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"We Create Chemistry for a Sustainable Future": Chemistry Creates Sustainable Solutions for a Growing World Population**

Andreas Kreimeyer, Peter Eckes, Christian Fischer, Harald Lauke, and Peter Schuhmacher*

active substances · catalysis · history of science · industrial chemistry · polymers

1. Chemistry—Driver of Innovation

Since the foundation of BASF, innovations based on research and development in the natural sciences, in particular chemistry and engineering, have been the basis of our entrepreneurial success. Friedrich Engelhorn founded the company "Badische Anilin- & Sodafabrik" on April 6, 1865 in Mannheim, Germany, convinced by the idea to produce aniline and the red dye fuchsine from the waste product coal tar. However, it soon became apparent that the first tar dyes did not demonstrate sufficient color fastness to meet the requirements of customers. BASF recognized that to overcome these shortcomings, intensive chemical research would be necessary and appointed the chemist Heinrich Caro as the first research director in 1868.[1]

Today, BASF is a widely diversified chemical company, which supplies its customers throughout the world with around 200 000 different products. We are suppliers and partners of most industrial sectors, especially the automotive, construction, electronic, and consumer goods industries as well as in the fields of agriculture, health and nutrition, energy, and natural resources.[2] Innovations based upon scientific and technical knowledge as well as a strong commitment to research and development remain the foundations of our success. We utilize our expertise to develop technologies and products for and with our customers that satisfy the needs of a growing world population. Intelligent application of chemistry is the driver of innovation when there is a need to provide sustainable solutions that reconcile ecological, economic, and social demands. This was already the case in the early years of BASF when our priority was to improve the utilization of available raw materials.[1] Today, sustainability is an essential growth driver at the core of our strategy, which is expressed by our corporate purpose: "We create chemistry for a sustainable future".[3]

More and more people live on Earth: In the year 2050, it is expected to be more than 9 billion (Figure 1).[4] Everyone has a claim to sufficient raw materials, healthy food, and an adequate quality of life. If we do not change our way of living and producing, in 2050, our descendants will need almost three times as many resources as the Earth can provide.[5] The challenges that lie ahead of us are tremendous, and chemistry will be essential to find answers to important and pressing questions. How can we ensure that there is enough food and clean water for everyone? How will we produce the energy that we require? How will we live, work, and travel? In order to make progress on these questions, we will need products that are sustainable, easy to use, and affordable. This is especially true in the regions that have the highest population growth as these are often associated with the lowest disposable incomes.

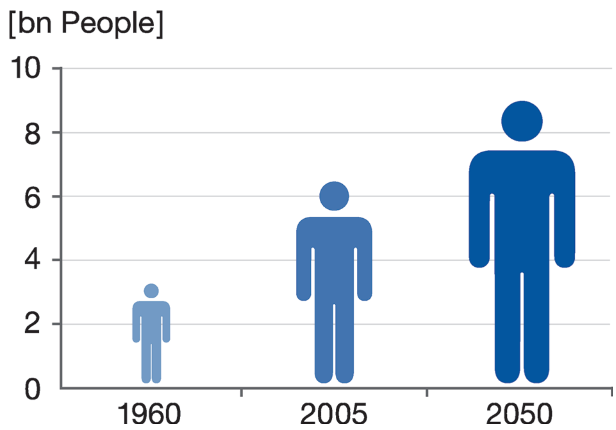

Figure 1. Growth of the world population.[4]

[*] Dr. A. Kreimeyer
Research Executive Director, BASF SE
67056 Ludwigshafen (Germany)
Dr. C. Fischer, Dr. H. Lauke, Dr. P. Schuhmacher
BASF SE
67056 Ludwigshafen (Germany)
Dr. P. Eckes
BASF Plant Science LP
27709 Research Triangle Park (USA)

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In light of the challenges introduced above, we have focused our research and development on three major needs:

1) Food and nutrition: A growing world population requires more food and nutrition of better quality. Plant breeding, plant biotechnology, crop protection, agricultural engineering, and post-harvest processing are more important than ever. Today, BASF provides a broad portfolio of chemical and biological crop-protection products, solutions for seed treatment and improved soil management, and intelligent chemical solutions and membrane systems for water treatment. We are innovating at all levels of the food chain and are conducting research on the efficient production of essential vitamins and other nutrients by chemical synthesis and biotechnology. We are also developing innovative methods to optimize the use of feed in animal nutrition.

2) Raw materials, environment, and climate: The efficient use of natural resources and the protection of the environment and climate are topics of increasing importance. We offer solutions for processes ranging from the production of raw materials and their usage to effective emission control. Our products for more efficient crude oil production, highly selective process catalysts for oil refineries and the chemical industry, corrosion protection coatings for industry and the transport sector, plastics and coatings for wind turbines as well as automotive emissions catalysts simultaneously fulfil ecological and economic requirements. We are investigating new chemical and biochemical processes for the utilization of natural gas, carbon dioxide, and renewable resources as alternative raw materials to crude oil. Aside from our focus on sustainable production processes, we are developing

From left to right:
C. Fischer, H. Lauke, A. Kreimeyer, P. Eckes, P. Schuhmacher

Andreas Kreimeyer *studied biology at the Universities of Hanover and Hamburg. After completing his doctorate on "DNA repair-associated ADP-ribosylation in vivo" under the supervision of H. Hilz (Institute of Physiological Chemistry, University Medical Center Hamburg-Eppendorf), he joined the biotechnology department of BASF's Main Laboratory as a protein chemist in 1986. There he was responsible for the biotechnological production and purification of recombinant proteins. From 1993 he was Head of Staff to the Chairman of the Board of Executive Directors. In 1995 he took over responsibility for investment, strategy, and regional marketing in Asia, and from 1998 to 2002, he was President of the Dispersions, Functional Polymers, and Fertilizers Divisions. With effect from January 1, 2003 he was appointed to BASF's Board of Executive Directors. Today, Andreas Kreimeyer is responsible for the Divisions Crop Protection, Coatings, and Bioscience Research as well as the region South America. He has been BASF's Research Executive Director since 2008.*

Peter Eckes *completed his Ph.D. in Organic Chemistry in 1990 at the University of Frankfurt, Germany, and pursued his postdoctoral studies at the Chemistry Department of Harvard University, United States. He joined BASF's Main Laboratory in Ludwigshafen, Germany, in 1992 in the Fine Chemicals group where he became Assistant to the Research Executive Director in 1994. Back to the United States in 1997, he became Technical Manager at Geismar, Louisiana Verbund site in the Intermediates Division. Still part of the Intermediates Division and after a short time as Marketing Manager based in Mount Olive, New Jersey, he took on the responsibility of Director of New Business Development in Ludwigshafen in 2000. In 2002 he joined the Crop Protection Division as Senior Vice President of Global Research and Development based in Limburgerhof, Germany. From 2009 to 2014 he was President of Plant Science Research, and since 2015 he is responsible for the Bioscience Research Competence Center based in Research Triangle Park, North Carolina, United States.*

Christian Fischer *studied Chemistry at the University of Regensburg, where he obtained his Ph.D. in Organic Chemistry in 1991. After a postdoc at the Institute of Materials Science at the University of Illinois, he started as a lab team leader in BASF Polymer Research in 1993. From 1993 to 1996, he studied in parallel Business Administration in Mannheim. From 1995 on, he worked in several fields at BASF Hong Kong for four years. Subsequently, he had diverse leading positions in marketing and sales for styrene co-polymers in Europe, before he assumed the Executive of the Fine Chemical Business in Asia in 2004. In 2008, he became President of Advanced Materials and Systems Research. In 2014, he was appointed as an honorary professor at the Technische Universität München. As of 2015, Christian Fischer is the President of Performance Chemicals.*

Harald Lauke *studied chemistry at the Technical University in Berlin. After completing a scholarship program at Northwestern University in Evanston, Illinois, he received his PhD with the topic "Novel metalorganic lanthanoid- and actinoid-compounds" under the supervision of Herbert Schumann. He joined BASF in 1986 as a research chemist in the Plastics Laboratory. After that, he held various positions within Engineering Plastics before becoming Managing Director of Comparex Sistemas Informáticos S.A. in Madrid, Spain in 1996. Two years later, he was transferred to Singapore as Director for Regional Marketing, Engineering Plastics. In 2002, he became President of BASF South East Asia, and from 2004, he was President for Functions and Market Efficiency Asia Pacific, also based in Singapore. From 2006 Harald Lauke was President of the Performance Polymers Division until March 1st, 2010, when he came back to Ludwigshafen and took over the responsibility for the Competence Center Biological & Effect Systems Research. As of January 2015, Harald Lauke is President of Advanced Materials & Systems Research.*

Peter Schuhmacher *studied chemistry at the Johannes Gutenberg University, Mainz and the University of Amherst, Massachusetts, USA. After completing his doctorate at the Department of Organic Chemistry, Johannes Gutenberg University, Mainz, he joined BASF as Research Manager, Colorants Laboratory in 1995. In 1998, he transferred to BASF's Inhouse Consulting Group as a Senior Consultant prior to joining BASF's operational Division Fine Chemicals as Head of Global Marketing Human Nutrition in 2000. He then transferred to BASF's Intermediates Division. There he was first responsible for the Global Strategic Marketing and then took over responsibility for the Intermediates Asia business in Hong Kong, China. As Senior Vice President, Strategic Planning, he was in charge of developing the group's "We create chemistry" strategy before taking over responsibility as President, Process Research & Chemical Engineering in May 2013.*

innovative solutions for the energy value chain, which encompasses energy production, storage, transmission, and utilization.

3) Quality of life: We are working on state-of-the-art solutions that mainly address challenges in construction, communication, and mobility. For example, BASF already offers an extensive portfolio of materials for various industries, such as special concrete and cement additives, coating materials, integrated heat insulation systems, automotive coatings, polyurethane systems, high-performance plastics, and biopolymers. We are developing solutions for lightweight automotive construction, building heat management, dyes for brilliant, flexible displays, light-collecting foils for functional facades, and battery materials for safe and convenient electromobility, for example.

In our anniversary year, we have chosen one topic from each of these three areas to focus on and address in detail in this Essay.

Food and nutrition: The world's need for food is expected to grow by more than 30 % over the next 35 years. At the same time, the supply of arable land is expected to shrink further owing to erosion, salination, and urbanization.[6] It is estimated that crop yields will have to double by 2050 to meet the increasing demand for food.[7] Enhancing agriculture productivity while improving nutrition is therefore essential to meet our future food requirements.

Intelligent energy: If the present trends continue, population growth and the growing industrialization in India and China will lead to a doubling or even tripling of the worldwide primary energy demand by 2050. Already in 2035, the demand for electricity is expected to have increased to 32 000 TWh,[8] which represents a market value equivalent to the gross domestic product of Germany. We urgently need answers to the following questions: How can we generate the required amounts of energy in a cost-effective, reliable, and environmentally friendly manner? How can we use energy more efficiently? What does the energy mix of the future look like? What role will energy from renewable sources play?

Urban living: Currently 54 % of the world's population live in urban areas.[9] The number of megacities with more than 10 million inhabitants is continually increasing and has tripled since 1990. Whereas London developed into a metropolis with eight million inhabitants over a period of 130 years, Mexico City, São Paulo, or Shanghai have seen a similar development in only 30 years. By 2050, two thirds of the world's population is expected to live in cities.[10] This impressive trend raises the question as to how we can design urban living to be economical and environmentally friendly for so many people while simultaneously ensuring a high quality of life.

Chemistry has been and will continue to be the innovation driver that enables us to address the needs of the growing world population. Throughout our history, we have continually refocused our research in response to developing needs and opportunities: Until the 1970s, the development of individual compounds was our primary focus whereas in the 1980s and 1990s, we concentrated on the development of materials with improved properties and for new applications. Since the turn of the millennium, tailor-made system solutions have increasingly become the focus of our research.[11] However, one aspect has remained the same throughout the 150 years of innovation at BASF: We concentrate on directly addressing the various needs of our customers with our broad portfolio of products, processes, and technologies.

In this Essay, commemorating the 150th anniversary of BASF, we have selected specific examples to illustrate how the innovation power of chemistry contributes to solving the challenges of tomorrow. We will first introduce several outstanding examples of innovation from the history of BASF and highlight how chemical and technical competencies[12] developed in the past still play an essential role in our current projects.

2. 150 Years of Research at BASF

Over the last 150 years, BASF has introduced more than two million products and technologies into the market. Figure 2 shows some key historical milestones, which are covered in this Essay in more detail.

The appointment of Heinrich Caro as BASF's first research director was the beginning of a series of groundbreaking innovations (Figure 2), which left their mark on our first two product segments, dyes and fertilizers, for 60 years. In 1869, together with the researchers Carl Graebe and Carl Liebermann, Caro secured the patent for the industrial-scale production of the dye alizarine for BASF "with the priority of one day".[13] Other dyes were to follow. With indanthrene blue, René Bohn discovered in 1901 a type of dye that was superior to all previously known artificial organic dyes owing to its outstanding color fastness. Following on from methylene blue and indigo, this was a very important advancement in dye chemistry and also in the early history of BASF.[1]

The successful dye era was followed by major breakthroughs in chemical process development. One of the most important milestones of the 20th century—not only for BASF—was the successful synthesis of ammonia by the Haber–Bosch process. This process was the decisive step forward in the development of fertilizers and still secures the food supply of billions of people today.

2.1. Ammonia

The foundation was laid in 1909 by Fritz Haber, professor of chemistry in Karlsruhe, with the first experimental synthesis of ammonia.[14] In 1910, Alwin Mittasch, later head of the "ammonia laboratory for process development" at BASF, identified a new catalyst after a systematic testing that involved around 20 000 individual experiments (Figure 3). These experiments revealed that the highly toxic and expensive osmium from Haber's experiments could be replaced by iron(II/III) oxide (Fe_3O_4). K_2O, CaO, Al_2O_3, and SiO_2 were found to serve as promoters. These advances made it possible for the starting materials nitrogen and hydrogen to react at a temperature of 450 °C.[15] Haber and Mittasch, in academia and industry, respectively, thereby laid the foundation for the field of heterogeneous catalysis and for

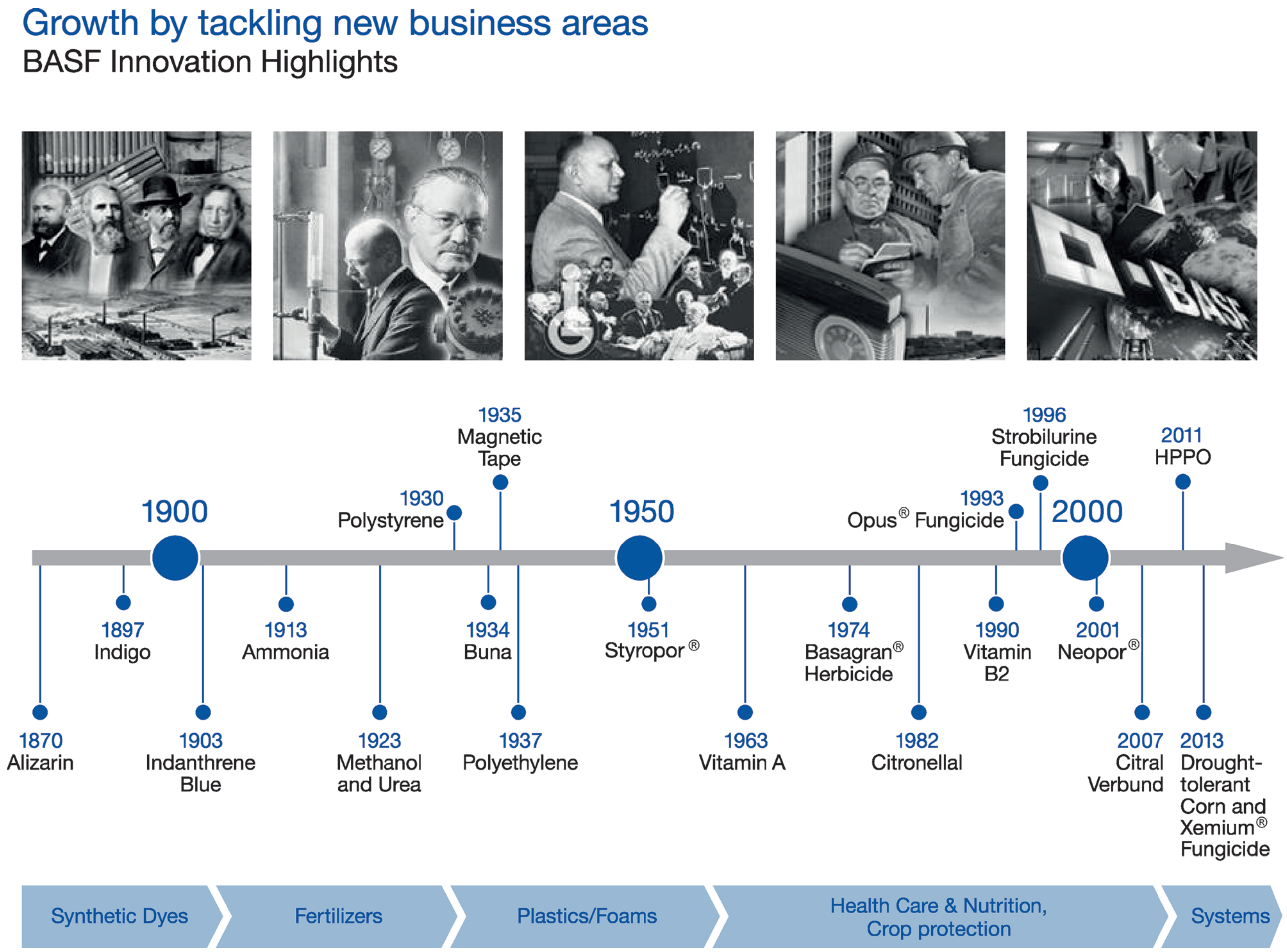


Figure 2. Milestones in BASF's research.

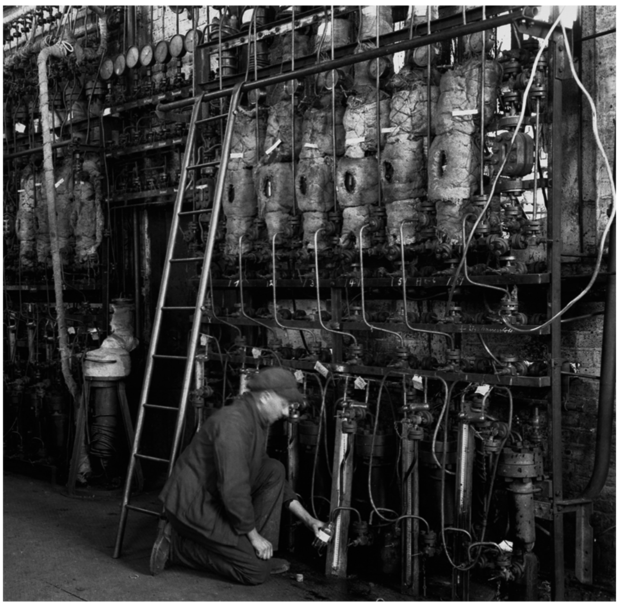


Figure 3. High-throughput synthesis in Mittasch's time.

modern high-throughput processes. Today, both form the basis for the development of functional inorganic materials.

The industrial-scale implementation of ammonia synthesis required a combination of high temperatures and high pressures in the range of 300 bar, which the steel reactors in use at that time could not withstand. In 1913, the future Chairman of the Board of Directors, Carl Bosch, identified the cause: Hot hydrogen under high pressure removed the carbon, which is essential for its strength, from the steel walls of the reactor, which consequently became soft and brittle. Using new approaches to apparatus construction and material development, Bosch succeeded in designing a high-pressure reactor in which ammonia synthesis could be safely performed on an industrial scale. He fitted the inside of the apparatus with a thin lining of low-carbon soft iron and drilled holes in the outer steel wall. This allowed the hydrogen to escape outwards without causing damage. In the same year, the first large-scale ammonia plant based on the Haber–Bosch process went into operation at the BASF site in Ludwigshafen. Both scientists were later awarded the Nobel Prize for their pioneering achievements (Haber in 1918, Bosch in 1931).

With the Haber–Bosch process, BASF realized the production of fertilizers and thereby established a second commercial pillar aside from dye chemistry.[1] Moreover, with the production of ammonia, BASF also established the foundation for the development of many new nitrogen-based product groups. Today, BASF uses ammonia mainly to produce glues and impregnating resins to treat paper, various amines, and caprolactam. Nevertheless, around three quarters of the global ammonia output are still used for the production of fertilizers.

In the following decades, the experience gained with high-pressure technology and advances in catalysis research led to further process innovation. In the late 1920s, Walter Reppe developed four catalytic reactions of acetylene under pressure: vinylation, ethynylation, carbonylation, and cyclic polymerization. They are known today as "Reppe chemistry" and enabled the synthesis of numerous organic compounds and intermediates, such as vinyl ether, butanediol, or acrylic acid. These compounds are still important raw materials for the production of synthetic fibers or plastics, such as spandex fibers for clothing or superabsorbers for diapers.

2.2. Styropor®

Concurrent with Reppe's activities, in the 1920s, Carl Wulff, a chemist at BASF, succeeded in developing a catalytic dehydrogenation of ethyl benzene to styrene (1929) and its subsequent polymerization to polystyrene (1930). This was the basis for the development of styropor® (1951).[16] Two important factors came together at that time: First, it was attempted to give polystyrene a broader range of uses. Second, the German Federal Postal Service required a cost-effective cable insulation with a low dielectric loss factor for the introduction of private subscriber dialing. The idea was to combine the favorable dielectric properties of plastics with those of foams (hard rubber foam and latex-based foam rubber were known at that time). Fritz Stastny, a chemist and engineer in the Application Technology Department of BASF with experience in the manufacture of hard rubber foam, therefore attempted to make a foam from polystyrene. First, he added substances that release gases at high temperature, such as ammonium bicarbonate, to the polymer. However, this did not lead to the desired result. He continued experimenting with liquids with low boiling points and used shoe polish cans as gas-tight reaction vessels (Figure 4).

By chance, in one of these experiments, a 25 cm high rigid chunk of foam was formed in one of the shoe polish cans. The can, which had been filled with a mixture of styrene, polystyrene, petrol ether, and benzoyl peroxide, was unintentionally left overnight at 80 °C in a drying cabinet. Stastny recognized the potential of this observation, and over the next few years, he developed, together with his colleagues, a suspension method in which styrene is polymerized in the presence of pentane and is thereby converted into a foamable, bead-shaped suspension polymer. In 1951, styropor® was registered as a BASF product brand and went on to become a worldwide success from 1952 onwards. Styropor®, which consists of 98 % air, still remains the quintessential foam for packaging and insulation. In the construction industry, styropor® is used mainly in composite systems for heat insulation and significantly contributes to saving energy while enabling more economic and environmentally friendly house designs.

Figure 4. Shoe polish can used as a reaction vessel for the manufacture of styropor®.

2.3. Magnetic Tapes

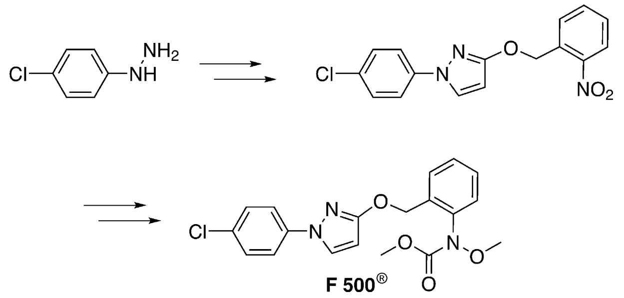
Although BASF's magnetic tapes disappeared from the market quite some time ago, they remained in the public awareness for a long time. They were the result of a collaboration between AEG and BASF in 1932 with the goal of developing tear-resistant homogeneously coated magnetic tapes for sound recording. The new tapes were based on the carrier plastic cellulose acetate and carbonyl iron, that is, highly pure, small particulate iron prepared by decomposition of iron pentacarbonyl, as the magnetically active substance.

The magnetic tapes are an early example of a successful collaboration in BASF's Knowledge Verbund[*] and the interdisciplinary use of knowledge to develop a system solution. Since 1924, BASF dominated the production of fine particulate carbonyl iron powder for induction coils of telephone lines. Systematic laboratory experiments by Mittasch using various sources of iron had resulted in an industrial-scale method for synthesizing the previously difficult to access iron pentacarbonyl compound from iron and carbon monoxide. The high-purity iron carbonyl product obtained by this method was used to produce high-purity iron oxide (particle size ca. 0.2 μm) by oxidative and thermal decomposition. BASF's dye production supported the development of this product with experience gained in the manufacturing of extremely fine dispersions. Furthermore, the plastics division, still new at that time, provided the know-how for the production of the carrier films. By 1934, the first 50 000 meters of tape had already been produced.[17] BASF subsequently established itself as the leading manufacturer of carbonyl iron powder and extended its expertise in industrial-scale inorganic synthesis. BASF continues to build on this expertise with its current research on magnetocaloric and superconducting substances, for example, as well as on battery materials for improved energy management.

[*] Verbund is a German word meaning "interconnected network". The Verbund is one of BASF's great strengths. It means intelligently linking our sites and creating value as one company. This idea is reflected everywhere in BASF and extends beyond production, as we also combine our expertise and technologies to develop innovative products and solutions for our customers all around the world. The word "Verbund" is quintessentially BASF and found increasingly in direct English usage.

2.4. Strobilurin Fungicides

In addition to fertilizers, which became available on a large scale through the Haber–Bosch process, the development of the strobilurin fungicides[18] was a further historical milestone for agriculture. This compound class is highly effective against harmful fungi and now accounts for more than 20% of the global fungicide market.[19] The strobilurins are derived from natural substances with fungicidal properties that were isolated from fungi of the *Strobilurus genus* (pinecone cap). First studies on this subject were undertaken in the 1980s as part of a university collaboration in which the stabilization of the active substances against sunlight proved to be the major challenge. This problem was finally solved by replacing the light-sensitive double bonds with various photostable groups, resulting in the first BASF compound of this class, kresoxim-methyl. An entire series of further innovative active substances from this class of molecules, including F 500® (Scheme 1), followed.[20]



Scheme 1. Synthesis of F 500®.

F 500® is not only effective against the most important pathogenic fungi, but also improves the tolerance of many crop plants against environmental stress factors, such as drought or ozone. This effect is due to the mode of action of F 500® in the respiratory chain.[21]

Structural information of the kind available for the Bcl enzyme, which is the target of F 500® (Figure 5), makes it possible to optimize the interactions between the active substance and the enzyme to be inhibited. Today, crystal-structure analysis of enzymes is an important method in our toolbox for research on active ingredients.

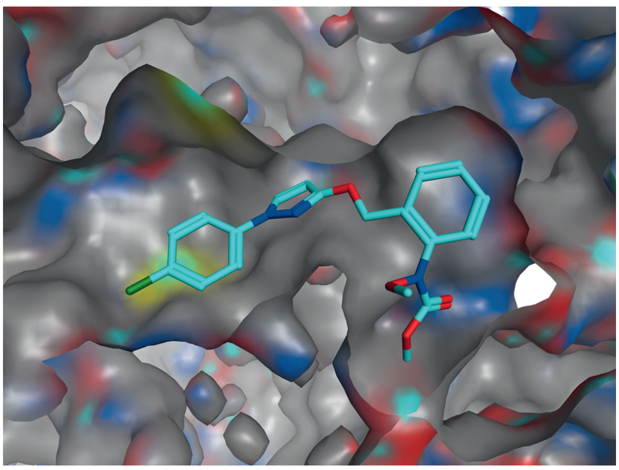


Figure 5. F 500® in the active site of the Bc1 enzyme.[22]

When used in integrated agricultural systems, innovative crop protection products such as F 500® result in healthier plants with higher crop yields and improved quality. Such products are essential if agricultural productivity is to be increased in the future.

The innovations discussed in this Section are good examples of how BASF has expanded its product portfolio over many decades by continuous research. After initially focusing on dyes, BASF has developed and commercialized a wide range of products, such as fertilizers, plastics, systems to support information technology, and crop protectants. The early innovations with their scientific breakthroughs have laid the foundation for the current research topics of BASF while shaping our present-day understanding of sustainability. They have also made a crucial contribution to developing the competencies that we now use to solve challenges in the fields of food and nutrition, intelligent energy, and urban living.

3. Current Research Areas of BASF

BASF has more than 10000 employees in research and development and collaborates with 600 partners from academia and industry in around 3000 projects. We spend approximately €1.8 billion per year on these activities, with three quarters of this funding devoted to research and development in existing fields of work. The remaining quarter, around €400 million, is invested into the development of new areas, known as growth and technology fields (Figure 6). In these fields, we explore novel concepts with a high potential to solve challenges in the key industries of transport, construction, consumer goods, energy & resources, electronics, health & nutrition, and agriculture.

From the 3000 research projects at BASF, we have selected a few prominent examples to illustrate our work in the three areas that we focus on in this Essay.

3.1. Food and Nutrition

Agricultural productivity needs to be increased substantially in order to support an increasing population from a shrinking supply of arable land (Figure 7). Furthermore, innovation will be required at all stages of the food chain to successfully master this challenge.

3.1.1. Innovative Crop Protection to Enable More Efficient Food Production

Food production has already increased considerably during the "green revolution" of the last century: Cereal production has increased by a factor of three while the area of arable land has expanded by only 30%.[24] However, for this trend of improved productivity to continue, further technological advances will be required.

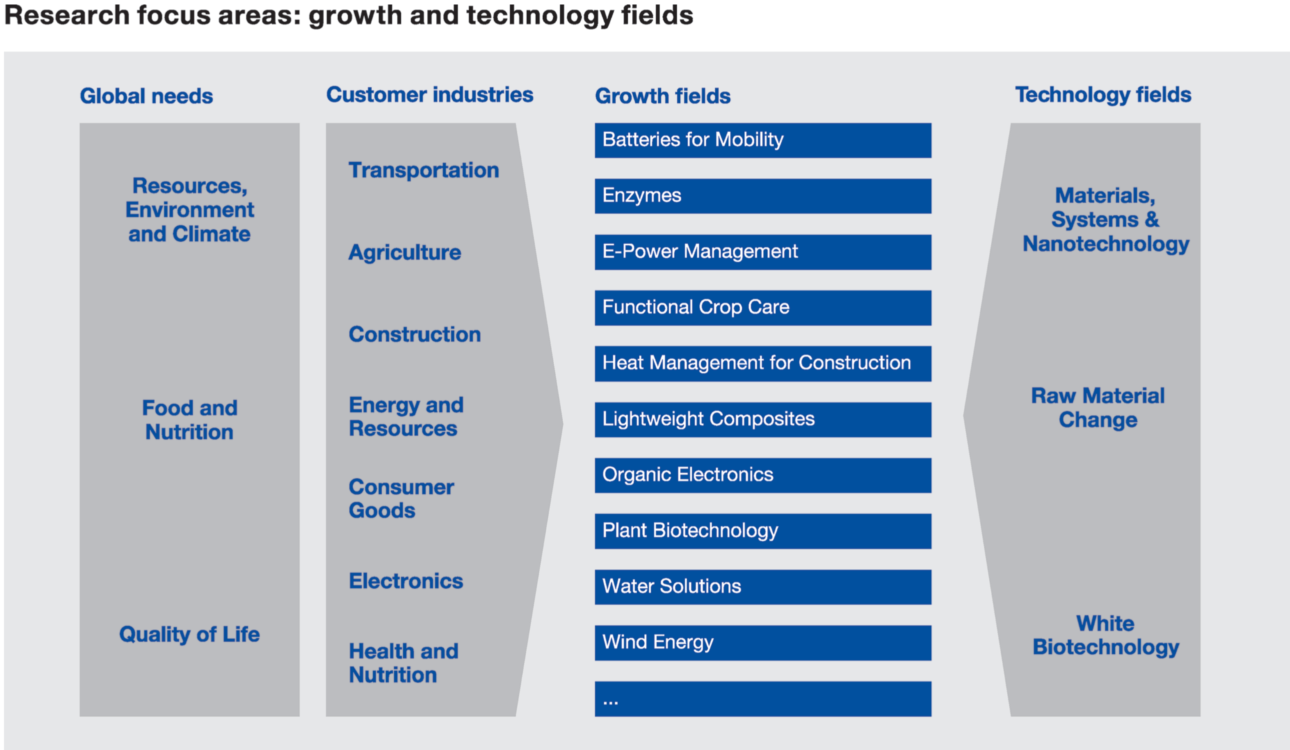


Figure 6. BASF's growth fields derived from three global need areas.

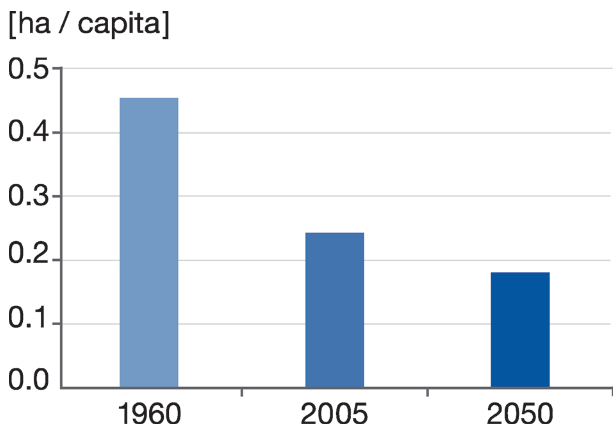


Figure 7. Arable land per capita.[23]

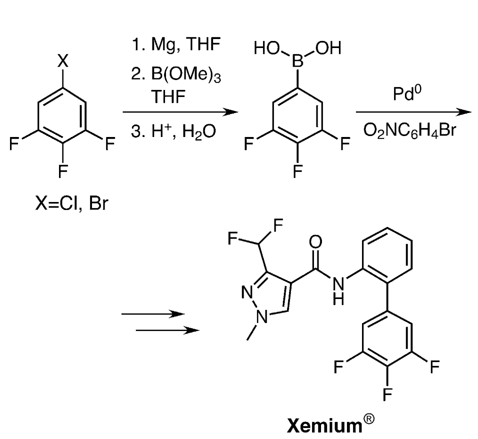
Around 100 years ago, concurrent with the development of synthetic nitrogen fertilizers, BASF founded its agricultural center in Limburgerhof, which has taken a comprehensive approach to advance agrochemical research.[25] Aside from the development of fertilizers, herbicides, fungicides, and insecticides, opportunities in plant health and plant breeding have also been studied. Today, our scientists continue to pursue an integrated approach to enhance crop yields and develop sustainable agriculture.

BASF introduced the first agrochemical, the herbicide 2,4-D, into the market in 1948, and a large number of further innovative herbicides, fungicides, and insecticides have followed. In many cases, these developments were only made possible by advanced technologies from BASF's Knowledge Verbund. For example, this was the case with kresoxim-methyl, which was introduced in Section 2.4 and is obtained by a coupled electrochemical synthesis.[26]

In a time of rising safety requirements for environment, farmers, and consumers and increasing resistance of weeds, fungi, and insects to many substance classes, earlier crop protectants are now being replaced by modern alternatives. Furthermore, novel active agents with favorable environmental properties and high efficacy need to be identified and developed. One recent example from BASF is the fungicide Xemium®, which sets a new standard in the control of fungi that cause diseases of crops such as cereals, corn, and soybean. One advantage of Xemium® is that less than 100 g of the active substance are required per hectare for the fungicide to be effective. It also provides exceptional protection against fungi in seed treatment thus allowing the plant to remain healthy from the outset and eliminating or reducing the need for later fungicide applications.

A key reaction in the synthesis of Xemium® is a palladium-catalyzed Suzuki cross-coupling (Scheme 2), with which BASF had gained industrial-scale experience since the manufacture of the fungicide Boscalid. Using this approach, more than 1000 metric tons per year of Xemium® can be produced.[27]

At BASF, the early toxicological assessment of new potential agrochemicals is an important method to rapidly assess the safety of novel lead compounds for farmers and consumers. We have developed a series of indicator tests, which have allowed a reduction in the number of animal experiments necessary during agrochemical development. Of



Scheme 2. Xemium® synthesis.

particular importance are tests that evaluate skin and eye irritation properties and approaches that can predict other toxicological properties.[28]

3.1.2. Enzyme Inhibitors and Plant Biotechnology for Improved Yields

Aside from damage caused by weeds, fungi, and insects, environmental factors, such as drought stress or nutrient deficiency, have a strong impact on yields. One innovation for improving nutrient availability is the urease inhibitor Limus®. Ammonia is synthetically converted into urea, which is spread onto the field as a fertilizer. The nitrogen bound in urea is released again as ammonia by an enzyme, urease, which is universally present in the soil. Especially under warm and dry conditions, a large proportion of the released ammonia can escape into the atmosphere. This is energetically inefficient and economically and ecologically undesirable. Limus® is a novel mixture of two synergistically acting urease inhibitors, which together reduce the loss of ammonia to the atmosphere by up to 90%. As a result, the efficiency and reliability of urea fertilizers are increased, which contributes to enhanced crop yields.[29]

Biotechnology also contributes significantly to increased efficiency in agriculture. Since the introduction of the first plant biotechnology products approximately 20 years ago, genetically modified (GM) crops have become widely adopted. In 2013, GM crops were cultivated on 175 million hectares, and around 18 million farmers are now using this technology worldwide.[30] Thus far, these successes have mainly been due to insect resistance and herbicide tolerance. However, the potential of plant biotechnology goes much further than this. For example, BASF research focuses on the next generation of GM crops with improved yields and higher stress tolerance.

A first innovative example of such a next-generation GM crop originated from a collaboration between BASF and Monsanto and was commercialized in 2013 as Genuity® DroughtGard®. In this case, a gene that provides drought tolerance, the cspB gene from the bacterium *Bacillus subtilis*,[31] was introduced into the genome of corn. This gene reduces the impact of dry conditions on the yield. In combination with a germplasm optimized for drought tolerance and specific advice on agronomic practices, the Genuity® DroughtGard® system demonstrated yield benefits of more than 300 kg/ha in comparison to non-GM drought-tolerant hybrids in 2012 and 2013 (Figure 8). In the ongoing collaboration with Monsanto, we focus on developing GM corn and soy lines that will enable further increases in yield.

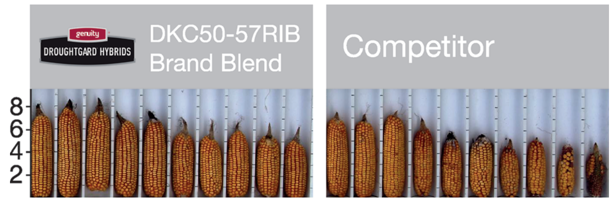


Figure 8. Genuity® DroughtGard® corn.

To develop the next generation of plant biotechnology traits, BASF has established a new technology platform based on its own research on metabolomics in the 1980s. Using high-throughput analysis, genes are correlated with specific plant metabolites and biosynthetic pathways (functional genomics). This technology platform also allows for the characterization of important genes that are related to yield enhancement and stress tolerance.[32]

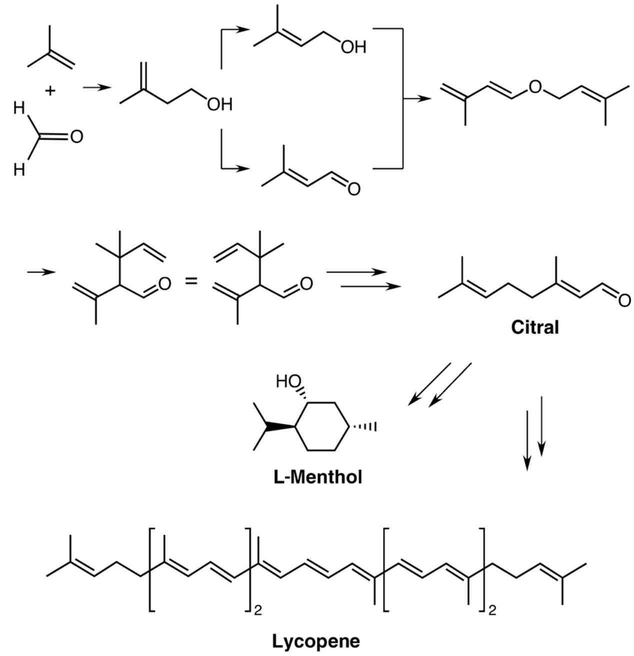
3.1.3. Vitamins and Dietary Supplements for a Healthier Nutrition

Aside from our solutions in the agricultural sector, we also develop innovative products that make our food healthier and increase the nutritional quality in animal production, for example, synthetic vitamins and dietary supplements.

One of BASF's most important intermediates for many dietary supplements is the terpene citral. Not only vitamin A and E, but also the carotenoids ß-carotin and lycopene as well as numerous aroma chemicals and fragrances, such as menthol, geraniol, and linalool, are produced on a large industrial scale from citral. A sequence of catalytic reactions enabled the industrial-scale production of citral (Scheme 3). A key reaction is the ene reaction of isobutene and formaldehyde, followed by a domino Claisen–Cope rearrangement, which produces citral with high atom economy as water is the only by-product.[33]

Citral has been manufactured in Ludwigshafen since 2004 in a continuously operating plant with an annual capacity of 40000 metric tons. This capacity is currently further expanded. Using citral as a starting point, the tomato pigment and dietary supplement lycopene, which acts as an antioxidant, has been produced on industrial scale since 2005.[34] Over the last few years, a new citral-based value chain for enantiomerically pure L-menthol has been established, and in 2012, a production facility with the largest capability for continuous asymmetric hydrogenation worldwide commenced operation.

BASF was also one of the first companies to use biotechnology for the synthesis of chemicals. In the early 1930s, we developed a fermentative reduction process for the synthesis of the drug ephedrine, which is still the state of the art today. In 1987, a fermentative process was also established



Scheme 3. Synthesis of citral.

for the production of vitamin B2, riboflavin.[35] Of similar importance is the biotechnological production of enzymes. For example, the efficient use of feed in animal nutrition is an increasingly important factor in the world's food supply. The supplementary use of enzymes, such as glucanases, xylanases, and phytases, can significantly improve feed conversion. The enzyme phytase (Natuphos™, Figure 9), which is produced biotechnologically by BASF, for example, increases the availability of phosphate from otherwise non-usable inositol hexaphosphate in plant-based animal feed. This contributes greatly to preventing phosphate overfertilization or eutrophication of waterbodies. Xylanases and glucanases as feed additives enable the use of otherwise indigestible plant components in feed, thereby allowing for their improved conversion. Aside from the biotechnological optimization of enzyme production, an increase in the stability of the enzymes is essential as they have to withstand the process for feed production. One of BASF's latest innovations in this respect is a thermostable phytase, which was obtained by structure-based optimization of the enzyme.

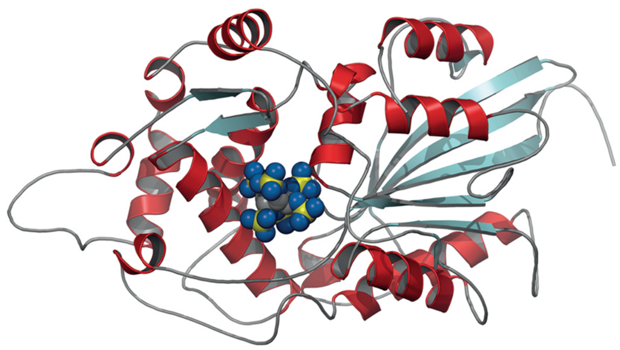


Figure 9. Phytase crystal structure.[36]

A further contribution of BASF research to healthier nutrition comes from the field of polyunsaturated fatty acids. A large number of scientific studies confirm that two essential polyunsaturated omega-3 fatty acids, namely eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), have beneficial cardiovascular effects.[37] They would therefore enhance many everyday foods, such as bakery and dairy products, if they could be easily added. In collaboration with the food manufacturer Cargill, BASF has used plant biotechnology to develop canola plants that produce EPA and DHA. To achieve this goal, BASF copied the metabolic pathway for EPA and DHA naturally present in algae and inserted it into canola plants. No other plant is currently able to economically produce EPA and DHA on a commercial scale. The market launch of this novel product is scheduled for the end of this decade.

3.2. Intelligent Energy

Chemistry also plays a key role in answering the energy-related questions raised above. Many essential elements of the electricity value chain (Figure 10) have to be fundamentally improved or changed to ensure a sustainable energy supply: from electricity generation through electricity transmission and storage to the usage of electricity. At BASF, we are working on material-based solutions for the entire value chain also to make the use of renewable energy more attractive. In the following Section, we will describe examples from the three areas of energy storage, conversion, and utilization.

3.2.1. Efficient Storage of Energy with Novel Cathode Materials for Batteries

As the leading automotive supplier in the chemical industry, BASF is also developing sustainable solutions for electromobility. We want to contribute to ensuring that electric cars will be affordable, energy-efficient, and suitable for everyday use.

With a cost of up to €10 000, the battery accounts for one quarter of the cost of an electric vehicle and determines its range. We are intensively studying materials for next-generation lithium-ion batteries (cathodes, electrolytes) and new technologies to make lithium–sulfur batteries feasible. Through these activities we want to ensure that future batteries will enable electric vehicles to have a much greater range at lower cost without an increase in weight. Naturally, this must be achieved without any compromises on safety. The decisive factor to achieve a greater operating range with a new type of battery is the energy density: When it is increased while the battery weight is kept constant, the range is extended. An energy density of up to 350 $Wh\,kg^{-1}$ is the current goal for future lithium-ion battery cells, and this can only be achieved with greatly improved cathode materials. In parallel, the performance of the electrolyte also has to be improved. We are intensely working on these goals together with our customers.

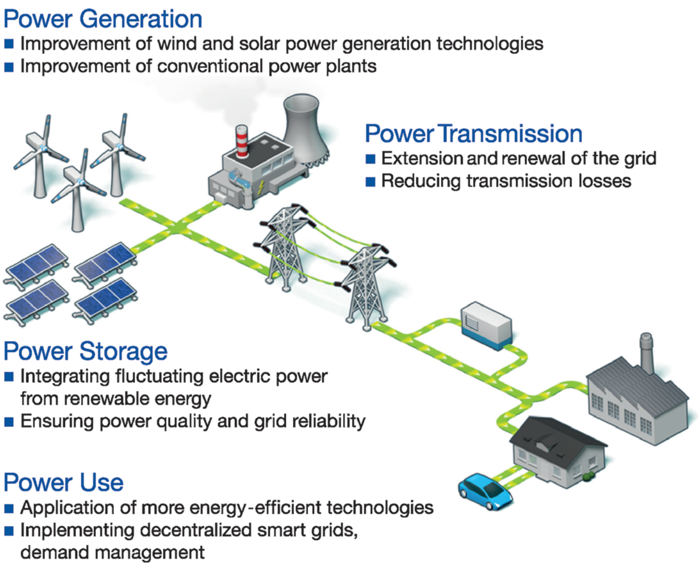
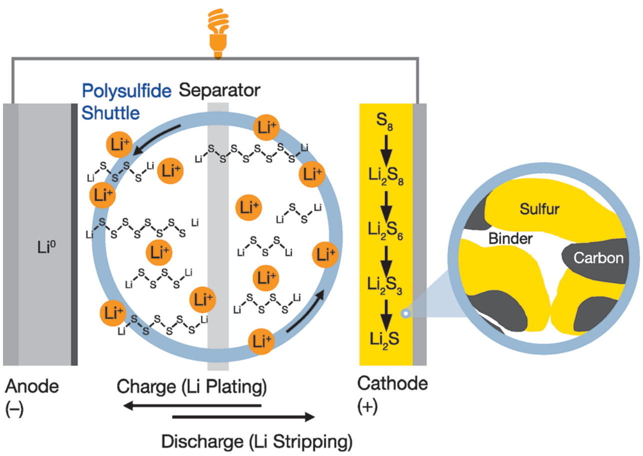


Figure 10. Electricity value chain.

Lithium–sulfur cells can provide a four to five times higher theoretical energy density than lithium-ion batteries (2600 Wh kg^{-1}; Scheme 4).[38] In practice, 500 Wh kg^{-1} has been achieved, and the lithium–sulfur battery might therefore contribute to achieving a further increase in the gravimetric energy density.

Lithium–sulfur batteries are still at the fundamental research stage. Since 2009, we have been investigating lithium–sulfur batteries together with Sion Power (Tucson, Arizona), the world leader in this technology, and also with academic partners. Our mid-term goal is to significantly increase the lifetime and cycle stability. In these endeavors, we are faced by two technical challenges: a) The polysulfides released in the charging/discharging process lead to a high self-discharge rate.[38] b) The electrolyte undergoes slow reductive decomposition on the highly reactive Li anode.[38a,40]

One approach to solving both challenges is the formation of a protective layer on the lithium surface, which, although permeable for Li ions, is not permeable for polysulfides and the electrolytes.[38a,39,41] The protective layer can be formed by two methods. In the first approach, a protective ceramic layer that conducts Li ions can be applied during manufacture of the anode, or the electrolyte is selectively combined with additives (salts or organic molecules). During battery operation, these additives decompose at the lithium anode and form an inorganic–organic layer together with the lithium. The resulting protective layer not only stops the direct contact of the electrolyte with the lithium and thus its decomposition, but should also prevent the growth of lithium dendrites on the lithium surface during the charging process. Therefore, contact with the cathode and a dangerous short circuit, which would result in failure of the cell, are prevented.



Scheme 4. Simplified representation of a lithium–sulfur battery.[39]

A second approach to prevent self-discharge and electrolyte decomposition is based on optimizing the cathode formulation. As both the main cathode component sulfur and the discharge product Li_2S are insulators, an electrically conductive material such as carbon must be added. Carbon, in interaction with a polymeric binder, forms an electron-conducting scaffold; on its surface, the electrochemical reactions of the sulfur species take place. Nanostructured carbon materials make the active material, elemental sulfur, accessible and create electrical contact owing to their defined porosity and structure.[40,42] With the aid of these materials, the cycle stability and utilization of sulfur were increased to match the lifetime of a lithium–sulfur battery. A further development is based on the incorporation of adsorbents into the cathode. During the charging/discharging processes, these adsorbents cause the transiently formed soluble polysulfides to remain bound to the cathode and thereby reduce the self-discharge rate. All of these results form the basis for the development of new, improved battery materials for electromobility.

3.2.2. Efficient Cooling with Magnetocaloric Materials

Studies by the US Department of Energy estimate that the proportion of energy consumed for cooling (by refrigerators, freezers, and air conditioners) amounts to about 20%

(4×10^{15} kJ) of the total energy consumed in a typical US household.[43] In order to curb energy consumption, legislators in many countries are demanding higher and higher energy efficiency standards and the certification and labelling of equipment. The thermodynamic efficiency of magnetic cooling systems is significantly higher than that achieved with the compression cycles of conventional compressors. Therefore, cooling with magnets offers the potential to reduce energy costs by up to 50% in comparison to standard refrigeration and air-conditioning units. Furthermore, magnetocaloric systems do not require the use of a conventional compressor, which means that these systems can operate with minimal vibration and noise. Finally, magnetocaloric systems do not require the use of any gaseous coolants, which are known to contribute to climate change.

The magnetocaloric effect was discovered by E. Warburg in 1881. It is based on so-called magnetocaloric materials, which heat up in a magnetic field and cool down again outside of that field.[44] Since 2006, BASF has been developing and producing magnetocaloric materials and integrating such technologies into refrigeration systems. The optimal arrangement in heat exchanger beds for operating a refrigerating machine depends on the physical properties of the materials. To date, magnetocaloric materials have only been used commercially in cryotechnology, for example, to cool helium to below 4 K. The development of new materials that are active at room temperature now enables their use in conventional cooling applications, such as air conditioners and refrigerators.[45] Figure 11 schematically shows the mode of operation of a magnetocaloric refrigerator. The Brayton cycle is a magnetocaloric process shown for comparison in the temperature–entropy chart.

A particularly high performing class of magnetocaloric materials is $Mn_{2-x}Fe_xP_{1-y}Si_y$, which is present in the hexagonal Fe_2P structure, with iron partially replaced by manganese and phosphorus by silicon (Figure 12).[46] This class of materials is the result of a collaboration between BASF and the Dutch Foundation for Fundamental Research on Matter (FOM) and Technical Sciences (STW) of Delft Technical University, Amsterdam University, and Radboud University Nijmegen since 2008.

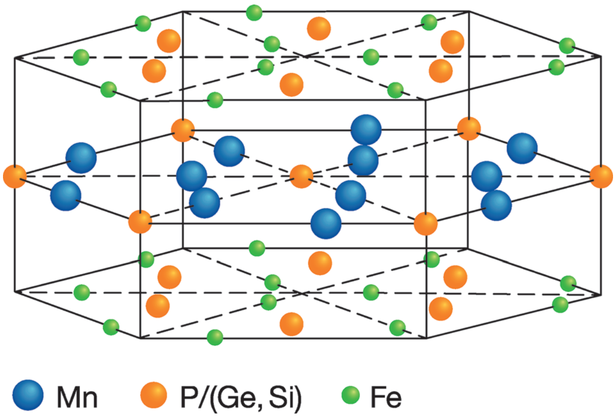


Figure 12. Structure of $Mn_{2-x}Fe_xP_{1-y}Si_y$.

The materials are ferromagnetic below the characteristic Curie temperature and enter a paramagnetic phase above this critical temperature. This structural magnetoelastic transition is accompanied by a pronounced change in entropy and temperature, which is utilized in the magnetocaloric cyclic process.[47] A strong magnetocaloric effect occurs only in a very narrow temperature interval of a few degrees around the phase transition. Since in conventional cooling applications a rise in temperature of >40 °C is necessary, several materials with different Curie temperatures are arranged serially in a cascade. Exactly adjusting the stoichiometry makes it possible to adjust the Curie temperature and the magnetocaloric properties and thereby to ensure optimal interactions in the cascaded bed. In practice, the materials are integrated, for example, in a porous polymer bed (Figure 13) through which the heat-transfer medium flows.

The decisive factor for this application is the efficient heat transfer from the material into the fluid transfer medium. This requires a large available surface area while only a small loss in pressure can be tolerated.[48] This task is equivalent to designing heterogeneously catalyzed chemical processes. Fluid dynamics calculations allow the most efficient geometries to be determined. Aside from the industrial-scale

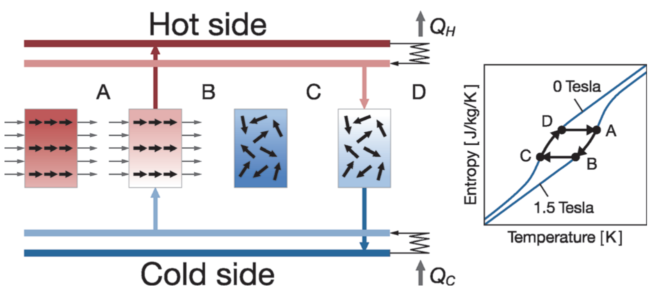


Figure 11. Magnetocaloric cycle (Left). D→A: Magnetization in the magnetic field. The magnetocaloric effect leads to an increase in temperature. A→B: Transfer of heat to a heat-transfer medium such as water. B→C: Demagnetization by removal of the magnetic field. The magnetocaloric effect leads to a decrease in temperature. C→D: Heating to the starting temperature by the heat-transfer medium. Temperature–entropy chart of the Brayton cycle (right).

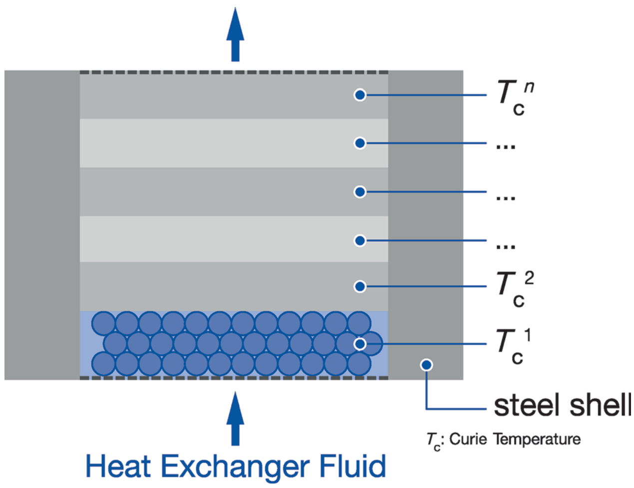


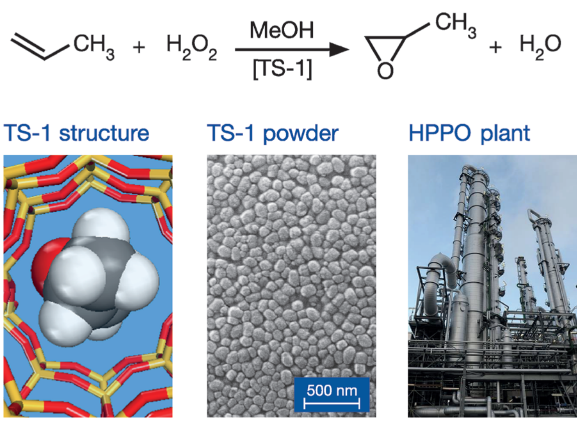
Figure 13. Cascaded porous bed of magnetocaloric materials in spherical form.

synthesis of the magnetocaloric materials, the structure of the heat exchanger bed is of great importance.

3.2.3. Energy-Efficient Production with Intelligently Designed Processes: HPPO as an Example

The chemical industry is one of the most energy-intensive industries. The availability of energy at competitive prices is decisive for our international competitiveness. Every year, the energy used by the production plants at BASF costs €2 billion,[2] and we are therefore constantly working on improving our energy efficiency, especially through innovative technologies such as catalyzed processes.

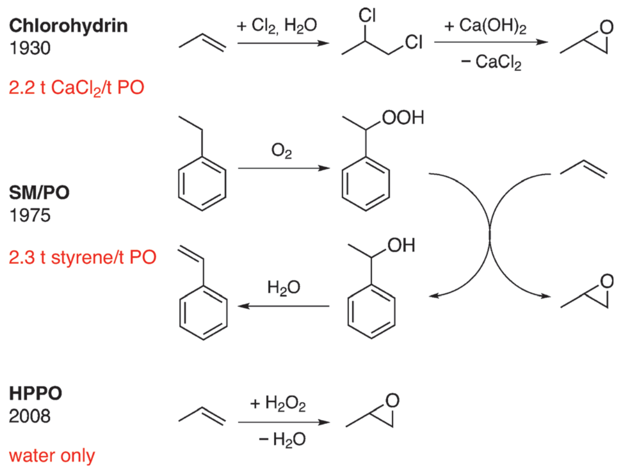
One example of an industrial-scale process that we have recently developed is the direct synthesis of propylene oxide (PO) from propylene and hydrogen peroxide (HPPO process).[49,50] With a global capacity of 7.5 million metric tons per year, PO is one of the top 50 "immortal" chemicals. It serves as a building block for polyurethanes, propylene glycols, and glycol ethers. In 2009, BASF, together with its joint-venture partner Dow and in partnership with Solvay as the H_2O_2 supplier, established a first plant at the Antwerp site (Scheme 5). A second plant was subsequently opened in Thailand in 2011 (Dow), and a third plant is planned to enter production in Saudi Arabia in 2015. Further facilities are also planned. The plants listed here together have a capacity of over 1 million metric tons per year.



Scheme 5. HPPO process of BASF/Dow with TS-1 as the catalyst.

There are enormous economic and ecological advantages of the innovative technology deployed in these new plants. Compared to previous conventional processes, the waste water output (0.5 metric tons waste water per metric ton PO) is reduced by 70–80%, while energy consumption is decreased by up to 35%. A further advantage is that no by-products are formed, but only PO and water. Furthermore, as the only feedstocks utilized in the innovative process are hydrogen peroxide and propylene, the new plants are much simpler than previous generation plants. Therefore the investment costs for a new plant are approximately 25% lower than for a plant based on conventional processes.

Further comparisons with the conventional CHPO (chlorohydrin) process,[51] which was developed in the 1930s and is still in operation in some plants today, make the benefits of the new HPPO process even clearer. For every ton of PO produced, 1.4 t chlorine and 1 t $Ca(OH)_2$ are required, 2.2 t $CaCl_2$ and 40 t water are obtained as waste products, and significant amounts of 1,2-dichloropropane are produced as a side product (up to 10% yield). Therefore, no reinvestments into the CHPO process are undertaken today. Even in the styrene monomer (SM)/PO process, the standard process for the synthesis of PO since the 1980s, 2.3 t styrene are obtained as a co-product along with 1.6 t waste water per ton of PO (Scheme 6).[52]



Scheme 6. Historical and current processes for PO production.

The technical challenges associated with developing the new HPPO process to the point that it could be used for production were enormous. Propene is preferably oxidized at the allylic position to acrolein or acrylic acid, but not to PO. However, with aqueous hydrogen peroxide an oxidizing agent was found that makes the reaction to PO possible. The catalyst used in the new HPPO process is titanium-impregnated silicalite 1 (TS-1),[53] a zeolite with MFI structure and a pore size of approximately 0.55 nm.[54] This material was discovered at EniChem in 1979[55] and has since been established as a catalyst for numerous oxidation processes with H_2O_2. The HPPO process has been recognized with several awards for its economic and ecological sustainability.[56]

3.2.4. Using Renewable Resources Energy-Efficiently and Sparingly

The demand for products from renewable raw materials is constantly increasing. Therefore, research in the technology areas raw material change and white (industrial) biotechnology occupies a central position in our strategy. For example, in 2012, BASF founded Succinity, a 50:50 joint-venture company with Corbion Purac, for the production and marketing of biobased succinic acid. Production is based on the bacterium *Basfia succiniciproducens*, which was selected and optimized by BASF to synthesize succinic acid from a large number of natural resources in a highly efficient process. The first fermentation plant, with an annual capacity of 10000 metric tons, came on stream in 2014 at the Corbion

Purac site in Montmelo near Barcelona (Spain). Succinic acid is used in the production of bioplastics, chemical intermediates, solvents, polyurethanes, and plasticizers. At our research sites in Ludwigshafen, Düsseldorf, and Tarrytown, we are developing further fermentative or biochemical processes for the energy- and resource-efficient manufacture of chemical and biochemical products from renewable resources. In this way we use the power of nature to obtain compounds that cannot be competitively produced using conventional chemical methods and reactions.

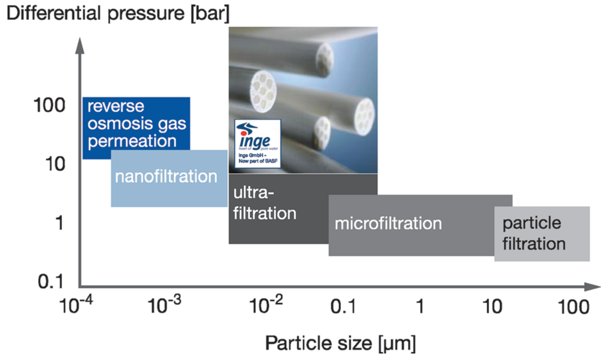


Figure 14. Overview of membrane separation processes depending on the size of the components to be separated and the pressure to be applied. A distinction is made between dissolution and diffusion membranes (blue) and porous membranes (gray).

3.3. Urban Living

Rapid urbanization brings with it many challenges, such as ensuring a sufficient supply of drinking water, waste water disposal, energy-efficient construction, low-emission transportation, and not least further improvements in the standard of living. BASF is addressing these tasks with holistic approaches and sees multi-material systems as one key to their solution. Whereas in the past, our polymer research mainly concentrated on monomeric building blocks, base polymers, and some engineering polymers, today the focus has shifted towards materials and systems. For us, system development means combining individual elements in a way that the properties of the whole are more than simply the sum of the components. Within this framework, we have established a complementary portfolio of technologies in the areas of functional polymers and additives over the last few years and deepened our understanding of customer industries. Thus, classical polymer research has developed into materials and systems research. Our research pipeline in this field is illustrated by the following selected examples.

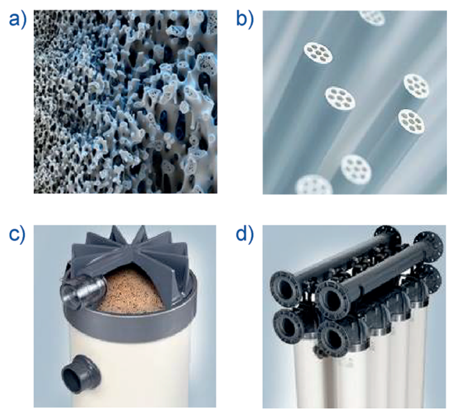


Figure 15. Membrane development along the value chain: a) porous materials; b) inge® Multibore® membranes; c) dizzer® module; d) T-Rack®.

3.3.1. Water Treatment

Water is often called our most precious resource. In the last 100 years, global water consumption has increased by a factor of ten, and at present, about 800 million people have no access to clean drinking water.[57] By 2050, water consumption is expected to have increased by approximately 55% owing to population growth, rising industrial production, and energy generation.[57] In water treatment, membrane technology occupies a key role.[58] Viruses and bacteria can be removed by microfiltration and ultrafiltration. Water softening and sea-water desalination can be achieved with nanofiltration and reverse osmosis techniques (Figure 14).

Since the 1990s, BASF has provided high-performance polymers, such as poly(ether)sulfone (PSU, PESU), as raw materials for membrane manufacture. Through the acquisition of inge® watertechnologies in 2011 and their system know-how, BASF extended its position further down the value chain (Figure 15). Chemists, physicists, material scientists, and engineers are working closely together on the various aspects of system development. Higher water flux and increased energy efficiency can be achieved both by improved membrane materials and by advances in engineering.

To ensure a high water flux over a long period of time, it is critical to avoid biological or inorganic deposits (fouling and scaling) on the membrane surface.[59] BASF is pursuing multiple approaches in this area, including modification of the membrane polymer, control of the pore morphology, incorporation of additives, and surface functionalization. For example, more hydrophilic membrane polymers or a regular pore structure can reduce fouling.[60] Furthermore, polyvinylpyrrolidone or block copolymers used as additives in the membrane matrix can also minimize the formation of a biofilm on the membrane surface.[61] Finally, the functionalization of surfaces, for example, by grafting of hydrophilic, anti-adhesive monomers, offers a further possibility to ensure a permanently high water flux.[62]

Membranes are, however, only one element of our research in the field of water management. BASF also develops process chemicals, such as flocculation agents or corrosion inhibitors and antiscalants, to address the globally rising water demand.

3.3.2. Sustainable Construction

The challenges in the construction industry include ensuring that buildings are energy-efficient and of high quality, cost-effective, quickly built, suitable for all climatic zones, and built in accordance with individual design requirements. Globally, with more than 9 billion cubic meters, concrete (consisting mainly of cement, sand, gravel, and water) is by far the most utilized material by man.[63] Much has happened in this field since the end of the 20th century. Improved, tailor-made additives and a deeper understanding of the chemical processes involved have enabled architectural innovations and spectacular construction projects (Figure 16).

Figure 16. One World Trade Center in New York City built with Green Sense® concrete from BASF.

The ability to achieve accelerated, energy-efficient hardening of concrete while maintaining or improving the quality of the end product remains the subject of much academic and industrial research and development. With the hardening accelerator Master X-Seed®, BASF recently achieved a significant acceleration in the early stages (6–12 h) of concrete hardening without applying heat while retaining the final hardness and durability of the concrete (Figure 17). The concept is based on colloidal suspensions of nanoparticulate calcium silicate hydrate crystals (C-S-H), which act as crystallization seeds.[64] One of the challenges that needed to be overcome was to stabilize the 2 nm thin C-S-H seed crystals in solution without extensively occupying the active C-S-H surface.[65] For this purpose, polymers that adsorb onto

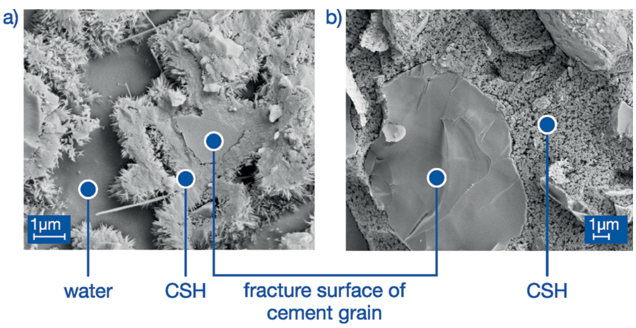


Figure 17. Cryo-SEM image of cement pastes with the same degree of hydration but different hardening times: a) without additives, after 14 h; b) with 1 wt% Master X-Seed®, after 4 h. In addition to the significant acceleration of the hydration process, Master X-Seed® promotes a homogeneous distribution of the C-S-H phase.

the positive surface of the inorganic nanoparticles (e.g., through carboxylate or phosphate groups) and contain neutral hydrophilic segments that act as spacers were developed.

Crystallization research is deeply rooted in BASF's history and already played an important role in the manufacture of indigo. Basic research into the influence of polymer additives on the crystallization of calcium carbonate in the 1990s for laundry detergents (inhibition of incrustation) and sea-water desalination[66] contributed greatly to the subsequent development of Master X-Seed®. This is only one example in which the interdisciplinary combination of know-how in BASF's research (in this case, polymer and inorganic expertise) laid the foundation for sustainable innovation.

3.3.3. Heat Management in Buildings

Currently around 40% of the global energy demand is consumed by the buildings sector. Global warming and rising prices for energy and raw materials make innovative solutions for improving the energy efficiency of buildings essential. In order to facilitate holistic thermal management, BASF is developing solutions for the management of light and heat radiation as well as high-performance insulation materials.

BASF can look back on a long history of success with insulation materials. As described in Section 2, this extends back to the 1950s. BASF is not only the inventor and pioneer of polystyrene-based foams such as styropor®, styrodur®, and neopor®, but also offers a wide range of insulation materials, including polyurethane-based hard foams (Figure 18).

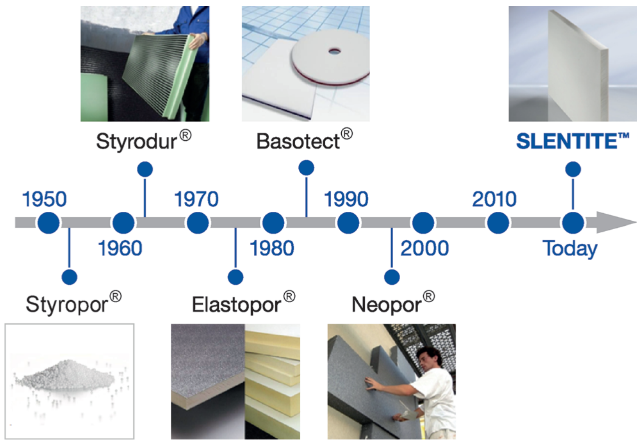


Figure 18. BASF developments of innovative insulation materials for the construction industry.

Also in the area of insulation materials, the focus has shifted towards material systems. In 2013, BASF researchers developed SLENTITE™, a polyurethane-based high-performance insulation panel that needs only half the space of conventional materials for the same insulation performance (Figure 19).[67] This polyurethane aerogel can be produced as a stable, monolithic panel. This research was initially carried at ISIS (Institut de Science et d'Ingénierie Supramoléculaires)

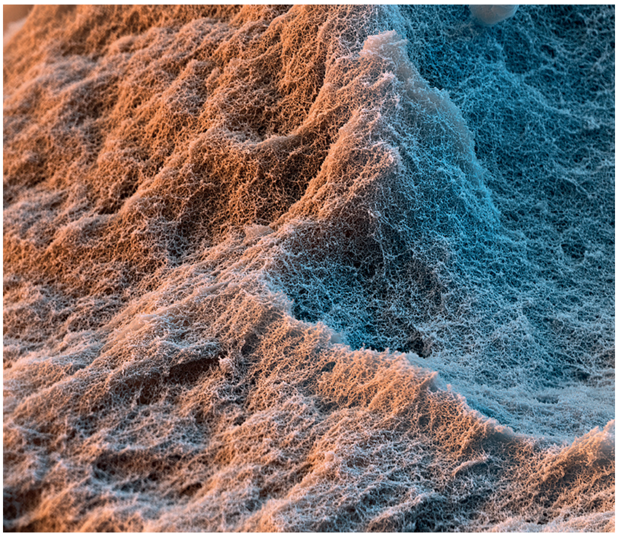


Figure 19. Scanning electron micrograph of the polyurethane aerogel SLENTITE™.

in Strasbourg as part of a BASF postdoc initiative. First, the focus was on the development of new chemical concepts for nanoporous materials (Figure 19) with very low thermal conductivity. The smaller the pore diameter, the lower the thermal conductivity is (Knudsen effect). However, compared to today's insulation materials, it is necessary to reduce the pore size by a factor of 1000 to achieve a significant effect. The open, 50–100 nm large pores of SLENTITE™ ensure a high insulation performance while providing sufficient water vapor permeability, which leads to a pleasant indoor climate.

For today's insulation materials, not only low thermal conductivities are decisive. Technical challenges faced by users, such as processing and transport as well as building regulations, have to be addressed in the early stages of the development process in partnerships. Therefore, the further development of SLENTITE™ for market introduction is occurring in close collaboration with construction engineers and customers.

3.3.4. Lightweight Automotive Construction

Population growth and growing urbanization are also increasing the demand for mobility. In 2020, 1.2 billion vehicles are expected to be on the road worldwide, 300 million more than today.[68] The limited availability of fossil fuels together with climate change creates the need for automobiles with higher efficiencies and lower emissions. Worldwide, countries have also enacted targets for the reduction of carbon dioxide emissions into legislation. The EU, for example, specifies that today's carbon emissions of 127 $g\,km^{-1}$ are to be reduced to 95 $g\,km^{-1}$ by the year 2021.[69] A more stringent target is under discussion.

BASF, as the world's leading automotive supplier in the chemical industry, has focused its research on producing improved catalysts for automotive emissions, new battery materials, and innovative lightweight materials. The latter contributes by enabling significant reductions in energy consumption per vehicle.[70] A holistic approach is essential for the development of lightweight composites, and BASF works together with its customers to keep the entire system, including design and process requirements, in mind.

For use in the automotive industry, the manufacturing processes for polyurethane and polyamide resins that are reinforced by glass or carbon fibers must be suitable for industrial-scale production. This is already the case for short- and long-fiber composite materials at BASF; for example, the BMWi3 already contains carbon fibers in combination with a polyurethane matrix in the rear seat pan. This composite solution saves weight, and despite its wall thickness of only 1.4 mm, it fulfills the high safety requirements of the BMW group.

Replacing aluminum and steel in structural parts by plastics is only possible by continuous fiber reinforcement. However, continuous-fiber-reinforced thermoplastic composites represent a technological challenge as they cannot be manufactured by the high-throughput process of injection molding. Thus, in 2013, BASF introduced a new concept into the market. The product and service package Ultracom consists of continuous-fiber-reinforced semi-finished products, adapted overmolding compounds, and a comprehensive service package, comprising simulation, process support, and testing capabilities (Figure 20). The core innovation comprises the semi-finished products, that is, laminates with woven fabrics and unidirectional tapes impregnated with polyamide. From the materials perspective, the challenge was to seek the optimal match between fiber and polymer, and then to pair this tape or laminate with the overmolding compound. The fibers must have a surface formulated for the specific polymers that they are impregnated with and vice versa. The overmolding materials, in turn, must satisfy the typical requirements for injection molding while simultaneously permitting optimum adhesion of ribs to the laminates. With this holistic approach, it is possible to design and produce complex parts with a very high mechanical reinforcement at

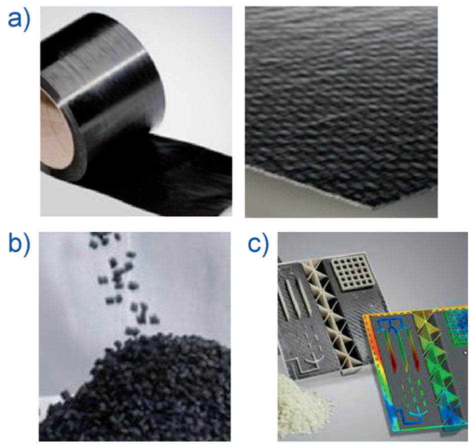


Figure 20. Ultracom: holistic approach for cost- and weight-optimized automotive structural components: a) continuous-fiber-reinforced semi-finished products (laminates and tapes); b) overmolding compound based on polyamide; c) engineering service comprising the simulation tool Ultrasim®, processing know-how, and support from BASF's testing laboratory.

the required locations. The first production application of this concept is in the front seat pan of the Opel Astra OPC.

Obstacles that still need to be overcome for lightweight composites are: improved fiber-matrix understanding (including the ability to simulate), high fiber costs, and high process costs resulting from long cycle times. Generally, developments towards electromobility will increase the requirements for composites. Parameters, such as temperature stability, electromagnetic screening, flame retardancy, and further weight reduction because of the additional battery weight, will play an increasing role.

4. Success Factors for BASF's Research

The innovation examples described in this Essay show that major global challenges call for increasingly complex solutions. The role of chemistry has expanded beyond the sale of large amounts of basic chemicals, intermediates, or plastics towards providing innovative solutions at the level of materials and systems. Time is also becoming increasingly important, with "time to market" being an increasingly decisive factor for competitive success. At BASF, we have focused on optimizing our organization and research process so that the time required to bring an invention to the market is minimized. At the same time, we also commit resources to long-term projects with groundbreaking potential, for example, in plant biotechnology or chemical process development. We still recognize, as Carl Bosch did, that "*a big technical problem needs 10 years to become ready for the factory*".

Innovation is and remains our driver for success. High-quality research and development work along with close collaborations with our customers will remain a pre-requisite. Over the last 150 years, BASF has continuously invested in research and development, €1.8 billion alone in 2013, while increasing its customer focus. This is illustrated by a recent example, the new adidas running shoe Energy Boost with the midsole material Infinergy® from BASF. The light and elastic polyurethane particle foam returns the majority of the absorbed energy to the wearer, making it ideal for runners.

To remain successful in the long term, we need to understand our customers' challenges even better in the future. We intend to increasingly participate at an early stage in the development of sustainable solutions with our partners: We will utilize our extensive chemical know-how and new interdisciplinary technologies, such as nanotechnology or biotechnology. From a deep understanding of our customers' markets to jointly developing technical solutions, we will engage closely with our customers' value chains.

The backbone of research at BASF is our global Knowledge Verbund involving more than 10000 employees with a wide range of expertise. Approximately 10% of our colleagues work directly in research and development. The examples discussed in this Essay are the achievements of many teams of exceptional individuals to whom we express our thanks. It is the creativity and tenacity of people that make innovation possible and successful. Today's interdisciplinary workforce of chemists, engineers and physicists, biologists, physicians, and pharmacists is engaged in around 3000 projects in the fields of chemistry, material science, and bioscience. In 2013, we launched more than 300 new products and achieved €8 billion of sales from products that had been on the market for less than five years. Furthermore, the current strength of our research and development pipeline is illustrated by the fact that we filed around 1300 patent applications and headed the industry in the Patent Asset Index[71] for the fifth time in succession in 2013.

A key factor for the success of innovation at BASF is our global reach with research sites located throughout the world (e.g., Research Triangle Park, Iselin, Tarrytown, and San Diego in North America; Ludwigshafen, Basel, Düsseldorf, and Ghent in Europe; Shanghai and Mumbai in Asia). BASF researchers collaborate with around 600 top-ranking universities, research institutes, and companies throughout the world in many different disciplines and multiple projects. This worldwide presence allows us to offer our customers global, regional, or local solutions that meet their specific needs. It also helps us to attract, recruit, and retain scientific talent on a global basis. Our main research and development location has historically been Ludwigshafen in Germany, but we plan to further enhance our global research presence in the coming years and have set a target that 50% of our research and development activities will be conducted in North America and Asia by 2020. In line with this target, we have expanded our research facilities and collaborations at leading innovative locations in these regions. For example, in 2013, BASF founded the "Network for Advanced Materials Open Research" (NAO) in Shanghai together with seven top-tier universities in China, Japan, and South Korea. In 2014, BASF inaugurated the "California Research Alliance by BASF" (CARA) as a multidisciplinary postdoc center together with the University of California Berkeley, Stanford University, and the University of California in Los Angeles. These new initiatives complement further postdoc centers that were established a few years ago on the East Coast of the United States (Harvard, MIT, and the University of Massachusetts) and in Europe (Strasbourg, Heidelberg, Freiburg, Zürich).

A further important success factor for BASF is our openness to explore new technologies and methods, which could become the basis for innovative solutions. Nanotechnology, for example, with its large range of potential applications, enables the development of materials and products with new properties, as we have shown with the Master X-Seed® and SLENTITE™ solutions (Section 3.3). It also contributes to the efficient use of resources. We use modern high-throughput methods to identify optimal catalysts, synthesis methods, and active ingredients. Computer-assisted methods, such as modeling, data mining, and statistical experiment planning, are now standard practice in our laboratories. Internet-based networking between different systems enables rapid global data exchange and analysis. In the future, we will expand the use of cyber-physical systems in which mechanical systems are precisely controlled by sensors.

Ronald Coase, the British economist and Nobel Prize winner, once commented: "*Knowledge is the only competitive advantage of our times, it grows through open interaction with* *others*".[72] This is more than ever the case today because competitive differentiation occurs increasingly through the application of knowledge in innovation. Successful and sustainable innovation through new products, technologies, and business models will be the essential driver of growth in the years ahead. To address the complex challenges in the fields of food and nutrition, energy, and urban living, we must achieve success through fundamental and radical innovation. This will require even closer interdisciplinary collaborations in the future to leverage our knowledge and potential. It is therefore essential for us to develop and foster ever stronger interactions with customers and partners. Only together, we can use chemistry to help us solve the challenges that lie ahead.

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