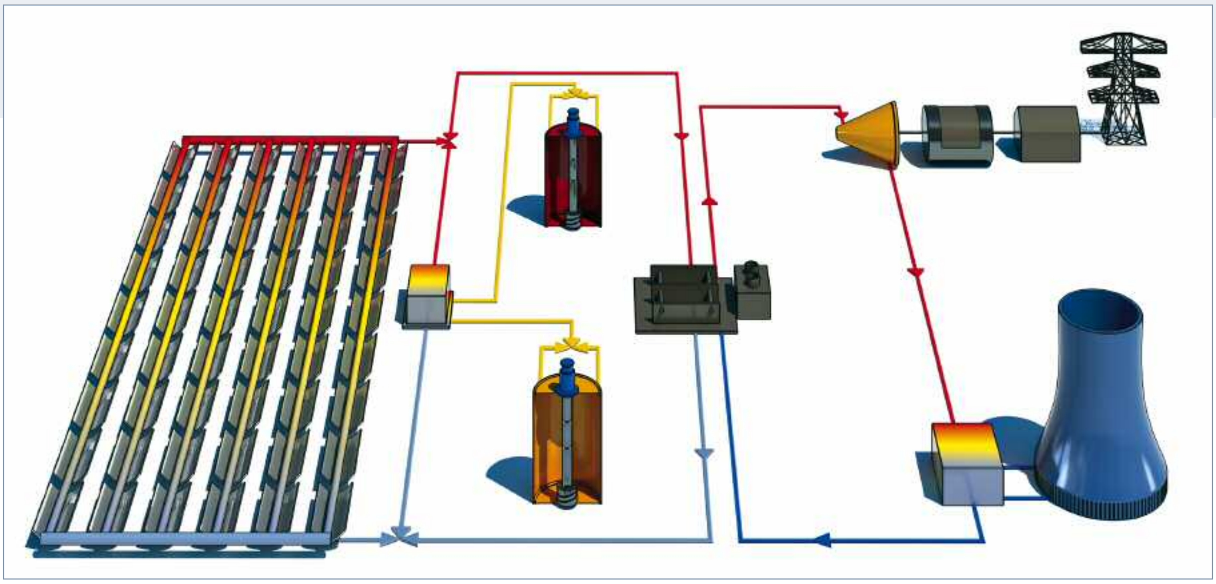


Diagram of a solar thermal parabolic trough power plant. Inside vacuum tubes, a heat transfer medium, such as thermal oil, is heated to around 400 degrees Celsius by concentrating sunlight using movable parabolic mirrors. The heat produced generates the steam for a downstream steam power plant. (Source: FRIATEC AG Division Rheinhütte Pumpen: www.exposegmbh.de)

3.2 Solar Thermal Energy

Solar thermal energy will play a greater role in utilising solar energy in the future, because it can cost-effectively provide both power and heat. The provision of solar thermal heating in buildings is decentralised using roof-mounted solar collectors, which convert solar energy to heat with efficiencies of approximately 60 to 70 percent. The solar thermal potential here is huge, because approximately 50 percent of the total final energy consumption in Germany is caused by heat applications. However, solar thermal energy is also used at an industrial scale for electricity generation in solar power plants. Globally, solar thermal power plants with a capacity of around 2.5 gigawatts are installed and around 1.5 additional gigawatts are under construction. The world's largest facilities are located in Spain at 150 megawatts capacity (Andasol facility with three power plant blocks of 50 megawatts each), in Abu Dhabi (100 megawatt Shams 1 facility) and the USA (Solar One in Nevada with a rated capacity of 64 megawatts). Of the solar thermal power plants, the parabolic trough power plants, in which sunlight is concentrated using parabolic mirrors and converted to heat in what are called 'receiver tubes', then subsequently exploited to generate steam and electricity, dominate with a market share of approximately 95 percent.

Research is also being carried out on solar updraft towers, which use the thermal flow of heated air layers to generate electricity. The European market for solar thermal power plants is currently being displaced from Spain to Italy, where fourteen solar thermal power plant projects with a total of approximately 400 megawatts are being developed and will probably go online by 2017 (EurObserv'ER 2014). German industry is predominantly involved in the export of key components such as absorbers, collectors and mirrors, used around the world in solar thermal power plants. In principle, solar thermal power plants at sites with intense insolation represent an economical alternative to electricity generated from fossil fuels. However, improvements in terms of efficiency, lower servicing intensity and a longer service life of the individual components still need to be achieved here.

Solar thermal power plant in the Negev Desert, Israel. (Source: iStock.com / byllwill)

Nanotechnology application opportunities

In contrast to photovoltaics, the nanotechnologies used for solar thermal applications are not required to optimise electronic band gaps and photoelectric conversion efficiencies. However, solar thermal energy is used to exploit the energy in sunlight as efficiently as possible, that is, to convert it to heat. Just like in solar cells, nanooptimised anti reflection coatings in solar thermal receivers ensure that sunlight reflection losses are kept as low as possible. In addition to this, coating solutions are used to minimise heat energy radiation losses due to what are referred to as low-e layers and thus to improve the absorption properties of the receiver. These coatings, usually produced using physical vacuum methods, must also be stable under mechanical loads and corrosion, as well as be heat-resistant. This applies in particular to solar thermal parabolic trough power plants in which the receiver tubes need to withstand working temperatures up to 450 degrees Celsius over extended periods. Nanotechnological coating expertise allows the various properties required to be integrated in an optimised layer design.

Nanocoated receiver tubes for solar thermal power plants. (Source: Fraunhofer ISE)

3.3 Thermoelectrics – Power from Heat

Thermoelectrics are used to directly convert a heat flow to electrical energy, utilising the Seebeck effect. The Seebeck effect describes the occurrence of electrical voltages between two points of an electrical conductor of different temperatures. The greater the temperature differential, the more energy can be produced by thermoelectric generators. Desirable thermoelectric material properties include low thermal conductivity in conjunction with good electrical conductivity, which directly affect the thermoelectric efficiency determined by the dimensionless parameter ZT (figure of merit).

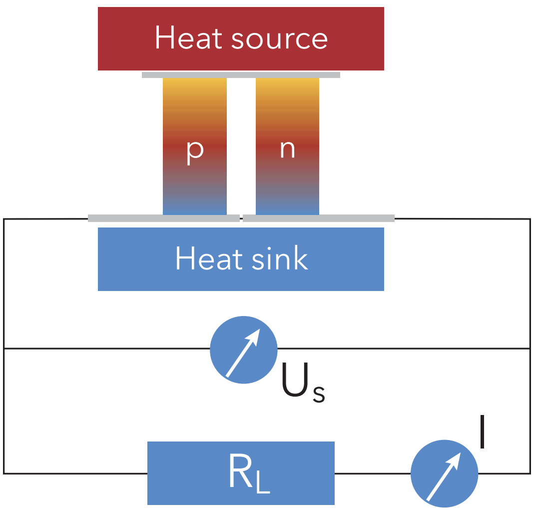
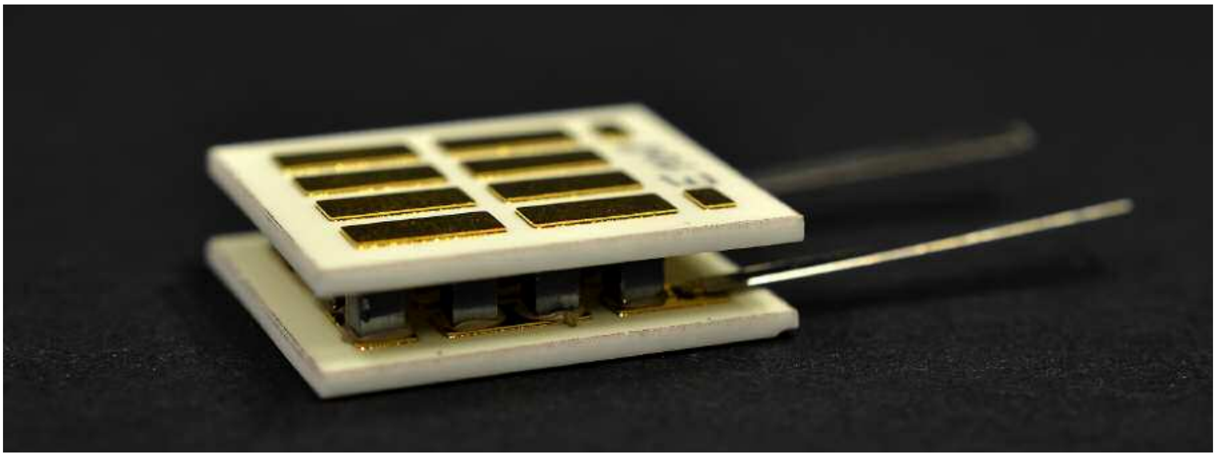


Diagram of a thermoelectric energy converter utilising the Seebeck effect. In an n-doped, that is, electron-rich, material, more electrons are raised from the valence to the conduction band and are available as charge carriers in the warm zone; correspondingly, in a p-doped, that is, electron-poor, material, more electron holes are available. This potential difference generates a flow of electric current. (Source: VDI TZ)

Different semiconducting solid state compounds are used, depending on the temperature range. At a temperature gradient of 700 degrees Celsius an efficiency between five and ten percent can be achieved using conventional silicon/germanium alloys. Due to their relatively low efficiencies, thermoelectric converters can currently only be economically employed in niche applications. However, in the mid to long term the utilisation of waste heat from automobiles presents a high energy-saving potential, because approximately two-thirds of the energy input into an automobile are lost as waste heat. In Germany alone, the theoretical energy-saving potential of thermogenerators is ten terawatt hours per year if all cars were fitted with one-kilowatt thermogenerators. Automobile manufacturers such as BMW or Daimler are driving pilot and prototype development.

As a result of stability problems during continuous operation, use in series applications is not anticipated before 2020. However, the market research company IDTechEx reckons with strong thermogenerator market growth. The company forecasts a global turnover of 950 million US dollars in 2024 (IDTechEx 2014). In the long term, industrial and power plant applications are also anticipated through the development of thermoelectric generators.

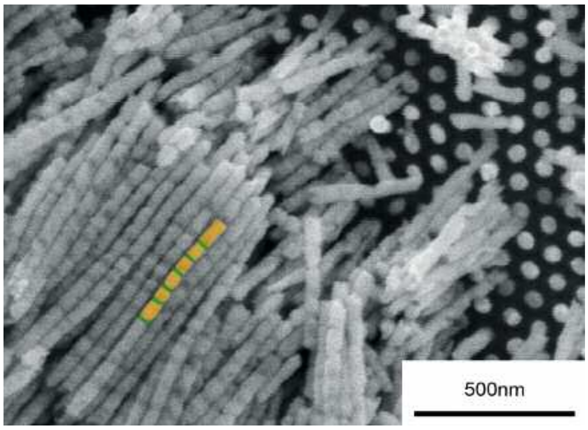


Silicon thermogenerator. (Source: Universität Duisburg-Essen)

Nanotechnology application opportunities

Nanotechnology innovations, demonstrated in recent research work, may provide thermoelectrics with new impulses thanks to substantially improved efficiency. Nanostructured thermoelectric materials are extremely interesting because the electrical and thermal properties of the material can be specifically influenced by the structure sizes. Nanostructured materials with a much higher proportion of grain boundaries can be generated using new manufacturing methods. The grain boundaries lead to a reduction in heat transport as a result of lattice vibrations in the solid body, while the electrical conductivity is not affected or only slightly impaired. This is a principal requirement for increasing the quality of the thermoelectric material. By characterising the relationship between structure, composition and properties at the nanolevel, it may be possible in the future to design materials with the desired properties. Nanostructures investigated in the context of thermoelectric materials comprise, among others, nanostructured surfaces, quantum dots or quantum wires. Bismuth telluride or antimony telluride quantum dot super lattices or nanostructured silicon, silicon/germanium, skutterudite (cobalt/arsenic sulphides) or clathrate compounds* have proven to be highly efficient thermoelectric materials.

Such efficiency improvements using nanostructured semiconductors with optimised boundary layer design may pave the way for the widespread use of thermoelectric materials in utilising waste heat, for example, in automobiles or even human body heat, for mobile electronics in textiles.



Semiconductor nanowires offer potentials for efficient thermoelectric generators. (Source: Universität Hamburg)

* Inclusion compounds of two materials, where a guest molecule is included in a lattice consisting of host molecules.

3.4 Fuel Cells

Fuel cells convert the chemical energy of an energy source into an electrical current with high efficiency. In addition to pure hydrogen, natural gas, methanol, petrol or biogas can be used, from which the hydrogen necessary to operate the fuel cell can be produced in a reforming process. Depending on the field of application, different fuel cell types with different working temperatures, from room temperature up to 1,000 degrees Celsius, based on various material systems, are used. Here, high-temperature fuel cells such as MCFC (Molten Carbonate Fuel Cell) or SOFC (Solid Oxide Fuel Cell) are particularly attractive because they allow combined heat and power (CHP) systems with high efficiencies to be implemented. Polymer electrolyte membrane fuel cells are best suited to providing the power supply of electric motors in fuel cell vehicles. This is a low-temperature fuel cell, operated in a continuous mode at approximately 80 degrees Celsius.

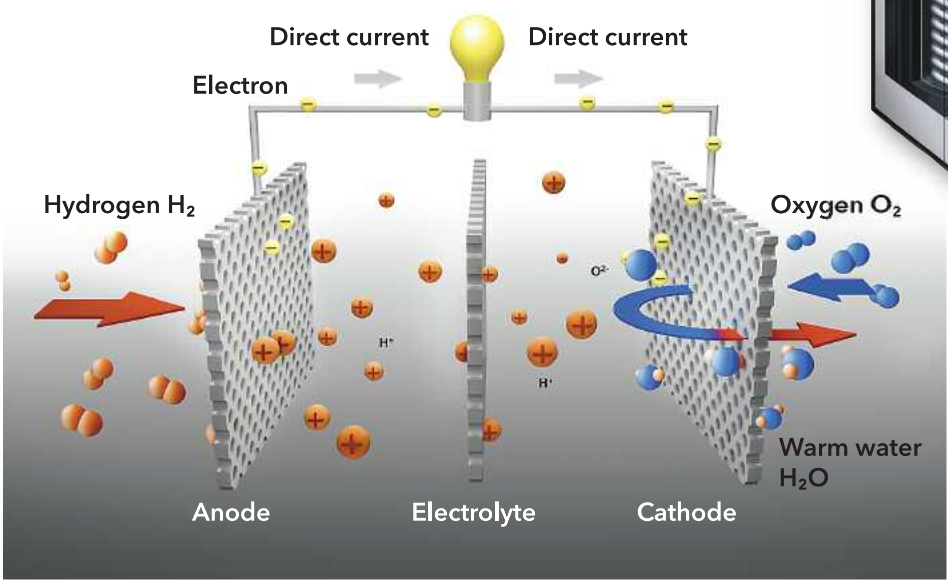
Fuel cell market and application potentials

The potential spectrum of fuel cell applications ranges from power supplies for electronic equipment, through electric vehicle drives and heat and power supplies for buildings, to power plants. The current, approximately two billion US dollar global market is primarily dominated by stationary fuel cells, in particular for domestic power and emergency electricity supplies. An important field of application is uninterrupted power supplies, for example, in information and communications technology or applications in luxury goods such as yachts or mobile homes, where the additional costs caused by the fuel cell are less important.

Right: PEM fuel cell-based domestic energy centre, capable of covering the electricity and heat demand base loads for a single-family home.

Bottom: Diagram of a fuel cell. Gaseous hydrogen or a hydrogen containing process gas is electrochemically converted to water at an electrolyte/electrode assembly using atmospheric oxygen, producing electricity and heat.

(Source: Viessmann)



Fuel cell drives in fork lift trucks, tested in an information campaign funded by the Hessian Ministry of the Environment, Climate Protection, Agriculture and Consumer Protection (Hessisches Ministerium für Umwelt, Klimaschutz, Landwirtschaft und Verbraucherschutz).
(Source: Hessen Agentur / H2BZ-Initiative Hessen)

Mobile applications also offer large potentials. In Germany, fuel cell vehicles have been demonstrated in a range of applications. Their suitability for everyday applications is tested in company vehicle fleets, for example. Rhein-Main Transport Association (German: Verkehrsverbund Rhein-Main) plans to use fuel cell drives in rail vehicles, and fuel cell-driven fork lifts are being tested in logistics operations. Two fuel cell-drive Daimler vehicles have also been in use for several years in the Industriepark Höchst. Furthermore, a fuel cell bus by Van Hool will operate on internal bus lines of the industrial park from the beginning of 2016.To facilitate the broad use of fuel cells in automobiles, it is necessary to create a suitable framework to make these vehicles economically competitive compared to those with combustion engines (total cost of ownership, or TOC), as well as to develop an adequate infrastructure such as sufficient capacity to generate 'green hydrogen', that is, CO_2-neutral hydrogen, and a network of filling stations. In Germany, several projects were started in 2012 as part of the national hydrogen and fuel cell technology innovation programme, with the aim of building around 50 hydrogen filling stations by mid-2015. The H2 Mobility joint venture plans to build and operate 400 filling stations in Germany by 2023 as the next phase of filling station network expansion.

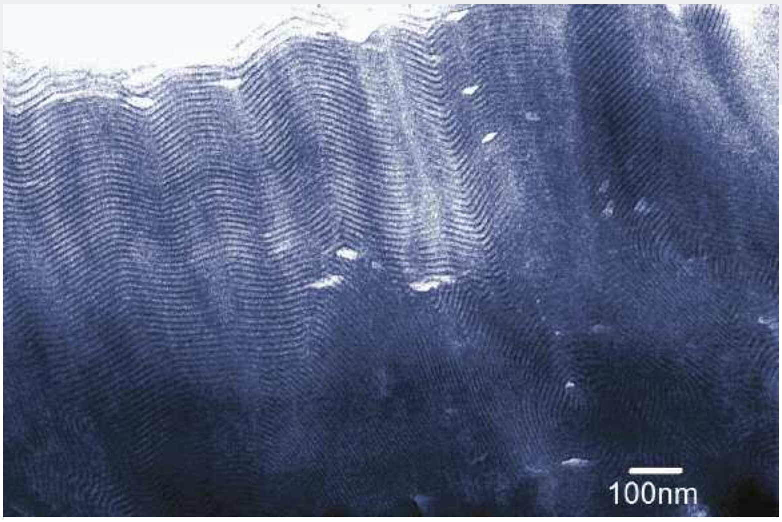
Hyundai in 2013 and Toyota in 2015 were the first manufacturers to introduce a series-production car with fuel cells to the German market. The German automobile manufacturers Daimler, BMW and VW (including Audi), who have also developed fuel cell systems for vehicles to series maturity during recent decades, have also announced their intention to enter the market with their first series vehicles in 2017 (Daimler) and 2020, respectively.

Series-production fuel cell car Toyota Mirai. (Source: Toyota Deutschland GmbH)

Mini fuel cell 'Kraftwerk' (power plant), for example for recharging a smartphone. (Source: eZelleron)

The use of miniaturised fuel cells for operating mobile electronic devices, which can be operated using methanol, for example, appears more promising in the short term and on a broader base. For example, the company eZelleron has developed a microtubular, portable SOFC fuel cell product to series maturity. The fuel cells can be operated with traditional and available gases such as propane/butane and hydrogen. The mini fuel cells are suitable as power supplies for mobile electronic devices, for instance, for charging emergency batteries in sensors for weather stations, smartphones, tablets or notebooks.


Fuel cell stack for mobile applications.
(Source: ZBT GmbH / Nadine van der Schoot)



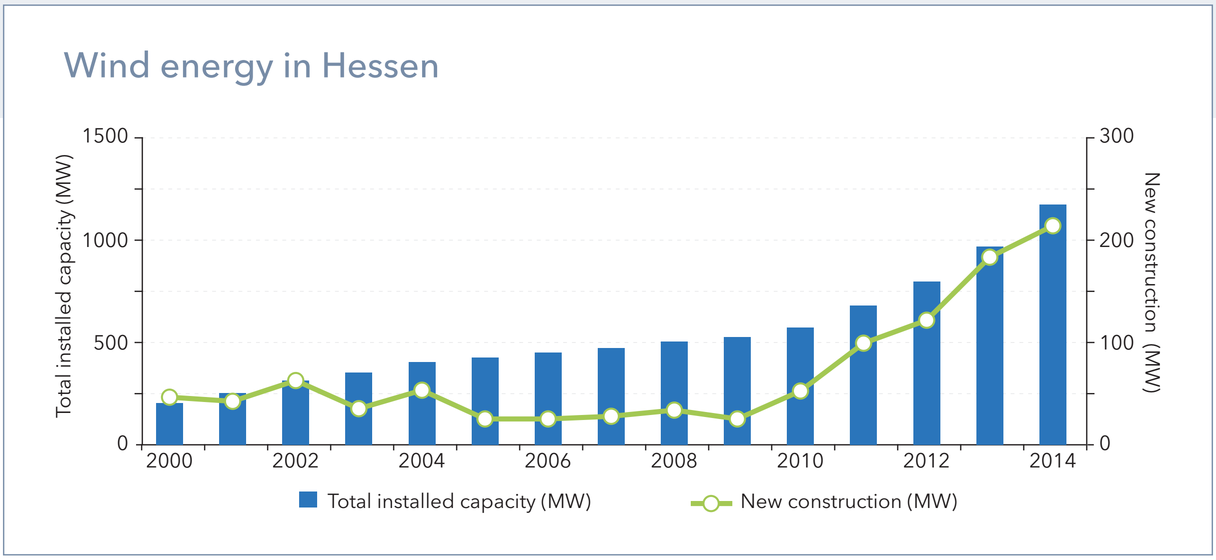
Nanomorphology of a membrane for PEM fuel cells.
(Source: Max-Planck-Institut für Festkörperforschung)

Nanotechnology application opportunities

Nanotechnologies open up innovation and optimisation potentials for all common fuel cell systems. Optimised electrodes, electrolytes, catalysts and membranes, in particular, facilitate increases in power yields in the conversion of chemical energy. In SOFC-type solid oxide fuel cells, for example, the ion conductivity can be improved by using ceramic nanopowder based on yttrium-stabilised zirconium. In terms of membrane fuel cells, the optimisation approaches primarily affect the polymer membrane, where the aim is to enhance its temperature stability by employing inorganic-organic nanocomposites, among other things. Here, the functionalised polymers are modified by inorganic nanoparticles using sol-gel processes. Higher operating temperatures mean that better efficiencies can be achieved and that the sensitivity of the catalyst to carbon monoxide, formed when producing hydrogen from methanol in the reforming process, is reduced. Moreover, nanostructuring of the electrode materials, which enlarges the active surface, has an important role to play. This allows the highest possible efficiency in electrochemical hydrogen/oxygen conversion or in hydrogen generation to be achieved by converting natural gas or methanol (in the direct methanol fuel cell), for the lowest possible use of costly precious metal catalysts.

Using nanomaterials, membranes can be structured and functionalised by targeted design in order to achieve higher conductivities and higher temperature and corrosion resistance for applications in polymer electrolyte membrane fuel cells (PEM fuel cells).

SolviCore, based in Hanau and taken over by the Japanese chemicals company Toray Industries in 2015, manufactures so-called membrane-electrode assemblies (MEA) for safe and more cost-efficient high-temperature membrane fuel cells. The MEA uses solid, non-extractable polymer electrolytes in the place of phosphoric acid-doped polymer membranes. A further development of MEA was achieved in the PSUMEA research project, where the membranes were manufactured from highly sulfonated polyphenylene sulfones. Here, so-called multiblock copolymers were structured such that a specially arranged nanomorphology was created. This nanostructuring allowed chemically and mechanically stable, high-temperature PEM fuel cells with very high proton conductivity to be developed.



Installed capacity and new construction of wind turbines in Hessen (MW: megawatt). All figures are based on Deutsche Windenergie Institut (DEWI) and Deutsche WindGuard surveys. (BWE 2015)

3.5 Wind Energy

The global wind energy market is estimated at approximately 99 billion US dollars. 25 percent growth is forecast for the next five years (Bloomberg 2014). Wind energy has become established in Germany as an important branch of industry, providing approximately 138,000 jobs and a turnover of twelve billion euros (Strom-Report 2015). Wind energy in Germany is already economically competitive today; that is, the power generation costs are of a similar magnitude as those of conventional power plants. For the future expansion of wind energy in Germany, the problem is more one of the choice of suitable and sufficiently windy locations, now increasingly shifted offshore.

Nanotechnology application opportunities

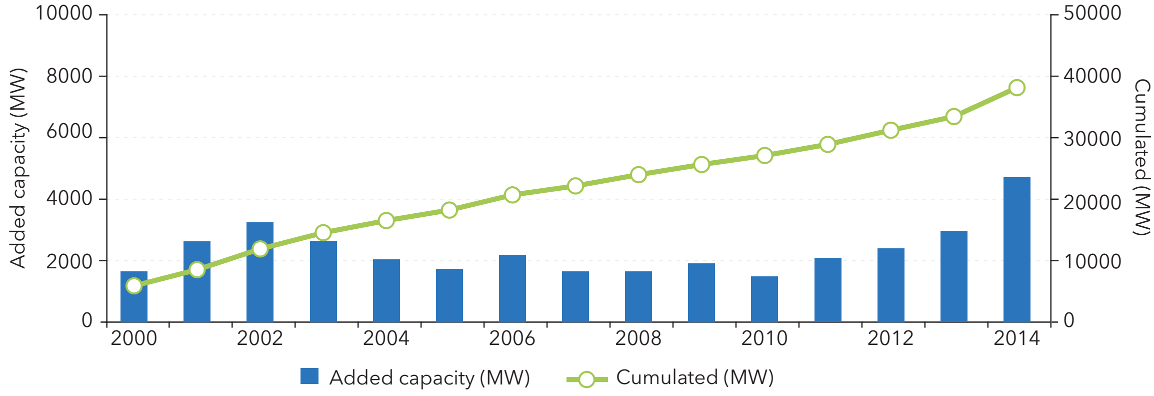
Nanotechnologies can make a considerable contribution to optimising wind energy exploitation with high-strength lightweight materials for rotor blades, based on nanocomposites, low-friction and wear protection layers for bearings and transmissions, and resource-saving magnets.

Replacing expensive magnetic materials with nanomaterials

Some of the generators commonly installed in wind turbines use large permanent magnets. The magnets contain metals of the so-called rare earths, which primarily need to be imported from China and are expensive. The aim of research work at TU Darmstadt is therefore to reduce the rare earth content in magnets. One approach, for example, is to not distribute the particularly problematic dysprosium homogeneously in alloyed materials, but instead, to apply it to the crystal boundary layers, where it is required for the high-temperature stability of the magnets. In this way, the dysprosium content could be reduced from, in some cases, eight percent by weight to less than two percent by weight (TU Darmstadt 2014).

Moreover, with nanotechnology it may be possible to dispense with dysprosium in general by reducing the grain sizes of the other metal constituents to the nanometre range and 'bonding' them to form composites.

Installed wind energy capacity in Germany



4,750 megawatt (MW) new wind capacity was installed in 2014. The total installed wind energy capacity is therefore 38,115 megawatts. (BWE 2015; data source: Deutsche WindGuard)

Longer service life of wind turbines thanks to nanolubricants

The service life of transmissions can be increased by surface coatings on gear wheel and bearings using nanomaterials. REWITEC, based in Lahnau, Hessen, has developed a nanocoating that can revitalise worn metal surfaces and protects against wear even under unfavourable conditions. The technology is based on targeted modifications to the surface structure of the rubbing materials, allowing a new metal silicate layer to form with a surface roughness of only a few nanometres. The active component is a mixture of various synthetic silicate compounds, which are added to the existing lubricant and react with the metal surfaces as a result of the high temperatures and pressures. The metal-metal friction pairs are thereby modified to metal silicate-metal silicate friction pairs with reduced friction.

Carbon nanotubes for lightweight materials and anti-freezing protection of wind turbine rotor blades

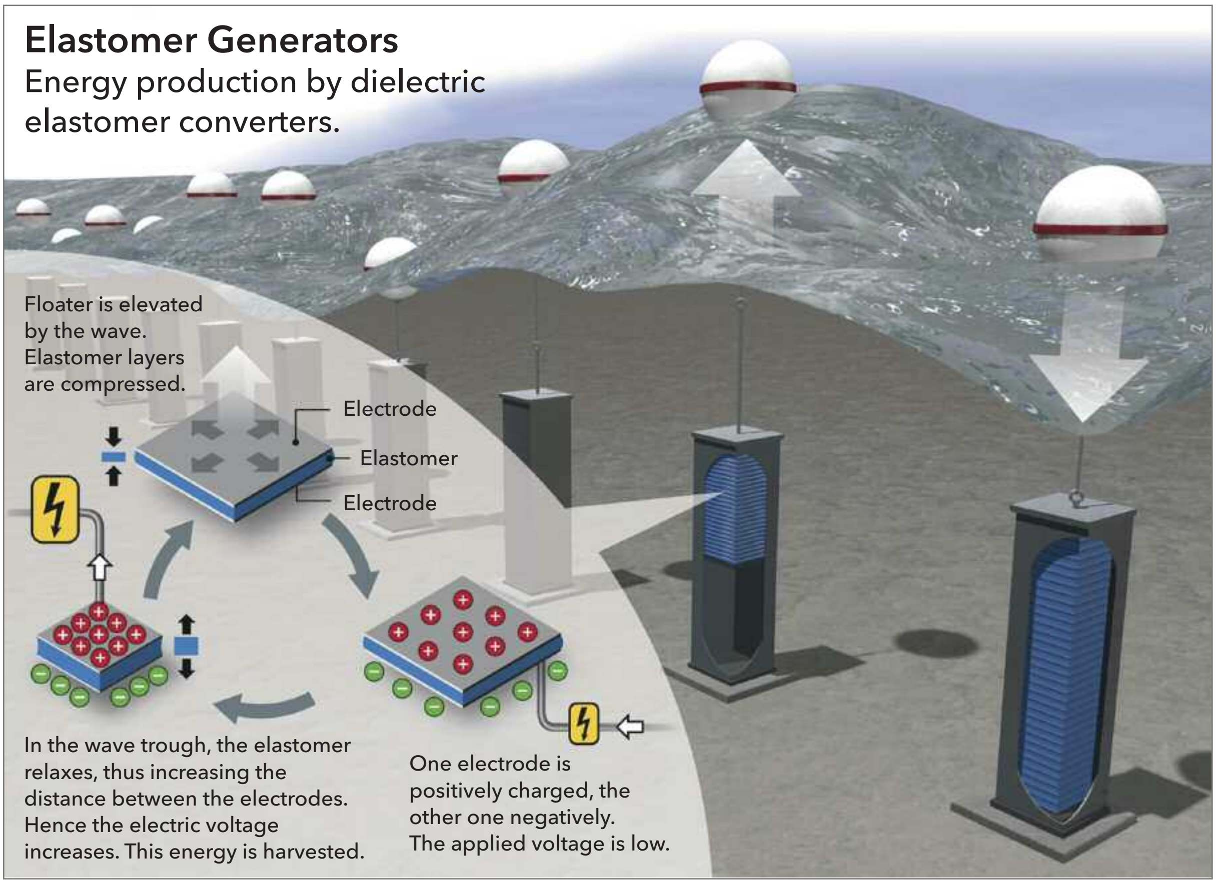
A wind turbine's rotor blades determine the maximum energy yield that can be extracted from the wind. In particular in offshore facilities with rotor diameters of up to 200 metres and blade weights of 50 tonnes and more, glass fibre-reinforced plastic (GFP) based rotor blades have long since reached their limits. Here, carbon fibre-reinforced plastics (CFP) offer an alternative. Innovative material systems for rotor blade materials may also become important, such as new, lightweight and stable nanocomposites consisting of carbon and glass fibre-reinforced epoxides, where carbon nanotubes (CNT) are added to the resin matrix as stabilising components.

Left: Wind turbine rotor blade icing can lead to considerable capacity losses in wind turbines. (Photo: iStock.com / kaspan)
Right: A new energy-efficient heating system can melt ice on wind turbines within seconds. The carbon nanotube coating heats up defined areas of the rotor blade as soon as integrated sensors detect icing. (Photo: Fraunhofer IPA)

Carbon nanotubes also offer potentials for protecting the wind turbine rotor blades against icing up. Ice covered rotor blades lose their original aerodynamics and generate less energy. These capacity losses are estimated to be as much as 20 percent. In order to avoid this problem, researchers have developed an intelligent rotor blade heating system coating solution based on carbon nanotubes. A carbon nanotube layer a few micrometres thick is applied by spraying onto a self-adhesive polymer film. Any size of wind turbine rotor blade can be thus treated, with the blades being subdivided into several heating sections. By integrating ice detectors in the heating sections, only those sections specifically affected by ice formation can be heated. In this way, the ice can be thawed in only a few seconds and very energy-efficiently because the complete rotor blade does not need to be heated.

3.6 Marine Energy

In the course of developing renewable energy sources, global efforts to produce clean energy from the oceans have increased. In principle, the world's oceans may be regarded as a practically inexhaustible energy reservoir. Their energy resources are estimated to be more than 10,000 terawatt hours per year by the International Energy Agency (IEA) and thus correspond to many times the annual global electricity demand. The technological approaches for exploiting this energy are manifold and range from current and tidal power plants, through harvesting wave energy, to exploiting temperature or salt concentration differentials. The majority of these approaches are at the basic research stage or in demonstration projects and are still far removed from economic usefulness.



Elastomer generators for wave power plants. (Source: Bosch)

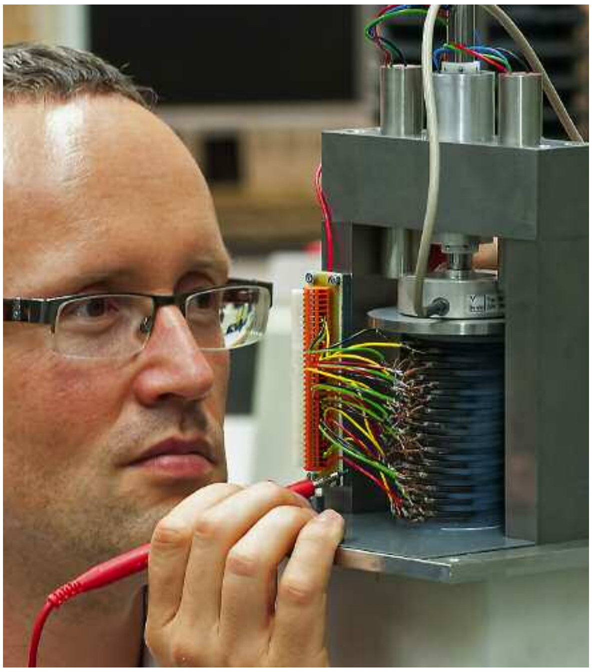
Nanotechnology application opportunities

The use of nanotechnologies as such is not in the focus of marine energy research. However, certain nanomaterials are increasingly important at various points in energy production.

They assume a more passive or conserving role in protecting components from the aggressive-corrosive and degrading effect of seawater as well as from fouling processes, and in reducing friction. Depending on their purpose, nanoscaled and nanostructured protective coatings and lubricants are highly water resistant (super hydrophobic), anti-microbial, frost protecting, friction reducing, anti-corrosive, etc., and contribute substantially to material preservation.

Electroactive polymers, for example, play an active role in terms of producing electricity from waves. These are plastics that change shape when subject to an electric voltage. They are also occasionally referred to as artificial muscles. In contrast, an imposed positive or negative external strain generates an electrical voltage, which may be used for power generation given suitable technical provisions. The thinner an electroactive polymer film is, the stronger is the relationship between shape change and voltage generation. A variety of research projects are testing the use of electroactive polymer components for generating wave energy. In Germany, the EPoSil (Electroactive Silicon-based Polymers for Energy Generation; German: elektroaktive Polymere auf Silikonbasis zur Energiegewinnung) research network, in which TU Darmstadt participates, is working to develop stacks of thousands of thin polymer films. They are covered with electrodes and amalgamated to form a generator. Attached to buoys on the surface of the water, they are constantly deformed as a result of wave action. The electrical voltage generated is collected by the electrodes. Other research approaches focus on nanoscaled polymer threads, placed between flexible electrodes.

An additional approach to energy generation from the sea is based on exploiting differences in the water's salt concentration. These gradients are particularly large in river estuaries. In the pressure osmosis approach, a net water flow in the direction of the salt water reservoir results when semipermeable membranes are installed between the fresh water and the salt water containers. The osmotic pressure can be used to drive a turbine. In reverse electrodialysis, alternating series of cathode and anode exchange membranes are placed in series, each being respectively permeable to potassium or chloride ions and separating salt and fresh water reservoirs from each other. The chemical potential difference between neighbouring chambers generates an electrical voltage at each membrane. The membranes are of decisive importance in both approaches. Nanotechnological innovations make substantial contributions to membrane efficiency optimisation in terms of pore structure, surface structure and material composition. Small demonstration power plants exist for both methods in Norway and the Netherlands.



Demonstrator of elastomer generators. (Source: Bosch)

3.7 Generating Chemical Energy Sources

Generating chemical energy sources from renewable energy resources plays a key role in implementing the 'energy revolution'. The highly fluctuating power generated by renewable energy sources requires the use of long-term energy storage systems to cope with the continuous balancing of power supply and demand. Those systems also need to be capable of being efficiently and cost-effectively stored, transported and converted back to electricity. Chemical energy sources such as hydrogen and hydrocarbons are particularly important in this context. The replacement of fossil fuels by regeneratively produced energy sources for mobile applications is also being studied. In addition to hydrogen, this predominantly affects biofuels produced from plant materials.

3.7.1 Hydrogen Production

In the long term, there are high hopes for hydrogen as an environmentally friendly energy source, because it produces no pollutants on combustion. However, in terms of its use as an energy source, currently existing obstacles regarding the market entry of the technology are to be overcome. Only by regulatory changes with respect to the energy system and government support that reduce production costs by rising quantities, its economically viable use will be succeeded. Besides investments in hydrogen generation, amendments to the existing supply infrastructure for distributing hydrogen (especially hydrogen fuel stations with high pressure compressors) are necessary. Technologies for efficient production and storage are a basic requirement for the widespread use of hydrogen as a future energy source.

Nanotechnology application opportunities

Electrolytic hydrogen generation

The efficiency of precious metal catalysts in the electrolytic separation of water can be increased by nanostructuring. In addition, optimisation potentials exist in the high-temperature electrolysis of water, where electrolysis occurs at around 1,000 degrees Celsius and high conversion efficiencies of greater than 90 percent are achieved. Here, ceramic materials are used as oxygen ion conducting solid electrolytes. By using nanomaterials, they can be improved in terms of ion conductivity and temperature-resistance. In addition, they are coated with micro- and nanoporous electrodes, on the large surfaces of which the passing steam is separated into its molecular constituents hydrogen and oxygen. In principle, high-temperature electrolysis is the reverse of the high-temperature fuel cell and as such is a subject of hydrogen research.

Membrane electrode assemblies (MEA) of electrolysers can be operated with low degradation rates at high current densities using innovative catalytic coatings (picture above: electrolyser stack with MEAs by ITM Power, Sheffield/UK). The electrolyser generates hydrogen with high power density and increased gas pressure at an efficiency factor of 77 percent because of the compact design. (Source: ITM Power)

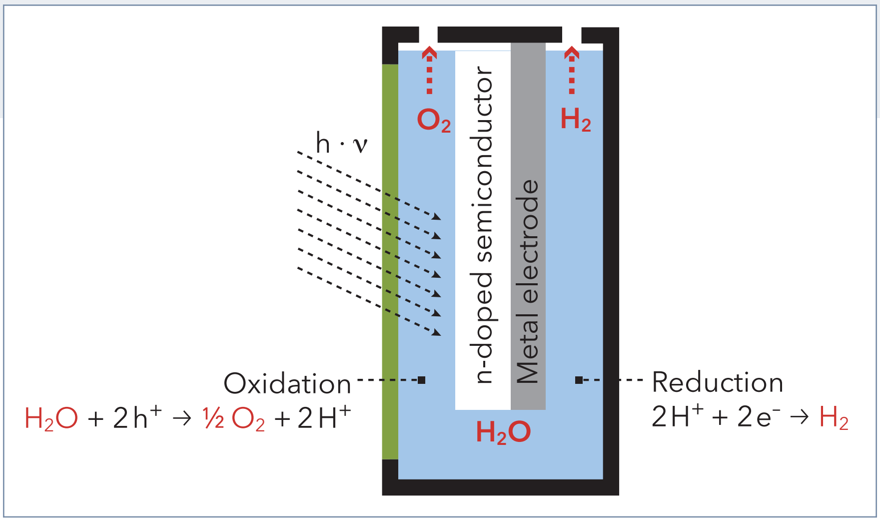


Diagram of photoelectrolytic hydrogen production. Electron hole pairs are created in the semiconductor by the absorption of light energy.
If a semiconductor is in contact with a metal auxiliary electrode, a photovoltage results, leading to splitting of the aqueous electrolyte into hydrogen and oxygen. (Source: ODB-Tec)

Photoelectrolytic hydrogen production

A very promising approach is photoelectrolytic water splitting. Here, the absorption of light at photoelectrodes in a photocell results in the photochemical separation of water, whereby oxygen oxidises at the anode and hydrogen atoms are reduced to elementary hydrogen at the cathode. These processes currently display only low conversion efficiencies. Great efforts go into pursuing efficiency optimisation. Nanostructuring and the selection of suitable material systems play a decisive role here.

Important criteria for the selection of semiconductor materials for photoelectrodes include their stability in aqueous solutions and the conversion efficiency resulting from band gaps optimally coordinated with the redox potentials of water. III/V semiconductor stacked cells display promising conversion efficiencies, but are generally unstable in aqueous media and expensive to manufacture. One alternative is cost-effective metal oxides, for example of the elements titanium, manganese, iron or tin as electrode materials. By using nanostructuring and nanocrystalline substances, further optimisation is possible. Non-metallic materials also appear promising. For example, good conversion efficiencies of around ten percent in the visible light range were achieved with carbon quantum dot and carbon nitride nanocomposites (Liu et al. 2015). However, photoelectrolytic water splitting processes are still at the research stage. Large scale economic applications are not currently envisaged.

3.7.2 Biofuels

Against the backdrop of climate protection, reducing the carbon dioxide input into the atmosphere is one of our most important social challenges. The EU's renewable energy directives stipulate that the proportion of renewable energy in the transport sector must be increased to ten percent by 2020. The gradual replacement of mineral fuels by biofuels, produced from renewable resources or biomass, will make a substantial contribution to this. However, the energy utilisation of biofuels is not uncontroversial in terms of climate policy, because it is associated with high land use and may be in competition with foodstuff production. The most important liquid biofuels are bioethanol and biodiesel, but biokerosene, biomethanol and certain vegetable oils also play a role.

First, second and third generation biofuels are often differentiated. In first generation fuels, only the fruit is utilised. Second generation fuels utilise the entire crop mass. Their production processes are often characterised by the designation BtL (Biomass-to-Liquid). Fuels from algae cultures, in particular, are referred to as third generation fuels. Compared to other energy crops, they display much greater productivity per unit area.

Nanotechnology application opportunities

A variety of processes for the production of biofuels are now established. Intense research into the optimisation of numerous process steps and the development of new second generation methods, in particular, is ongoing. Nanotechnologies deliver optimisation contributions in monitoring process technology using sensors and, especially, in conversion methods. Numerous process paths are aimed at generating synthesis gas from the thermochemical gasification of biomass. Liquid fuels can be synthesised (also referred to as the Fischer-Tropsch process) from the gas mixture consisting of hydrogen, carbon gases, sulphur and nitrogen compounds. Nanostructured catalysts, such as zeolites, for example, are often used to increase the efficiency of the synthesis reaction.

3.7.3 Power-to-Gas

The term power-to-gas describes a process that uses excess electricity for the large-scale generation of hydrogen gas by electrolysis as the fundamental process step (also known as power-to-hydrogen, PtH). Optionally, methane is produced in a subsequent step. If necessary, the hydrogen or the methane can be reconverted using fuel cells or gas turbines.

Intense work is being carried out on testing and optimising power-to-gas processes and a number of demonstration facilities have been commissioned. For example, the Hessian Ministry of Economics, funds the joint demonstration project involving SolviCore, RheinMain University of Applied Sciences, Mainova and the Hanau municipal utility company (German: Stadtwerke Hanau), in which hydrogen is generated from renewable electricity in Wolfgang Industrial Park. Among other things PEM electrolysis technology (PEM: Proton Exchange Membrane) is tested. In addition to conversion efficiency, the focus is on the dynamic operation of electrolysis under fluctuating conditions, as given by the irregular supply of wind and solar power. The EKOLYSER project, as part of the Federal Government's energy storage systems funding initiative and involving SolviCore, researches new and cost-effective materials for PEM electrolysis. For example, the aim is to develop new membrane materials and reduce the proportion of expensive precious metals in the catalyst.

Another power-to-gas concept demonstration facility in Hessen is located in Frankfurt am Main. Under the leadership of Mainova it analyses the technical feasibility of converting electricity from renewable energy forms to hydrogen and feeding in hydrogen to municipal gas networks (DENA 2015).

The hydrogen produced using the power-to-gas process can be utilised directly or stored in pressurised reservoirs or in the natural gas network. Up to five percent hydrogen may be introduced into the public gas network. Extrapolated to the entire German natural gas network, this corresponds to a huge amount of hydrogen.

Methanisation

In order to integrate power-based hydrogen in the gas sector beyond the direct feeding-in of hydrogen, it is possible to chemically convert the hydrogen gas to methane by adding concentrated carbon dioxide gas as accumulated in coal-fired power plants or industrial plants like cement production or biogas plants, and to then feed it in to the natural gas network. The methanisation reaction has to be performed by microorganisms or initiated by using catalysts. In the latter case, the efficiency of the catalytic process depends on the material and the surface characteristics. Nickel catalysts are primarily used; among others, ruthenium is also being tested. Catalyst efficiency optimisation can be achieved by nanostructuring. This allows the surface accessible to the reactants to be increased. However, methanisation goes hand in hand with a reduction in the overall efficiency and with additional costs, but allows less problematic feed-in to the natural gas network than does hydrogen.

The achievable efficiencies for hydrogen production are currently around 64 percent. If the methanisation stage is downstream, the overall efficiency is reduced further to around 50 percent (Krause and Müller-Syring 2011). For comparison: for direct electricity transport and energy storage in a pumped storage power plant, the efficiency is greater than 70 percent. However, the storage capacity of pumped storage in Germany is very limited.

Work on the development and optimisation of electrolysis methods to improve the efficiency of the power-to-gas process is intense. Efficiencies of 90 percent appear achievable in the foreseeable future. Other development objectives are to make electrolysers more flexible in terms of a fluctuating electricity supply and frequent load changes, and the upscaling of production processes. Nanotechnologies play a key role here in terms of the further development of electrolysis (see Section 3.7.1).

Process engineering and the methanisation stage are also being developed further. For example, a current Fraunhofer Institute for Wind Energy and Energy Systems Technology IWES research project utilises the carbon dioxide contained in biogas as a CO_2 source without previous separation or complex scrubbing stages. The gas produced using this direct methanisation is therefore of 100 percent renewable origin. Corresponding demonstration facilities are located at the Hessische Biogas-Forschungszentrum (HBFZ) (Hessen Biogas Research Centre) in Bad Hersfeld and at the Viessman factory in Allendorf (Eder).

Power-to-Liquid

In a process related to methane production by power-to-gas processes, so-called power-to-liquid processes are being researched, which produce liquid fuels instead of gases from electrical energy, water and carbon dioxide (CO_2). These approaches are based on the production of synthesis gas, a mixture of carbon monoxide and hydrogen, whereby the carbon monoxide is chemically reduced from CO_2. Liquid hydrocarbons such as diesel, petrol, etc., can be specifically synthesised from this synthesis gas. In Germany, power-to-liquid is being addressed with the aid of extensive funding by the Federal Ministry for Education and Research, among others. The aim is to develop the technology to industrial scale. However, compared to power-to-gas processes, power-to-liquid is still at an early research stage.

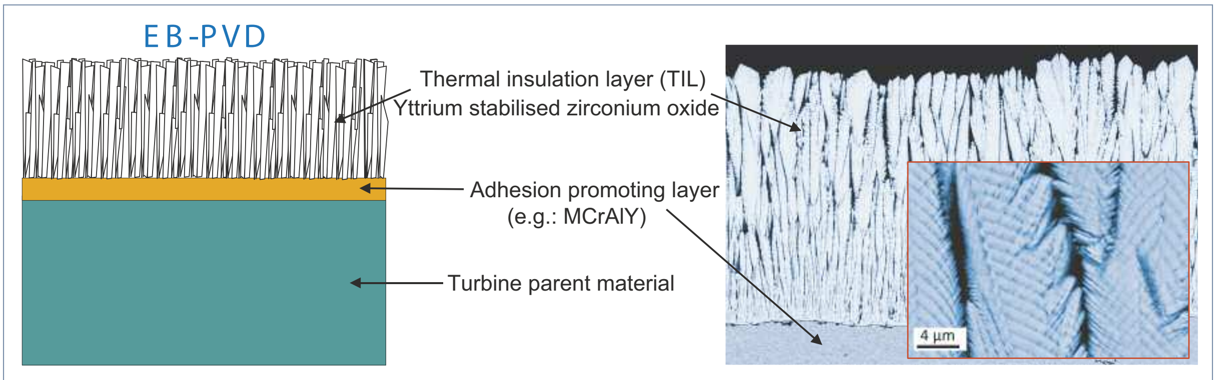
Power-to-gas plant in Allendorf (Eder), Hessen, which was realised as part of a project funded by the Federal Ministry for Economic Affairs and Energy. (Source: Viessmann Werke)

3.8 Power Generation by Fossil Fuel-Fired Power Plants

Despite growing efforts to develop renewable energy sources, the conversion of fossil fuels to power and heat still represent the backbone of today's global energy supply. To save resources and reduce carbon dioxide emissions, conversion processes that are as efficient as possible are required. Optimisation potentials are available in coal-fired power plants, in particular, because they represent a large percentage of global power generation. The world's operational black coal power plants have an average efficiency of around 30 percent, while new plants exhibit efficiencies of more than 45 percent. Gas turbine power plants achieve efficiencies of around 60 percent. By completely replacing the world's operational black coal power plants with modern plants, carbon dioxide emissions from firing black coal for power could be reduced by 35 percent (DECHEMA 2007).

Gas turbine. (Source: industrieblick / Fotolia.com)

Optimisation by further increasing power plant efficiency would require higher working temperatures while simultaneously retaining the fundamental power plant processes. One prerequisite for achieving these efficiency improvements and CO_2 savings potentials is the availability of new, extremely heat resistant materials. Other approaches for reducing CO_2 emissions are available in the separation and storage of carbon dioxide in underground reservoirs (CCS: carbon capture and storage) or otherwise utilising the separated carbon dioxide. In addition to coal-fired power generation, CCS technologies could also be employed in other high CO_2 industries such as in steel, aluminium and cement production, for example. Currently, more than 20 large CCS projects are operating globally. Once initial pilot projects had run their course, CCS research activities in Germany have generally been discontinued as a result of current structural changes and falling profits in the energy sector. The energy group Vattenfall aims to exploit the insights gained in its 'Schwarze Pumpe' oxyfuel CCS pilot plant in Canada. Generally speaking, CCS technologies are associated with significant costs for the power plant operator, assuming 85 to 100 percent carbon dioxide capture, depending on the type of process, and overall efficiency losses of around ten percent. However, in the long term, the separation of carbon dioxide from power plant processes is regarded as an important baseline technology for converting to a climate friendly energy system on a global level.



Structure of thermal insulation layers produced by means of electron beam physical vapour deposition.
(Source: TU Darmstadt, Institut für Werkstoffkunde)

Residues on electrostatic filter funnels in power plants or waste incineration plants can be avoided by using ceramic nanocoatings. The coating ensures that dust can run off and does not lead to adherence or plugging in the funnel. (Source: CeraNovis GmbH)

Nanotechnology application opportunities

Nanostructured thermal insulation layers for gas turbines

Thermal insulation layers are indispensable for protecting gas turbine blades against heat. At 1,500 degrees Celsius, the gas temperatures at the turbine inlet are substantially higher than the melting point of the turbine materials used. The principal demands on thermal insulation layers include low thermal conductivity and thermal expansion properties suited to the substrate, in order to minimise stresses and crack formation in the material. Modern, multi-source plasma coating methods allow complex thermal insulation systems, consisting of active, adhesion and barrier layers, to be manufactured with nanoscale precision and a variety of material combinations. This creates additional optimisation potentials, for example to further reduce the thermal conductivity of the layers, increase the durability of the turbine components and thus to facilitate higher operating temperatures. The efficiency of gas turbines can thus be further enhanced, leading to considerable cost and carbon dioxide emission savings.

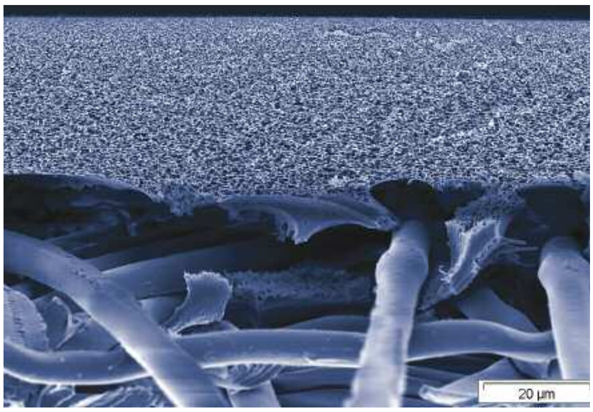
Nanostructured membranes for carbon dioxide separation

The separation of carbon dioxide from coal-fired power plant flue gas is currently one of the most intensely driven technological developments for achieving CO_2-neutral coal-fired power plants or respectively the use of carbon dioxide as a raw material. Nanotechnologies may contribute to the development of methods for selective separation of carbon dioxide using specific membranes, for example, by the use of nanostructured polymer membranes coated with catalysts, which convert the carbon dioxide to hydrogen carbonate in the presence of water. The solid hydrogen carbonate can then be easily separated from the remaining flue gas constituents.

Another possible option is the development of ceramic nanotubes, facilitating the highly efficient separation of oxygen from the air. If this pure oxygen was used for the combustion of fossil fuels, the flue gas would almost exclusively consist of carbon dioxide, which could then be easily separated and utilised.

Anti-adhesive coatings for boilers and heat exchangers in coal-fired power plants

One of the problems in operating coal-fired power plants or waste incineration power plants are encrustations of combustion residues in the boiler and heat exchangers, which must be expensively serviced at regular intervals. Ceramic anti-adhesive coatings based on nanoparticle coating materials substantially reduce encrustations, thereby increasing the service life of heat exchanger tubes and extending servicing intervals.



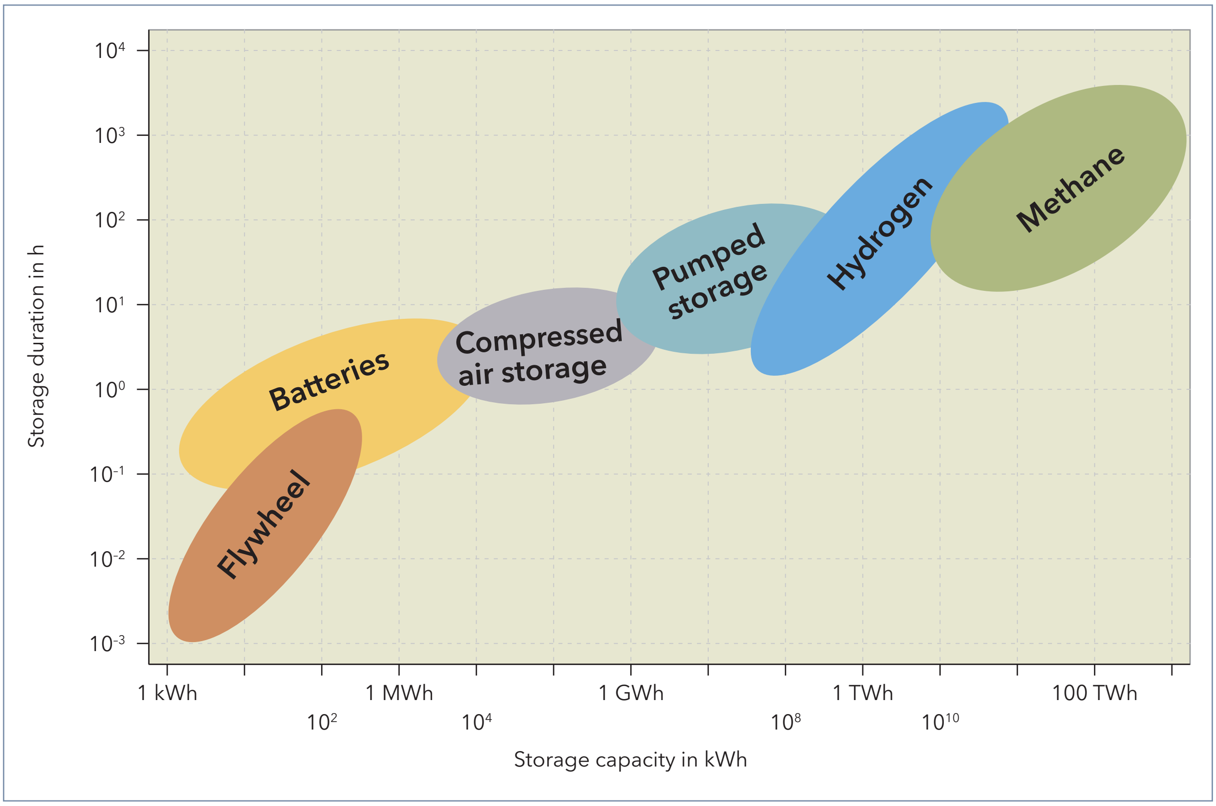
Nanostructured membranes play a key role in selective gas separation. (Source: Helmholtz-Zentrum Geesthacht)

4. Energy Storage

Regenerative sources such as solar, wind and hydropower increasingly contribute to power supplies in Germany. The Federal Government's energy strategy aims for a 35 percent share of power generation from renewable sources in gross power consumption by 2020. It aims to increase this share further to 50 percent by 2030. However, because renewable power generation is closely linked to weather conditions, the development and use of high capacity energy storage systems play a critical role. With their aid, it is possible to adapt the daily and annually fluctuating energy supply to demand. Moreover, they can contribute to mains power grid stabilisation by providing energy at short notice.

Energy can be stored in a number of formats: The storage options range from mechanical flywheels, through batteries, compressed air and pumped storage systems, and on to gas storage in pressurised tanks, gas networks and cavern storage systems. The natural gas network possesses the most extensive storage capacity and simultaneously offers the longest storage duration. In principle, this makes seasonal buffering in the range of several months possible.

Particularly relevant to these applications are electrochemical storage systems, chemical energy storage systems (for example for hydrogen and methane or natural gas) and thermal storage systems.



Energy storage technologies compared (kWh: kilowatt hours). (Source: DLR)

4.1 Electrochemical Storage Systems

Electrical power is a universally utilisable energy source. Systems that allow the direct storage of electricity without conversion to other types of energy are therefore particularly relevant.

The range of applications of electrochemical energy storage systems is wide. It can be initially divided into mobile and stationary applications. In terms of mobile applications, the fields of electromobility and portable small electronics such as smartphones, tablets, etc., are differentiated. Stationary applications can be differentiated into large-scale storage and decentralised systems.

The availability of high capacity energy storage systems with high efficiencies, energy and power densities are critically important for all of these applications. The primary drivers of innovation in Germany are the energy revolution and the precise shape of future mobility concepts. For example, one of the Federal Government's objectives is to see one million electric vehicles on the roads by 2020. Parallel to this, hybrid vehicle drives are becoming more widespread. Local public transport also offers additional potential.

In the field of stationary decentralised storage, the expansion of internal consumption plays an increasing role. The feed-in tariffs for domestic solar power installations will continue to fall in line with the requirements of the Renewable Energy Sources Act. Installation of these systems now often only pays off for home owners with optimised self-use of the generated energy. Greater internal consumption necessitates suitable storage systems. Complete systems consisting of solar power installation, storage battery and the corresponding energy management system are increasingly available commercially.

In view of the expansion of renewable energy forms, large scale storage systems for the mains power grids are also becoming increasingly relevant. They can provide a buffer between fluctuating power generation and power demand. Moreover, they can compensate for fluctuating renewable energy sources and contribute to stabilising municipal and regional grids. A share of fluctuating power sources greater than 15 percent can cause instabilities in local grids. Given a storage potential of four hours, this threshold value can be increased from 60 to 70 percent (H2BZ 2013).

In an emergency, large batteries can even bridge short-term power failures and provide an uninterrupted power supply. The potentials of an extensive electric vehicle fleet are also discussed in this context. It may be possible to also utilise their batteries for energy storage, accepting excess power from the grid and feeding it back in as necessary.

Supercapacitors

Supercapacitors are electrochemical double-layer capacitors characterised by a high power density. They consist of two flat electrodes, are surrounded by an electrolyte and kept apart by a separator. The charge carriers accumulate at the electrodes and are stored there. Because the storage capacity is a function of the surface area of the electrode, nanostructuring and the associated increase in surface area can achieve a substantial increase in the performance of supercapacitors.

(Source: Petair / Fotolia.com)

Supercapacitors with energy densities in excess of ten watt hours per kilogram are now being marketed. Substantially higher values are already being achieved in the laboratory (Zhang et al. 2013). However, compared to batteries, only small amounts of energy can be stored. The storage capacity of modern lithium ion batteries, for example, is more than ten times greater. The advantage, however, lies in the high power density of supercapacitors. Typically, and in contrast to batteries, energy storage is not facilitated by creating chemical bonds. This means that supercapacitors have greater cyclic stability (number of charging and discharging cycles), and charging and discharging are not limited by slow chemical reactions. The power density determines not only the amount of energy stored but also the speed of charging and discharging. Supercapacitors are therefore especially suitable for the rapid acceptance and delivery of electrical energy (so-called peak power). Their range covers mobile applications, in which large amounts of energy must be delivered or accepted in a short time (for example, when recuperating the braking energy in electric cars, or during acceleration).

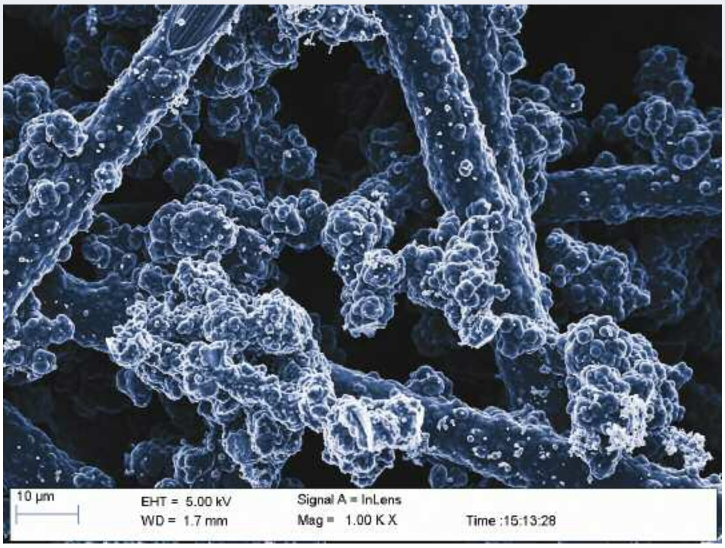
Lithium ion battery for electric cars. (Source: iStock.com/zorazhuang)

Batteries

In batteries, chemical energy is stored at the molecular level in certain material systems consisting of electrodes and electrolytes. The chemical energy can be converted to electrical energy in electrochemical reactions. Rechargeable batteries, also known as accumulators, are particularly important with regard to future energy, mobility, Internet and communications challenges. With them, the conversion of chemical to electrical energy is reversible. They can be charged and discharged many times. The governing parameters are the achievable storage capacity/energy density, the charging and discharging speed (power density), the cyclic stability or service life, and the size, weight and manufacturing costs. A wide range of different material systems are used in batteries.

During the last ten years, lithium ion technology has come to the fore wherever size and weight are particularly important. It is used in rechargeable batteries for portable electronics, as well as in traction batteries in the electromobility field. Stationary power storage is another growing application field.

Lithium systems are regarded as one of the most promising future power storage options. Compared to traditional batteries such as lead-acid batteries, for example, they deliver considerably higher cell voltages and energy densities. Technologies based on lithium, cobalt, lithium-nickel or lithium-manganese are now well established. More recent developments such as lithium-phosphate and lithium-titanate systems are now also matured and available on the market. The achievable energy densities in series production are up to 200 watt hours per kilogram.



Scanning electron microscope photo of a fibre-reinforced carbon-aerogel that is used as an electrode material in supercapacitors. (Source: ZAE)

Despite these high values for batteries, a comparison with the 11,000 watt hours per kilogram energy content of mineral oil is modest. In particular against the backdrop of the desired expansion of electromobility, much energy is currently being expended in battery research to increase energy density.

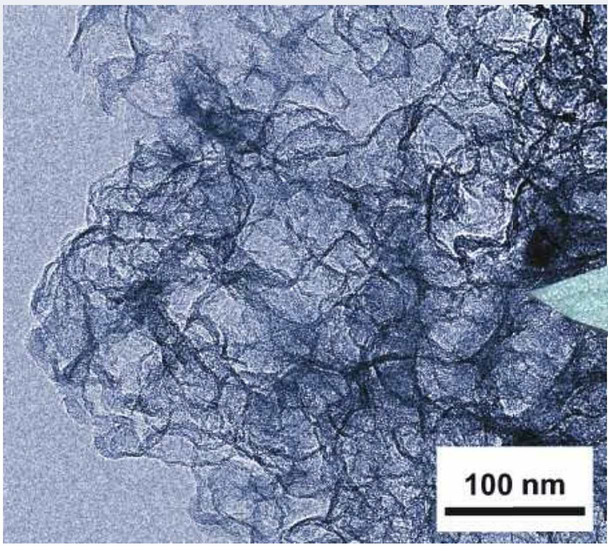
Lithium-sulphur (LiS) based systems are regarded as having a large potential. LiS batteries are viewed as being particularly favourable and promise an increase in energy storage capacity by a factor of three or four compared to conventional lithium ion technology. However, market maturity is not anticipated for around ten to fifteen years. Research into lithium-sulphur systems is global and German research institutions are also intensely occupied with this technology.

The development of so-called metal-air battery concepts, in which the ambient air, or more exactly, the oxygen it contains, replaces the cathode, is even longer term. The lithium-oxygen system, presenting the possibility of energy densities greater than 1,000 watt hours per kilogram, is especially promising. However, market maturity is not anticipated for at least fifteen to twenty years.

Nanotechnology application opportunities

The use of nanotechnologies is increasingly seen as a prerequisite for powerful batteries and supercapacitors. In terms of the demands on the various applications, a wide range of criteria need to be optimised, among others, the energy and power densities, service life, fast reaction times, large operating temperature range, robust safety and high efficiency. Development objectives include electrodes with high charging/discharging capacity, for example, using nanoporous carbon materials (for example, carbon aerogel, carbon nanotubes, graphene, etc.), higher cell voltages facilitated by using mixed oxides, the substitution of organic liquid electrolytes with polymer electrolytes, or the use of nanomaterial-based ceramic films as separators.

Graphene-based supercapacitor SkelCap 4500F. (Source: Skeleton Technologies)



Left: Nanostructured carbon as substrate for sulphur cathodes. (Source: Fraunhofer IWS)
Right: Free-standing carbon/sulphur nanocomposite electrodes. (Source: Fraunhofer IWS)

As nanoporous substances, carbon aerogels are eminently suitable as graphitic electrode materials in supercapacitors, because of their extremely large internal surfaces, adjustable pore distribution and pore diameters. Other electrode designs are based on nanocrystalline graphite, carbon nanotubes and other, generally carbon-based, materials.

Innovative developments utilise the surface properties on monolayered carbon, known as graphene. Embedding lithium ions in the electrodes has proven beneficial. With these lithium supercapacitors the beginnings of mass production and initial commercial marketing can already be recognised.

4.2 Hydrogen Storage Systems

In a future energy system, chemical energy sources gained from regenerative sources, in particular hydrogen, will play an increasingly important role. In addition to the necessary infrastructure adaptations, the efficient storage of hydrogen is regarded as one of the critical success factors on the road to a possible hydrogen economy. This is especially the case for mobile applications, in which the hydrogen is stored in a compressed form. In addition to the traditional high-pressure or liquefied gas storage, the industry uses chemical hydrogen storage systems consisting of metal hydride compounds, in particular. However, the currently available storage methods still display a number of disadvantages, which rule out broad economic use.

High-pressure storage systems are very heavy; liquefied gas storage is expensive because it must be highly insulated to keep losses from hydrogen evaporation as low as possible. Metal hydride storage systems are also associated with high costs and are relatively heavy. Moreover, the materials currently employed for chemical storage do not correspond to the technical and economical requirements as demanded by the automotive industry, for example, in terms of a hydrogen storage capacity of up to ten percent by weight.

Hydrogen storage system overview				
Storage medium	**Temperature or pressure**	**Weight* or volume***	**Storage capacity**	**+ Advantages/– disadvantages**
Liquid hydrogen	–270 °C	140 kg, 86 l	7.5 % by weight	+ low space demand – highly elaborate insulation – energy loss due to gas liquefaction – gas escape during storage
Gaseous hydrogen	700 bar	125 kg, 260 l	6 % by weight	+ small technical investment – large space required for cylindrical high-pressure tank – high storage pressure represents safety risk
Nanoscaled metal hydrides (for example MgH_2)	> 300 °C, 8 bar	175 kg, 73 l	4–7 % by weight	+ little space required – high weight – very high temperatures required
Nanoporous metal-organic materials (MOFs) (for example MOF-177)	< –210 °C, > 50 bar	86 kg, 160 l	7,5 % by weight	+ low weight – low temperature – large space required

*Calculated for 500 km range.
Various hydrogen storage systems compared.
(Image: VDI TZ; data sources: Prof. Dr. Stefan Kaskel, TU Dresden, and Prof. Dr. Birgit Scheppat, RheinMain University of Applied Sciences)

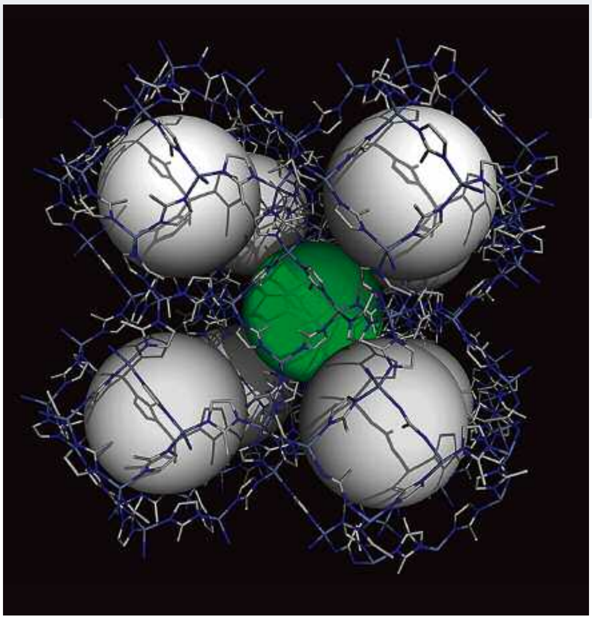
Nanotechnology application opportunities

Research in recent years has demonstrated that nanomaterials offer promising development potentials as hydrogen storage systems for operating fuel cells in vehicles and in mobile electronics. Research is being carried out on a variety of nanostructured solid state storage systems, capable of efficiently binding and discharging hydrogen, either chemically or by adsorption. Highly porous materials or complex hydrides, in which hydrogen is chemically reversibly stored in the lattice structure, appear promising here. Complex hydrides are compounds similar to salt consisting of hydrogen and light alloy mixtures, such as the alkali metal hydrides, for example lithium borohydride, which contain gravimetric hydrogen densities up to 20 percent. However, only part of this can be used as a reversible hydrogen storage system; in addition, the high temperatures required to liberate the hydrogen again are problematic, for both practical and economic reasons.

Porous metal borohydrides such as magnesium borohydride, which, as a light alloy hydride, also possesses a highly porous metal organic skeleton structure (33 percent pore volume), are more advantageous. Such materials can not only store large weight percentages of hydrogen (14.9 to 17.4 percent) but can also liberate the hydrogen again at relatively low temperatures (approximately 300 degrees Celsius). In the EU-funded research project BOR4STORE – Development of solid state hydrogen storage from fundamentals to application, a number of borohydride materials are being investigated and developed to achieve efficient hydrogen storage.

Another approach is based on nanoporous metal-organic compounds (so-called metal-organic frameworks, or MOFs), which provide very high specific surfaces of greater than 6,000 square metres per gram. This means that one gram of this compound has a surface area corresponding to the area of a football field. The material structure consists of metallic clusters (for example copper, chromium, zinc) and organic bridging molecules. However, the currently achievable storage capacities are still relatively far removed from any possible use as hydrogen storage systems in automobiles. The first cost-effective applications are therefore anticipated more for operating fuel cells in mobile electronics. In general terms, however, much remains to be researched in the development of solid state storage systems.

Sodium aluminium hydride / hydrogen storage tank.
(Source: Helmholtz-Zentrum Geesthacht / Christian Schmid)



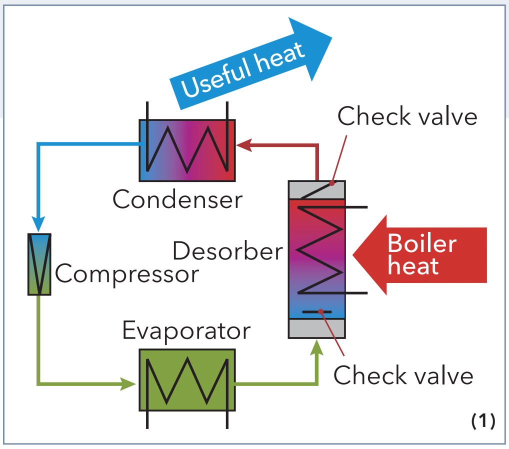
Metal-organic skeleton structure materials with pore sizes up to three by three nanometres, which allow extremely high storage capacities for gaseous hydrogen. (Source: Fraunhofer ICT)

4.3 Thermal Storage Systems

There are a variety of technical options available for storing thermal energy and liberating it again when needed. So-called latent heat storage systems are already widespread. They consist of phase change materials, or PCMs, which can absorb heat in a reversible phase transition in the operating temperature range and liberate it into the environment again. The storage substances are salt hydrates or organic compounds, such as paraffins and sugar alcohols. Phase change storage systems are used for thermostatic control in buildings, for example. Phase change materials are also being developed by automobile manufacturers to store waste exhaust heat, which can then be used to reduce energy consumption, among other things, to quickly warm the engine on cold starts. Phase change storage system products developed for this purpose by Merck, for example, are available on the market.

Other thermal storage system concepts are based on the use of so-called adsorption storage systems, using zeolites or silica gels, for example. These storage systems can dry out when heat is added (charged) and liberate heat again by passing moist air through them (discharged). Adsorption storage system applications include zeolite heating systems for residential buildings, for example, heating systems from Viessmann and Vaillant, or a zeolite dishwasher offered by Siemens.

When heating buildings using solar thermal collectors, in particular, high-capacity thermal storage systems are necessary to increase the solar proportion in the annual useful heat, by making available in winter the solar heat stored during the summer months.



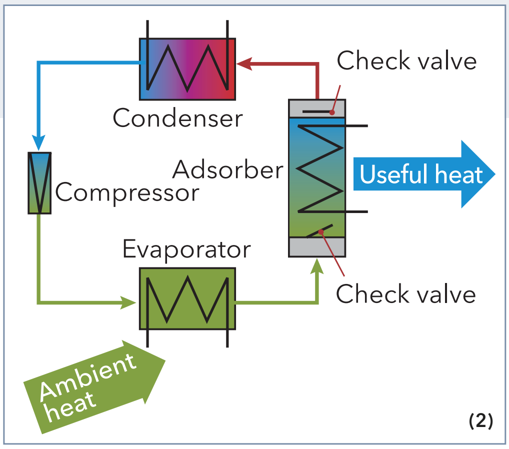
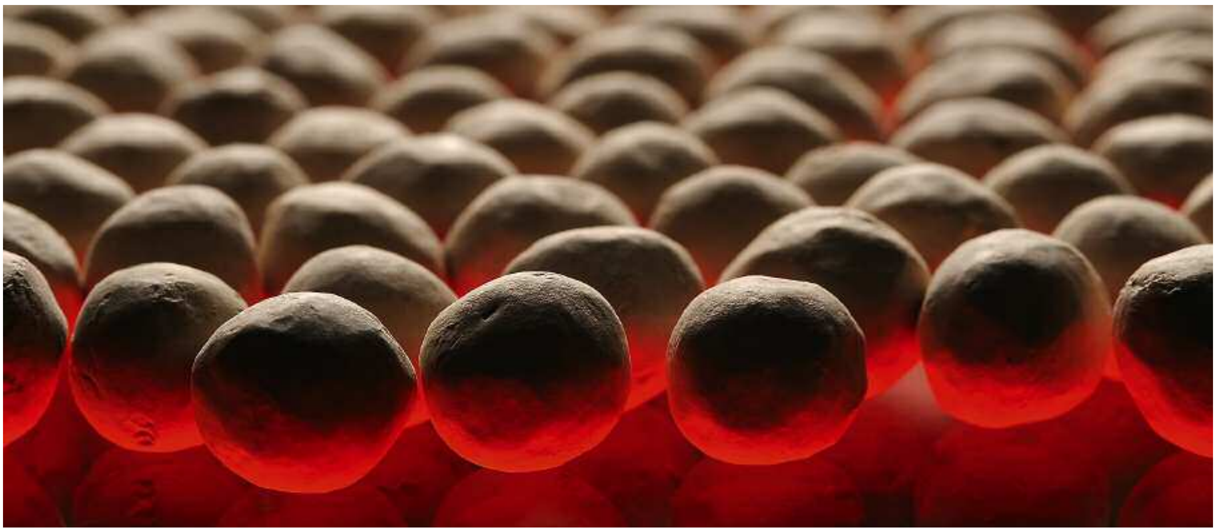


Diagram of a periodic adsorption heat pump consisting of a sorber heat exchanger, operating as desorber **(1)** or adsorber **(2)**, depending on the operating phase. The condensation and latent heat of the water vapour in the zeolite structures is delivered as useful heat to the heating loop. (Source: Viessmann)

Nanotechnology application opportunities

Nanotechnologies play an important role in the development of efficient thermal storage systems. For example, in zeolites, nanometre-sized pores are deliberately configured such that the bonding strength of the water molecules to be incorporated, or the energy density, are increased. Moreover, the heat and substance transport in adsorption thermal storage systems can be improved by using nanofluids.

Phase change storage systems based on nanoencapsulation and nanocomposites such as nanographite or carbon nanotube phase change composite materials are also being developed in order to enhance the thermal conductivity and heat transport within the storage systems.



Various materials like ceramic beads, liquid salts, different types of concrete and natural stones are investigated with respect to their potential as heat-storage systems. (Source: DLR (CC-BY 3.0))

5. Energy Distribution

5.1 Low-Loss Power Supply and Conversion

The growing deployment of renewable energy sources to generate electricity increasingly necessitates transporting power over large distances from the point of generation to the final consumer. The expansion and conversion of power distribution grids therefore represent a central aspect of the energy revolution. In this context, technologies transmitting high power output with only minor losses have a role to play. These predominantly comprise the superconductors and new transmission technologies such as high-voltage direct current transmission.

Low-loss power supply using nanostructured superconductors

Superconductors will increasingly assume a role in power engineering in loss-free cable-based power transmission, in coil windings and the bearings of electric motors, and in ground current limiters in high-voltage grids. The world's longest superconducting cable, at 1,000 metres in length, has been installed in Essen city centre since 2014, where it connects two transformer stations. It saves the space for routing and a transformer because a lower voltage than usual is sufficient due to the transmission without losses. For reasons of cost the high-temperature superconductors are more interesting, which use high-tech materials based on oxide ceramics.

Processing the brittle metal ceramics to technically utilisable components such as flexible wires and cables is a particular technical challenge. Control of the material at the nanoscale plays a decisive role in the manufacture of high-temperature superconductors using flat wires produced from a powder-filled tube or thin-film techniques. Sufficient current carrying capacity in the high-temperature superconductors is only achieved by highly homogeneous ceramics nanostructuring. In wire manufacturing from tubes, the ceramics are initially in powder form. This powder contains both coarse particles (grain sizes greater than two micrometres) and an approximately ten percent proportion of nanoparticles. The nano proportion is the key to the quality and performance of the material because during sintering, this is what bonds the grains such that their current carrying capacity becomes a macroscopically exploitable property. When using thin-film coatings, so-called nanodots, that is, extrinsic phases such as yttrium oxide, are generated or added on a nanometre scale (approximately 35 nanometres, finely distributed) in order to contribute to performance enhancement.

Structure of the superconductor cable beneath Essen city centre: the superconductor cable is provided with central nitrogen feed **(1)** for nitrogen cooling. Three superconductor layers **(2)** alternate with polypropylene coated paper insulation **(3)**. This is followed by copper screening **(4)** and a nitrogen return **(5)**. All layers are amalgamated in what is known as the cryostat **(6)**, a double-skinned, corrugated stainless steel, super-insulated vacuum enclosure. The outside of the double-skinned, super-insulated cryostats is protected by a polyethylene casing.
(Source: BINE Informationsdienst / Anna Durst)

Considerable advances have been made in recent years in the development of high-temperature superconductors thanks to the manufacturing of yttrium-barium-copper oxide (YBCO) on metallic substrates (so-called coated conductors), which have substantially extended the processability and usability of this material class. The greatest challenge is manufacturing all deposited coatings (superconductor and buffer protection coatings) by chemical means from low-cost precursors, in order to decrease costs to an economically attractive range. In the long term, other nanomaterials such as carbon nanotube composites, representing highly efficient conductors, may offer an alternative for low-loss electricity transmission. However, this requires substantial advances in terms of economical processes and technologies for manufacturing longer, homogeneous carbon nanotube fibres.

Nanostructured insulation materials for high-voltage lines

The efficiency of power transmission in high-voltage lines increases with increasing voltage. In Europe, power is generally transmitted at approximately 400 kilovolts, while in large countries such as China and India, 1,500 kilovolts are aimed for. The electrical and mechanical loads on high-voltage lines grow with increased voltages and the multiple feed-in points of decentralised power generators, as well as by supplying large conurbations. One of the central roles of high-voltage engineering is therefore to develop electrical insulation systems, for example by using nanomaterials. The material design at the nano scale allows the electrical insulation properties, such as the breakdown voltage, to be optimised, for example, by using nanostructured metal oxide powder in varistors to protect against overvoltages in power lines. Multifunctional, non-linear and auto-adaptive insulation systems are currently being developed, whose electrical and mechanical properties change with the field strength, the temperature or the mechanical load, and which adapt optimally to the performance demands.

5.2 Smart Grids

The globally advancing liberalisation of the power markets and further decentralisation of production noticeably increase the demands on the flexibility of the power grids. Any trans-European power trading system requires efficient power distribution, even over large distances, flexible adaptation to occasionally heavily fluctuating demands, as well as rapid control of the load flow, in order to limit the extent of grid perturbations and the risk of widespread blackouts. In terms of the growing decentralised power feed-in from fluctuating regenerative power sources, the existing power distribution grid is also increasingly reaching its limits. Efficient power distribution demands power grids that allow dynamic load and fault management, and demand-driven power supply with flexible price mechanisms. Nanotechnologies could provide valuable contributions to achieving this vision, for example by using nanosensory and power electronics components, which are capable of managing the extremely complex control and monitoring of these types of power grid.

Nanooptimised power electronics and sensors

Transforming and controlling strong current-using power electronics components will increase in relevance in the future. Power electronics guarantees low-loss power transformation en route to the final consumer and also plays a central role in transmitting power through long submarine cables. Similarly, decentrally generated photovoltaic electricity can only be utilised after power electronics transformation in inverters. Further development of power semiconductors using materials with large band gaps, such as silicon carbide, facilitates applications for high voltages (transmission grids and railways) or high temperatures (for example for controlling electric motors in automobiles). The development of power electronics can profit greatly from nanotechnologies, for example, by the optimisation of the coating design in so-called wide band gap semiconductors or the use of carbon nanotubes as connecting wires for high current flows and minimal heat development.

Miniaturised, magnetoresistive sensors based on magnetic nanocoatings offer the potential of facilitating the complete online measurement of current and voltage parameters in the power grid. One example of this is a wireless sensor network for monitoring overhead transmission cables, which can increase the transmission capacities of high- and extra high-voltage lines. The energy autarkic microsensors determine the prevalent current flow at 500 metre intervals, the cable temperature, the sag and the wind movement, and transmit these data to a receiving station. Here, using the recorded data, grid capacities can be quickly increased because reserves are utilised that result from the difference between the weather forecast and the true condition of the cables. The Fraunhofer Institute for Electronic Nanosystems ENAS has implemented this technology in the ASTROSE (Autarkic Sensor Network for Power Engineering Monitoring; German: Autarkes Sensornetzwerk zum Monitoring in der Energietechnik) project, which started pilot operations at the end of 2014.

Nanocrystalline soft magnet materials for intelligent power grids

Due to properties such as high permeability and temperature stability, nanocrystalline soft magnet materials, which can be manufactured by rapid solidification processes applied to iron alloys, for example, are eminently suitable for power engineering applications. These materials are employed in low-loss transformers, such as, for example, electronic power meters, residual current operated circuit-breakers or power electronics components. Companies in Hessen such as Vakuumtechnik in Hanau or MAGNETEC in Langenselbold (see success story in Section 7.7) are global market leaders in marketing these nanocrystalline magnetic materials as toroidal cores for diverse electrotechnical applications.

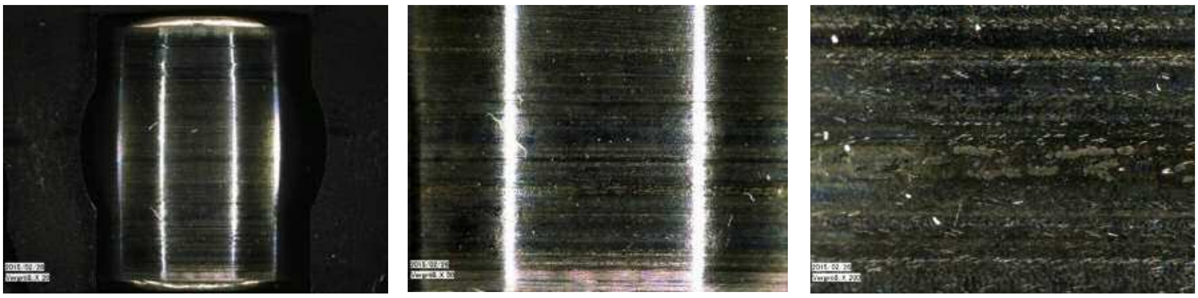
6. Energy Efficiency in Industrial Applications

In the short term, nanotechnologies will primarily have the greatest impact in efficient energy utilisation in terms of reducing resource use and carbon dioxide emissions in the energy sector. In almost all branches of industry and in the private sector, nanotechnologically optimised products and production facilities present considerable energy-saving potentials.

Numerous examples of applications in the respective branches can be found in the series of brochures published by Hessen-Nanotech (for example, automotive, civil engineering, bionics, optics, production technology). Some examples of the most relevant applications are described below.

6.1 Friction Reduction in Machines and Vehicles

Around ten to fifteen percent of the fuel consumption of car combustion engines is determined by friction in the engine. By coating the moving engine components such as the cylinders, pistons and valves with nanocrystalline composite materials, friction and wear can be reduced and thus fuel saved. Nanocrystalline piezomaterials and nano wear protection coatings based on DLC (diamond-like carbon) allow the efficiency and precision of diesel injectors to be optimised.



Microscopy of rolling-element bearing, Castrol X320 without REWITEC®

Microscopy of rolling-element bearing, Castrol X320 with 0,2 % REWITEC®

Long-term stress tests of rolling-element bearings demonstrate the reduction in wear due to REWITEC additives compared to untreated lubricants. (Source: REWITEC)

REWITEC, in Lahnau, has developed an innovative coating technology, which ceramises the surfaces of metallic components in engines, transmissions, etc., using nanoparticles, thus protecting them from wear. The nanoparticles react with the metal surfaces at the pressures and temperatures caused by the friction contact to form hard ceramic compounds. This not only prevents new damage to the components, but previous mechanical damage can even be compensated for and repaired. In addition to its use in combustion engines, the process can also be applied to numerous mechanical components such as transmissions, bearings or pumps, and leads to substantial energy savings and extended periods of use (see REWITEC success story, Section 7.3).

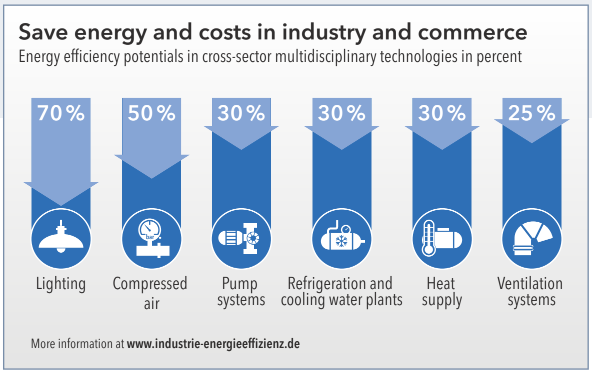
6.2 Lightweight Construction Using Nanocomposites

In the transport sector in particular, highly stable lightweight construction materials can contribute substantially to energy savings. Nanomaterials offer numerous potentials for achieving weight savings and combining various material properties, for example:

- extremely favourable strength to weight ratios
- enhanced hardness, toughness and wear resistance
- improved thermal capacity and corrosion resistance

Nanostructured metal-matrix composites (MMC) or polymer nanocomposites, for example, offer lightweight construction potentials. Metal-matrix composites are metallic materials, the mechanical and thermal properties of which are improved by introducing a reinforcing phase (primarily ceramics and carbon compounds). Light metal materials/alloys, predominantly with aluminium, and more rarely with magnesium and titanium, are used as a matrix. Metal-matrix composites are predominantly used in applications in which high mechanical (for example the ratio of strength to weight or the toughness) or thermal demands (such as high conductivity or low thermal expansion) are made. Applications here are primarily in the aerospace sector and the automotive or electronics industries. Metal-matrix composites unify metallic properties such as formability and toughness with the hardness and tensile strength of ceramic materials. A development trend of recent years is the use of nanoscaled fibres and particles as a reinforcing phase, with which a broad spectrum of material properties can be optimised to match the demands of the respective individual applications.

Nanobased protective coatings will expand the use of magnesium alloys in automotive engineering. Compared to conventional chrome coatings, environmentally friendly, silicon dioxide based coatings, which can be manufactured using physical vapour deposition or sol-gel processes, offer improved abrasion and corrosion protection for magnesium materials. Polymer composites reinforced by nanoparticle or carbon nanotubes also have the potential to form ultra-light, high-strength construction materials. However, for practical applications, a number of technical problems in terms of alignment and integration in the polymer matrix, as well as further cost reductions in material manufacturing, must be addressed.



Energy-saving potentials as a result of innovative building services engineering. (Source: Initiative Energieeffizienz)

Organic light-emitting diodes for ultra-thin large-scale displays and lighting objects. (Source: Novaled)

6.3 Intelligent, Energy-Efficient Building Technology

Building technology offers large energy-saving potentials, for example in lighting, heat supply, air conditioning and ventilation. Modern technologies mean that energy savings between 25 and 70 percent can be made compared to conventional solutions.

Substantial cost benefits may be achieved for companies, private households and public budgets through the use of new technologies. Around ten percent of electrical power in Germany is used for lighting alone. This corresponds to around 50 billion kilowatt hours (AG Energiebilanzen 2013). Of the total power costs of a commercial operation, lighting may reach more than 50 percent; in some wholesale and retail companies this may even be as much as 70 percent.

Nanotechnology applications in lighting engineering primarily concern the development and use of energy-efficient light-emitting diodes (LEDs) based on inorganic and organic semiconductor materials. Due to its compact construction, the variety of colours and the high energy yield, LED technology has already captured large market potentials in display, building and automobile lighting. Organic light-emitting diodes (OLEDs) have the potential to provide large lighted areas and screens on flexible substrates, which can be integrated in numerous areas in interior design. Points of contact for nanotechnology are provided by further optimisation of LEDs using quantum dots, for example, which allow the energy efficiency and light yield to be increased further. Moreover, LED scatter effects can be minimised and thus the light yield increased by using nanoscaled light-emitting particles. It is necessary to coat the particles in order to increase their stability.

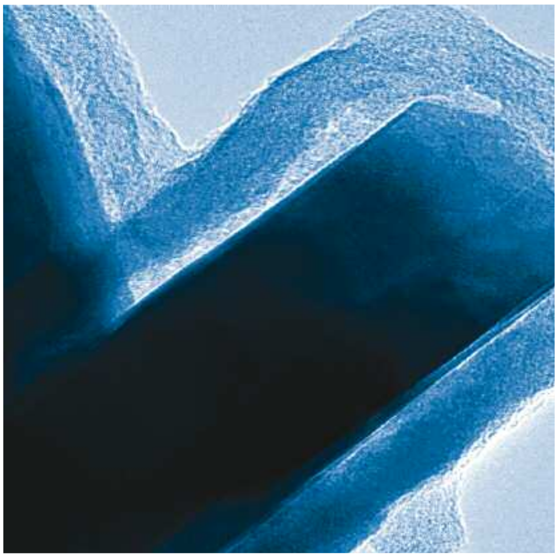
The further development of OLEDs will also depend on nanotechnological innovations, which involve, among other things, optimisation of substrates, the sequence and thickness of coatings, the use of dopants and the purity of the materials used. An OLED consists of a glass or flexible film substrate to which a transparent electrode, one or more layers of semiconducting organic materials, each a few nanometres thick, and an auxiliary electrode are attached. If an electric voltage is applied, positive and negative charges in the organic semiconductor produce an excited state from which light is subsequently emitted. As flat light sources, OLEDs can open new application dimensions for lighting, such as integrated light sources on walls and wallpapers, or in furniture and fabrics. OLED features include high energy efficiency and flat, glare-free light with natural colour reproduction.

Another field for nanotechnology is adaptive window and facade elements, where nanotechnological solutions can make significant contributions to energy savings. These include, for example, responsive shading systems (smart glazing), which present an alternative to conventional mechanical sun/glare protection systems (blinds, shades, etc.) and permanently coloured sun shield glazing. Annual growth rates for smart glass of 20 percent, up to 5.81 billion US dollars in 2020, are anticipated (Marketsandmarkets.com 2014). The technological basis for smart glass is provided by layers introduced into the glazing system, which can be reversibly coloured as a function of their chemical and physical variables, and in this way modify the opacity and heat conductivity of the glass. In addition to active systems, there are also passive systems, which alter their opacity automatically as a function of the lighting conditions. These include special liquid crystal mixtures with inclusions of tailor-made dyes, developed by Merck, which either allow light to pass or block it by absorption. In the first case, the panes are transparent, in the second, they are darkened. The required electricity is generated within the window itself, independent of external power sources. The special dye-doped liquid crystal mixture transfers the solar energy to the photovoltaic cells integrated in the window frame, where it is then converted to electricity. The first pilot projects are already running in the Netherlands (Merck 2014).

Electrically controllable colouring of electrochromic window panes. (Source: EControl-Glas)

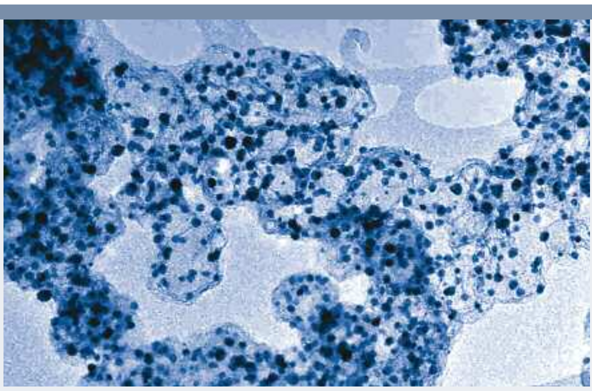
6.4 Energy Efficiency of Production Processes

Technical processes in industry, in particular in primary chemical products or metal production, are often associated with high energy inputs and contribute significantly to operating costs. The energy saving potential provided by using nanotechnologies is predominantly given by replacing or optimising energy-intensive reaction stages, for example, by employing nanostructured catalysts or thermal insulation materials. The catalytic process plays a role in more than 80 percent of all products produced by the chemicals industry. Because of their increased active surface area, nanostructured catalysts allow improved reaction yields or even, in some cases, new, energetically more favourable synthesis routes. One example is the use of fullerenes as catalysts in the industrially relevant styrene synthesis process, which can significantly increase reaction yields and reduce process temperatures.



Iron oxide catalyst (Fe_2O_3) encased in fullerene-like carbon layers for optimising styrene synthesis.
(Source: Fritz-Haber-Institut)

7.1 Umicore: Nanostructured catalysts for efficient membrane fuel cells



Platinum nanoparticles on carbon black substrate as electrocatalysts for fuel cells. (Source: Umicore)

Umicore is a global leader in the manufacture of car exhaust catalytic converters and numerous products containing precious metals. In many cases, these products considerably contribute to facilitating environmentally friendly processes or to reducing their energy consumption.

The company's research primarily focuses on the development and production of electrocatalysts as the key components for membrane fuel cells (PEMFCs, proton exchange membrane fuel cells), which are regarded as an environmentally friendly and highly efficient energy conversion technology. Nitrogen oxides or other pollutants generally produced in traditional combustion do not occur in PEMFCs. The use of PEMFCs in automobiles, domestic power supply systems and even for portable power supplies (for example in laptops and mobile telephones) has already been successfully demonstrated. In Japan, several tens of thousands of domestic fuel cell power systems have already been deployed and the Asian car manufacturers Toyota and Hyundai have initiated series production of fuel cell-powered vehicles.

The nanofine distribution of the precious metal and its stable union with the catalyst substrate are decisive for the use of the electrocatalysts developed by Umicore in membrane fuel cells. This increases the catalytic effect per gram of precious metal used and thus contributes to the conservation of resources in terms of valuable input substances and to reducing costs.

Umicore is a globally operating materials technologies group with headquarters in Brussels, Belgium. In 2014, the company had a turnover of 8.8 billion euros (2.4 billion euros without precious metals) and is globally active with 14,000 employees at 86 locations. Activities are concentrated on the business sectors recycling, energy & surface technologies and catalysis.

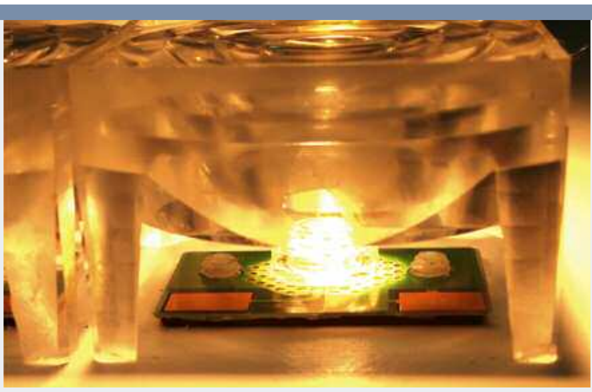
In Hessen, the group operates a site at Wolfgang Industrial Park in Hanau. Here, around 1,000 employees work in a total of seven business sectors.

umicore
materials for a better life

Contact:
Umicore AG & Co. KG
Rodenbacher Chaussee 4
63457 Hanau-Wolfgang, Germany

Dr. Ralf Zuber
Telephone: +49 (0)6181 59-6627
E-Mail: ralf.zuber@eu.umicore.com
www.umicore.de

7.2 NAsP III / V: Small is beautiful – miniaturised solar cells offer the highest conversion efficiency for concentrating photovoltaic systems



Concentrating solar cells with 1,000-fold light concentration.
(Source: Isofoton)

Solar cell wafers in a chemical process box.
(Source: NAsP III/V)

In 2004, NAsP III/V was spun off as a stand-alone company from the materials sciences centre of Philipps-Universität Marburg. The main business sector is the development and marketing of new materials and technologies for integrating optical and photonic functions with silicon-based micro and nanoelectronics for high power lasers and highly efficient solar cells, based on innovative III/V compound semiconductors with the appropriate nanostructures.

Together with domestic and international university, research and industry partners, NAsP III/V is working on developing the next generation of highly efficient multiple solar cell structures, to be used in concentrating photovoltaics (CPV) with conversion efficiencies of greater than 50 percent in the CPV solar cells. This project objective demands integration of an innovative solar cell material, such as the complex III-V solid solution system (GaIn)(NAs) with a suitable energy gap of approximately one electron volt in the multiple solar cell stack.

NAsP III/V's development work on manufacturing these innovative materials were performed on state-of-the-art multiwafer production facilities in order to guarantee fast and efficient transfer to industrial applications. The newly developed production method is characterised by the use of special chemicals that can be exploited in a radically more efficient way and are less environmentally hazardous.

In addition, NAsP III/V is pursuing a recycling concept in order to ensure that the high purity chemicals and other input materials are reused as efficiently as possible. This sustainable production method and enhanced conversion efficiency guarantee an additional significant improvement in the cost/benefit ratio for CPV applications.

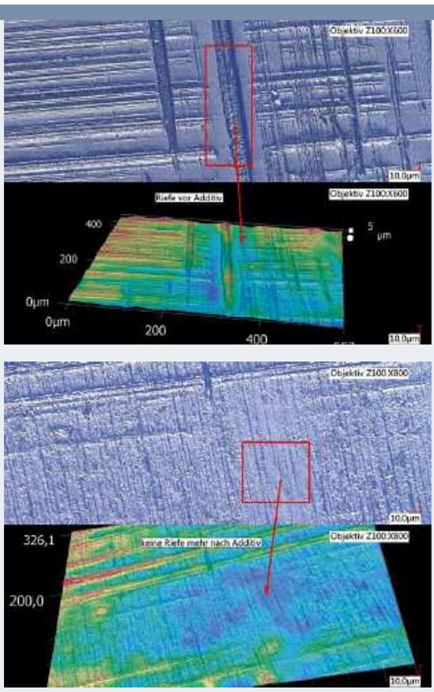
NAsP III/V

Contact:
NAsP III / V GmbH
Am Knechtacker 19
35041 Marburg, Germany

Dr. Wolfgang Stolz
Telephone: +49 (0)6421 2825696
E-Mail: wolfgang.stolz@nasp.de
www.nasp.de

Multiwafer production facilities.
(Source: Aixtron)

7.3 REWITEC: Higher performance for engines, transmissions and bearings



View through the laser microscope: the lower gearwheel surface displays considerably less wear thanks to optimisation of the material properties using REWITEC technology. (Source: REWITEC)

High availability, low wear, long running times and low operating costs are crucial aspects for decision makers, engineers and service technicians in industrial companies and power generators, as well as for the shipping and automotive industries – regardless of whether extensive production lines, cost-intensive building and plant engineering or the more mundane commercial vehicles are involved.

The medium sized company REWITEC, which globally develops and sells innovative nano- and microparticle-based lubricant additives, provides a comprehensive solution. The tried and tested REWITEC technology is used in tribological systems such as transmissions or bearings, and permanently enhances their surfaces. In this way the original material properties are optimised: friction can be reduced by up to 33 percent, the temperature by up to 20 percent and the surface roughness by up to 50 percent (scientifically proven in lubricant tests at Mannheim University of Applied Sciences Kompetenzzentrum Tribologie (Tribology Competence Centre), 10/2012).

'Our technologies are literally additives, that is, additions to engine and transmission oils and to greases consisting of a combination of up to seven different raw materials', explains REWITEC CEO Stefan Bill. However, the modus operandi of the lubricant additives cannot be compared to more traditional additives: the synthetic and mineral-based silicate compounds use the lubricant as a transport agent only and, in this way, reach the relevant surfaces in the so-called tribosystem.

At operating temperatures, the coating particles react with the metallic surface in a chemical process and the rubbing metal surfaces are ceramised. Thanks to the metal-ceramic surface, the original material properties are considerably enhanced with regard to friction and wear, and the lubricant properties, in contrast, remain unaltered.

Against this backdrop, the product series of this central Hessen company are not only deployed by servicing companies and so-called technical operations managers in the wind energy field but also by numerous global players around the world. With regard to lubricant additives for wind turbines, REWITEC has grown into a market leader. Despite, or perhaps because of, the enormous demands on wind turbines in terms of engineering and materials, years of practical experience have shown that the consistent use of REWITEC products leads to extended running times, reduced servicing needs and spare parts requirements, and to less downtime. 'The relevance of substantially enhanced performance of wind turbines is obvious and represents a considerable positive change in return on investment for the operator', CEO Stefan Bill adds. 'This experience can be transferred to numerous other applications where engines, transmissions and bearings are in use. By the way, we have also received positive feedback on our technology and our products from the field of motorsports.'

REWITEC

Contact:
REWITEC GmbH
Dr.-Hans-Wilhelmi-Weg 1
Gewerbepark Lahnau
35633 Lahnau, Germany

Stefan Bill
Telephone: +49 (0)6441 44599-0
E-Mail: info@rewitec.com
www.rewitec.de

7.4 Hochschule RheinMain – University of Applied Sciences: Hydrogen storage in nanoporous powder materials

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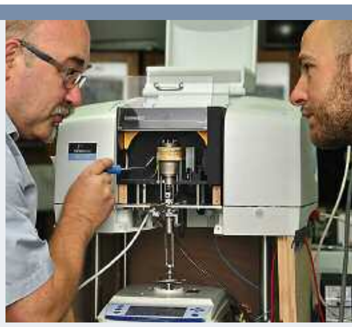

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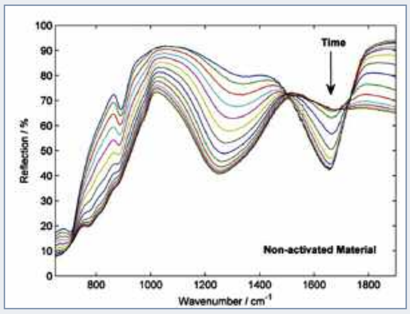

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Fuel cell vehicles powered by hydrogen: **(1)** Buggy. **(2)** Pedelec. **(3)** Setup to measure infrared spectra of a metal hydride sample while simultaneously measuring its weight. **(4)** IR-spectral changes of a metal hydride sample during hydrogen desorption.
(Source: Hochschule RheinMain – University of Applied Sciences)

Hydrogen is regarded as the 'greenest' of all energy sources, because it can be easily produced by electrolysis anywhere with sufficient sunlight and water. When burned safely and noiselessly in fuel cells, electricity is produced directly and on demand, with only water being liberated as a combustion product. At first glance, even hydrogen storage does not appear to present problems. However, in the usual compressed gas bottles, the energy storage density of 0.77 kilowatt hours per litre at 350 bar is only one twelfth of the storage density of petrol. If hydrogen is liquefied before storage, the storage density is substantially increased, but temperatures below minus 252 degrees Celsius are needed to achieve this, which requires extremely large amounts of energy.

However, a group of crystalline chemical compounds are available for numerous applications: the metal hydrides. They can take up hydrogen in their relatively loose crystal lattice like a sponge with nanometre fine pores and absorb it safely and securely. If these metal hydrides are ground to a micrometre fine powder, they acquire an extremely large surface area, which makes the absorption of hydrogen gas even easier. Hydrogen absorption takes place under pressure, while desorption (liberation) occurs simply by warming. Here, the desorption temperature is substantially reduced and the desorption speed increased by adding catalysts.

However, a reliable fill level indicator is required for each tank, especially for mobility applications, where it must be possible to estimate the range of the vehicle with respect to the next filling station. This represents a particular challenge for the metal hydride-hydrogen tank. At the RheinMain University of Applied Sciences, a double measuring method was developed allowing the infrared spectrum and the weight change of a powder sample of only 0.5 grams to be simultaneously determined during desorption. The infrared spectrum changes considerably during desorption because the crystal structure of the powder and the stoichiometric composition change when hydrogen is liberated. The spectral data can now be related to the quantity of liberated hydrogen. That is, it would then be possible to develop a calibrated optical sensor that would display the amount of hydrogen remaining in the tank. In addition, this method is suitable for investigating the desorption kinetics of other hydrogen storing substances: for example, the liberation rates and activation energies can be measured. It would also be interesting to investigate their relationship to the degree of grinding or the powder porosity because the thermal conductivity of the bulk and the release of hydrogen from the powder tank depend on these factors. Moreover, other solid state reactions in which gaseous substances are liberated from powders can be investigated.

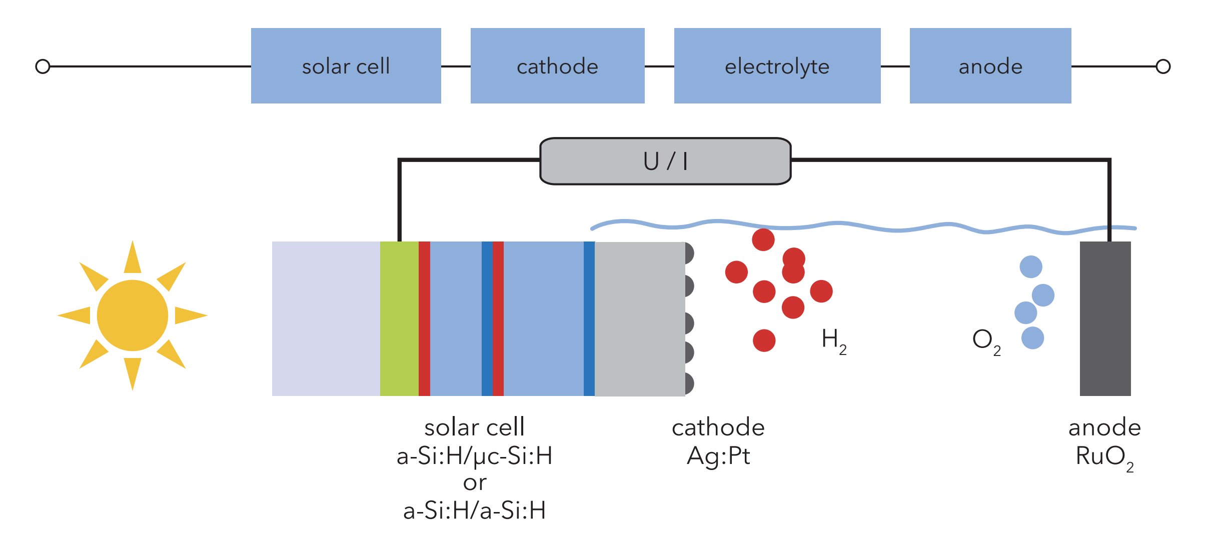
Contact:
Hochschule RheinMain
University of Applied Sciences
Am Brückweg 26
65428 Rüsselsheim, Germany

Hochschule **RheinMain**
University of Applied Sciences
Wiesbaden Rüsselsheim

Labor für Wasserstofftechnologie
(Hydrogen Technology Lab)
Prof. Dr. Birgit Scheppat
Telephone: +49 (0)6142 898-4512
E-Mail: birgit.scheppat@hs-rm.de
www.hs-rm.de/en/

Institut für Mikrotechnologien
(Microtechnologies Institute)
Prof. Dr. Hans-Dieter Bauer
Telephone: +49 (0)6142 898-0
E-Mail: hans-dieter.bauer@hs-rm.de
www.hs-rm.de/en/

7.5 TU Darmstadt Energy Center: Nanotechnology in energy research



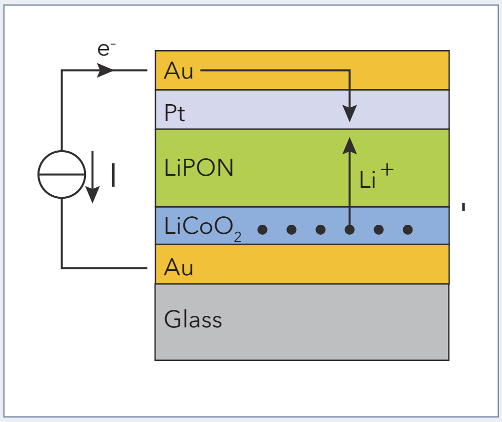
Representation of a photoelectrochemical cell for splitting water. (Source: TU Darmstadt)

The objective of materials research in TU Darmstadt Energy Center is to secure a sustainable energy technology for the future by researching the necessary material science fundamentals for producing competitive elements at all technological levels (primary energy collection, energy conversion, storage, transport). The research and development work and the existing expertise present in the different departments at Technische Universität Darmstadt, spanning a bridge between the natural and the engineering sciences, are brought together and coordinated such that academic education, research, opportunities management and public relations all contribute to the successful implementation of the energy revolution. The institutionalised cooperation between the university, industry, government and the public forms an integral component of the concept of addressing the manifold relationships between energy and environmental questions, but also the technological, economic and social implications of a sustainable energy future.

Many innovative energy systems are based on nanotechnology and the combination of different materials with properties adapted at the atomic scale. A number of research topics at Technische Universität Darmstadt use new materials and material combinations at the nanometre scale to develop innovative energy systems. Examples include:

- Optimisation of thin-film solar cells for low-cost direct generation of electricity from sunlight. Here, inorganic or organic thin-film absorber materials or composites are particularly interesting. The efficiency is determined by the structure and the electronic properties of the homogeneous and heterogeneous phase boundaries in submono layers down to the micrometre range. Thin-film solar cells can now achieve efficiencies greater than 20 percent, but often consist of rare or ecologically worrisome materials (cadmium telluride, copper-indium-gallium selenide (CIGS) or perovskite cells), so new, but ecologically safe, substitute materials would be of interest. Moreover, new absorbers with large band gaps around two electron volts are an option for thin-film tandem structures for third generation solar cells with drastically enhanced efficiencies.

- Innovative photovoltaic converters for directly converting sunlight in chemical storage systems, in particular hydrogen. To achieve this, adapted photovoltaic tandem structures must be developed, which can split water into hydrogen and oxygen with high efficiency, similar to solar cells. Challenges are adapted surfaces and catalysis layers on the nanometre scale. Efficiencies of ten percent solar-to-hydrogen were achieved in cooperation with Research Centre Jülich. However, the materials used still need to be stabilised and further improved.
- Identification and development of new, highly efficient catalysts for converting hydrogen and carbon dioxide or biomass into hydrocarbons to form liquid or gaseous fuels, or of electrocatalysts for electrolysis, or in fuel cells consisting of metallic nanoparticles on porous oxide graphitic substrate materials. The aim is to substitute expensive catalysts containing precious metals with more economical, but more specifically effective catalysts.
- Improved energy storage systems such as lithium ion batteries are manufactured from composite structures of interconnected, electronically conducting carbon nanotubes with active nanocrystals that store and liberate lithium. Innovative cathode materials based on olivines, a group of silicate-based minerals, but also thin-film batteries, are being researched.
- Ceramic nanometre-thick protective coatings serve to increase the temperature stability of turbine materials and therefore also their efficiency. Beginning with specific synthesis and processing methods yet to be developed, the required functional properties must first be researched, characterised and optimised by means of a variety of feedback processes before the specific required elements and systems can be developed for practical applications.



Representation of a thin-film lithium ion battery.
(Source: TU Darmstadt)

The necessary research and development chains extend across the spectrum from the atomic natural science fundamentals to engineering implementation, and including the social implications. Only with this holistic TU Darmstadt Energy Center approach, will it be possible to ensure the social conditions and secure the approval of the population for the energy revolution.

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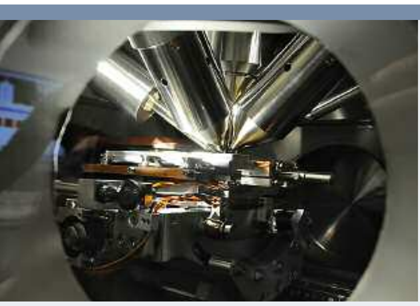
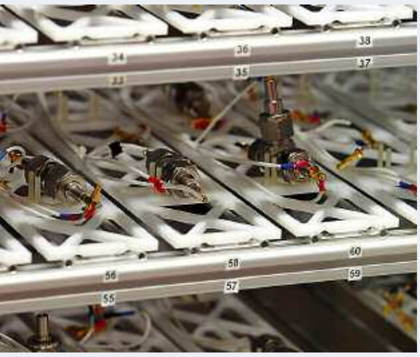
DARMSTADT

Contact:
TU Darmstadt Energy Center
Franziska-Braun-Strasse 7
64287 Darmstadt, Germany

Prof. Dr. Wolfram Jaegermann
Telephone: +49 (0)6151 16-6304
E-Mail: jaegermann@surface.tu-darmstadt.de
www.energycenter.tu-darmstadt.de

7.6 Justus Liebig University Giessen: Electrochemical and solid state ionics – materials research for electrochemical energy technologies





Top: Complex analysis techniques in an ultra-high vacuum, such as secondary ion mass spectrometry or photoelectron spectroscopy, are used to analyse energy storage materials.

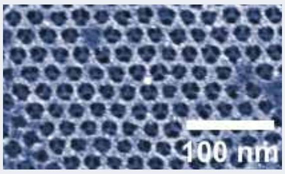
Bottom: Battery cells with new cell chemistries are tested at laboratory scale.

(Source: Universität Giessen)

The working groups at the Institute of Physical Chemistry at Justus Liebig University (JLU) work intensely and in close cooperation with other university institutes on research into new material concepts for energy storage systems and energy conversion technologies. Some of these activities have, since 2013, been extensively funded by the State of Hessen as part of the LOEWE (Hessian initiative to create excellence in science and economy; German: Landes-Offensive zur Entwicklung Wissenschaftlich-ökonomischer Exzellenz) priority programme STORE-E. The aim of the research work in Giessen is to develop new materials for use in batteries and fuel cells. It will also investigate the stability of the materials under real life conditions. The application fields of the projects covered by the LOEWE priority programme and coordinated by both Jürgen Janek and Joachim Sann consist of innovative thin-film batteries and electrochromic cells, supercapacitors and storage catalysts. In addition, new analytic methods for materials and computer simulations also play an important role.

A key topic of the work in Giessen are boundary layers (both surfaces and internal boundary layers) in electrochemical systems. The governing electrochemical reactions occur at the boundary layers, and the structure and morphology of the boundary layers govern the properties of the system as a whole. Accordingly, the boundary layer form, for example, in the shape of electrodes for batteries or other electrochemical cells, plays a very important role. This is particularly apparent in the example of thin-film batteries, in which several layers of functional materials must be combined and structures at the nanometre scale are critical to the battery properties. By using efficient coating deposition methods and highly advanced analytical methods, the optimal materials can be identified and their properties characterised.

Nanostructured, electrochemical functional materials also play an important role in electrochromic cells. Here, an electrochromic coating is coloured by applying an electrical potential. Electrochromic coatings of nanostructured materials possess particularly favourable properties and are therefore also subject to intense investigation in STORE-E.



Defined nanoscaled pore structures allow the electrochemical properties of known materials to be modified and used for completely new purposes.
(Source: Universität Giessen)

The Institute of Physical Chemistry is excellently equipped for almost all types of research in the field of solid state chemistry and electrochemistry. An extensive range of analytical methods guarantees that work takes place at the highest international level. Current work includes projects investigating lithium ion batteries and solid state batteries, new materials for use in high-temperature electrochemistry, but also specifically prepared, porous solid state systems. Targeted nanostructuring is often an inherent part of research work.

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

Contact:
Justus Liebig University Giessen
Institute of Physical Chemistry
Heinrich-Buff-Ring 58, 35392 Gießen, Germany

Dr. Joachim Sann
Telephone: +49 (0)641 99-34512
E-Mail: Joachim.Sann@phys.chemie.uni-giessen.de
www.uni-giessen.de/cms/fbz/fb08/Inst/physchem/janek

7.7 MAGNETEC: Highly efficient and compact energy conversion using nanocrystalline toroid cores

Forms of supply of inductive elements with nanocrystalline toroid cores. (Source: Magnetec)

Current compensated noise suppression chokes for EMC filters. (Source: Magnetec)

NANOPERM® parent material for nanocrystalline toroids. (Source: Magnetec)

In the renewable production and processing of electrical energy, as practised by the wind and solar power industries, for example, the focus is on the efficiency of the process in order to minimise the losses in the energy supply chain to the final consumer. In the electronic energy conversion circuits, high-performance components are therefore increasingly employed because particularly in these applications investment in the highest quality also makes sense from an economic perspective.

MAGNETEC in Langenselbold has manufactured high quality inductive elements for more than 30 years. Production of toroid cores using the at the time novel nanocrystalline material NANOPERM® began approximately 15 years ago. This soft magnetic material, produced using the so-called rapid solidification process as a 15 to 20 micrometre thick strip or as a film, initially has an amorphous internal structure and is magnetically neutral. During a specially designed heat treatment under a shield gas, and with precisely defined magnetic fields, an inner, fine nanocrystalline structure is created, producing soft magnetic properties that were barely conceivable around 15 years ago.

This means that magnetic cores, shunt reactors and transformers can not only be designed smaller by several factors, for example, but they also facilitate extremely low-loss operations at high switching frequencies (typically 100 kilohertz). These advances go hand in hand with the long-term trend in the semiconductor industry of achieving the envisaged efficiency improvements by adopting ever increasing transistor switching frequencies. This increases the efficiency of devices and facilities while simultaneously reducing the dimensions and weight. A new semiconductor generation based on silicon carbide is currently in the starting blocks.

In recent years, the applications of NANOPERM® have expanded from the field of installation engineering/personal safety (residual current operated circuit breakers) to include electromagnetic compatibility (EMC filters), bearing protection on large motors and generators (wind turbines), modern electrical energy meters (smart meters) and, more recently, burgeoning electromobility, where operating temperatures up to 180 degrees Celsius are generally required.

MAGNETEC employs around 400 staff and has previously been awarded an innovation prize for its products by *Initiative Mittelstand*.

MAGNETEC®
MAGNET - TECHNOLOGIE

Contact:
MAGNETEC GmbH
Industriestrasse 7
63505 Langenselbold, Germany

Dr. Martin Ferch
Telephone: +49 (0)6184 9202-27
E-Mail: MFerch@magnetec.de
www.magnetec.de

Top: Single conductor shunt cores for generator bearing protection in wind turbines.

Bottom: Forms of supply of inductive elements with nanocrystalline toroid cores.

(Source: Magnetec)

8. Further Information

8.1 Expertise and Addresses of Actors in Hessen

Colour key:

- Energy conversion renewable
- Energy conversion conventional
- Energy storage
- Energy transport/distribution
- Energy efficiency

Companies

Bruker HTS GmbH
Ehrichstrasse 10
63450 Hanau, Germany
Telephone: +49 (0)6181 4384-4100
www.bruker.com/best.html

Relevant products/research:
Nanooptimised high-temperature superconductors for power engineering; energy transport/distribution

Dockweiler Chemicals GmbH
Emil-von-Behring-Strasse 76
35041 Marburg, Germany
Telephone: +49 (0)6421 396380
www.dockchemicals.com

Relevant products/research:
Specialised chemicals and precursors for semiconductor layers on thin-film solar cells and LEDs

Heraeus Deutschland GmbH & Co. KG
Heraeusstrasse 12–14
63450 Hanau, Germany
Telephone: +49 (0)6181 35-0
www.heraeus.de

Relevant products/research:
Nanostructured precious metal powders for fuel cell catalysts, sputter targets for functional coatings on thin-film solar cells, solar receivers and functional glasses

Hollingsworth & Vose GmbH & Co. KG
Berleburger Strasse 71
35116 Hatzfeld (Eder), Germany
Telephone: +49 (0)6467 801-0
www.hollingsworth-vose.com

Relevant products/research:
Nanostructured, high porosity, oxidation resistant fibres for separators in batteries

MAGNETEC GmbH
Industriestrasse 7
63505 Langenselbold, Germany
Telephone: +49 (0)6184 920210
www.magnetec.de

Relevant products/research:
Nanocrystalline, magnetic toroids for inductive elements in power and electronics engineering

Merck KGaA
Performance Materials
Frankfurter Strasse 250
64293 Darmstadt, Germany
Telephone: +49 (0)6151 72-0
www.merck-performance-materials.de

Relevant products/research:
Semiconductors and special dyes for organic photovoltaics and organic light-emitting diodes; coating materials for antireflection layers on solar cells and electrode membrane units in fuel cells; liquid crystals for energy saving, responsive windows

NAsP III/V GmbH

Hans-Meerwein-Strasse
35032 Marburg, Germany
Telephone: +49 (0)6421 2825696
www.nasp.de

Relevant products/research:
Highly efficient III-V semiconductor solar cells

REWITEC GmbH

Dr.-Hans-Wilhelmi-Weg 1
35633 Lahnau, Germany
Telephone: +49 (0)6441 44599-0
www.rewitec.com

Relevant products/research:
Nanoadditives for lubricants providing wear protection and energy savings in motor and transmission components (wind turbine rotors, mobility)

Schunk Kohlenstofftechnik GmbH

Rodheimer Strasse 59
35452 Heuchelheim, Germany
Telephone: +49 (0)641 608-1460
www.schunk-group.com

Relevant products/research:
Nanooptimised components of carbon, graphite, carbon fibre reinforced carbon (CFC), silicon carbide for applications in power engineering

SGL Carbon AG

Rheingaustrasse 182
65203 Wiesbaden, Germany
Telephone: +49 (0)8271 83-2458
www.sglcarbon.de

Relevant products/research:
Nanostructured carbon materials as electrode materials for energy storage systems

SolviCore GmbH & Co. KG

Rodenbacher Chaussee 4
63457 Hanau, Germany
Telephone: +49 (0)6181 59-5432
www.solvicore.de

Relevant products/research:
Membrane electrode units for fuel cells and electrolysis of water

Umicore AG & Co. KG

Rodenbacher Chaussee 4
63457 Hanau, Germany
Telephone: +49 (0)6181 59-6627
www.umicore.de

Relevant products/research:
Nanostructured catalysts for membrane fuel cells

Vacuumschmelze GmbH & Co. KG

Grüner Weg 37
63450 Hanau, Germany
Telephone: +49 (0)6181 38-0
www.vacuumschmelze.de

Relevant products/research:
Nanocrystalline, magnetic alloys, for example for toroids for inductive elements in power and electronics engineering

Viessmann Werke GmbH & Co. KG

Viessmann Strasse 1
35107 Allendorf (Eder), Germany
Telephone: +49 (0)6452 70-3410
www.viessmann.de

Relevant products/research:
Nano-CHP with fuel cells and zeolite adsorption heat pumps for highly efficient heating devices

Research institutions

DECHEMA-Forschungsinstitut

Theodor-Heuss-Allee 25
60486 Frankfurt am Main, Germany
Telephone: +49 (0)69 7564-337
www.dechema-dfi.de

Relevant research activity:
Electrochemical energy storage systems and converters such as fuel cells and metal-air batteries

Fraunhofer Institute for Wind Energy and Energy System Technology

Königstor 59
34119 Kassel, Germany
Telephone: +49 (0)561 7294-0
www.energiesystemtechnik.iwes.fraunhofer.de

Relevant research activity:
Intelligente Stromnetze, Integration regenerativer Energiequellen

Hochschule RheinMain - University of Applied Sciences

Rüsselsheim Campus
Institut für Mikrotechnologien
Am Brückweg 26
65428 Rüsselsheim, Germany
Telephone: +49 (0)6142 898-521
www.hs-rm.de/en/

Relevant research activity:
Nanostructured thermoelectric materials, optical metrology for charging hydrogen storage systems

Hochschule RheinMain - University of Applied Sciences

Rüsselsheim Campus
Labor für Wasserstofftechnologie
Am Brückweg 26
65428 Rüsselsheim, Germany
Telephone: +49 (0)6142 898-512
www.wasserstofflabor.de

Relevant research activity:
Fuel cells, hydrogen storage systems, electrolysis

Justus Liebig University Giessen

Institut für Angewandte Physik
(Institute of Applied Physics)
Heinrich-Buff-Ring 16
35392 Giessen, Germany
Telephone: +49 (0)641 99-33401
www.uni-giessen.de/cms/fbz/fb07/fachgebiete/physik/einrichtungen/institut-fur-angewandte-physik/agschlett

Relevant research activity:
Dye-sensitised solar cells, electrochemical energy storage systems

Justus Liebig University Giessen

Institute of Physical Chemistry
Heinrich-Buff-Ring 58
35392 Giessen, Germany
Telephone: +49 (0)641 99-34500 oder -34501
www.uni-giessen.de/cms/fbz/fb08/Inst/physchem

Relevant research activity:
New materials for energy storage systems (hydrogen storage systems, batteries), electrochemistry

Philipps-Universität Marburg

Wissenschaftliches Zentrum für Materialwissenschaften
Hans-Meerwein-Strasse
35032 Marburg, Germany
Telephone: +49 (0)641 99-25696
www.uni-marburg.de/wzmw

Relevant research activity:
Gas phase epitaxy and structural analysis of compound semiconductors, among other things, for solar cells

Technische Universität Darmstadt

Energy Center
Franziska-Braun-Strasse 7
64287 Darmstadt, Germany
Telephone: +49 (0)6151 16-6304
www.tu-darmstadt.de/fb/ms/fg/ofl/index.tud

Relevant research activity:
Thin film solar cells, photovoltaic hydrogen production, improved lithium ion batteries, catalysts for producing fuels from biomass and CO_2

Technische Universität Darmstadt

Fachgebiet Materialwissenschaften
Alarich-Weiss-Strasse 2
64287 Darmstadt, Germany
Telephone: +49 (0)6151 16-5377
www.mawi.tu-darmstadt.de

Relevant research activity:
Nanomaterials for solid oxide fuel cells (SOFC), batteries, hydrogen storage systems, gas separation membranes

Technische Universität Darmstadt

Center for Engineering Materials, State Materials Testing Institute Darmstadt (MPA), Chair and Institute for Materials Technology (IfW)
Grafenstrasse 2, 64283 Darmstadt, Germany
Telephone: +49 (0)6151 16-3351
www.mpa-ifw.tu-darmstadt.de

Relevant research activity:
Nanostructured thermal protection coatings for turbine blades

University of Kassel

Fachbereich Maschinenbau
Mönchebergstrasse 3, 34125 Kassel, Germany
Telephone: +49 (0)561 804-2830
www.uni-kassel.de/maschinenbau/institute/iaf/lmt0/startseite.html

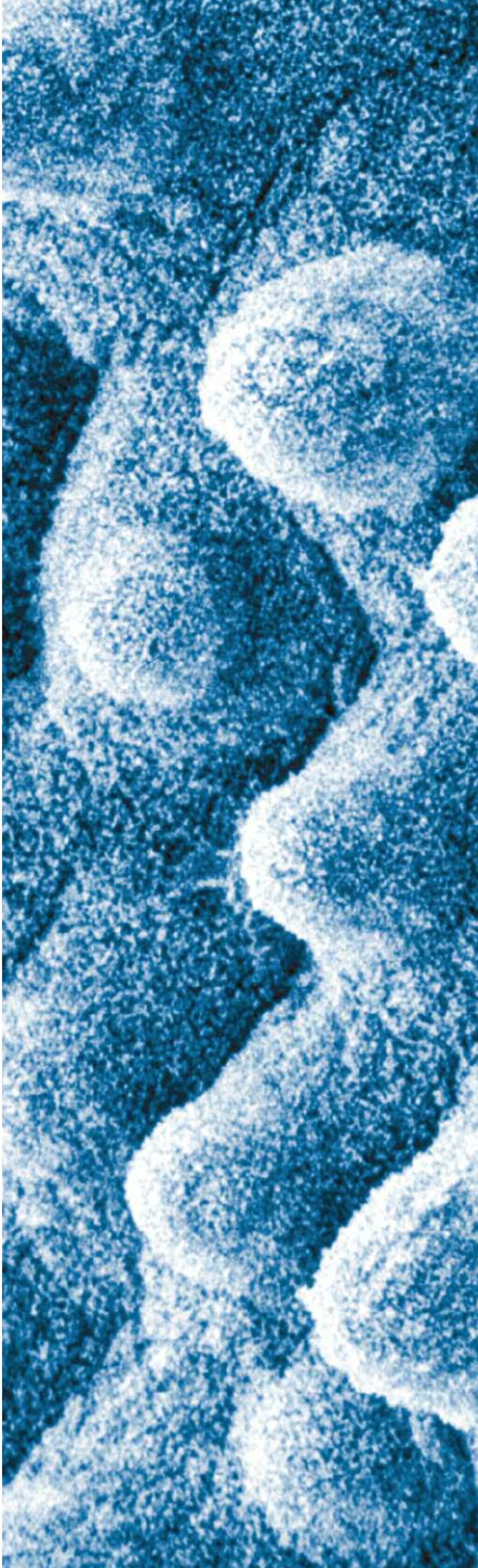
Relevant research activity:
Tribological nanolayers, wear protection

University of Kassel

Institute of Nanostructure Technologies and Analytics
Heinrich-Plett-Strasse 40
34132 Kassel, Germany
Telephone: +49 (0)561 804-4485
www.te.ina-kassel.de

Relevant research activity:
Innovative light guidance systems based on micromirror arrays, among other things, for concentrating light in photovoltaics

The ForschungsCampus FC³ Nachhaltige Mobilität offers information regarding energy for sustainable mobility at www.forschungs-campus-hessen.de (German only).



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