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Technologies for Sustainability and Climate Protection - Chemical Processes and Use of CO_2

Federal Ministry of Education and Research Funding Programme Information Brochure

RESEARCH

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Introduction

In the public perception, carbon dioxide (CO_2) is first and foremost a troublesome greenhouse gas, but that could change in the future. The need to avoid CO_2 emissions will not disappear. The development of energy-efficient industrial production techniques that minimize CO_2 emissions is still a major industrial and social imperative. This is particularly true for energy-intensive sectors such as the chemical industry.

CO_2 can, however, be beneficial as well as problematic, as it can be used in combination with water (or hydrogen) as a feedstock and chemical building block to produce chemical precursors and fuels. Reactions of CO_2 with more complex chemicals provide pathways to value-added plastics and other products. The goal of the programme "Technologies for Sustainability and Climate Protection - Chemical Processes and Use of CO_2" which is funded by the Federal Ministry of Education and Research (BMBF) is to realize such projects. The programme is a subset of the Sustainable Development Research framework and is directed specifically at the re-use of CO_2 as a material resource as well as at strategies for increasing energy efficiency in order to cut emissions.

Innovative R&D projects which will contribute to long-term structural change in industry and society at large ("alternatives to oil") are underway. Pioneering research initiated by BMBF addresses the somewhat conflicting goals of protecting the climate and ensuring a secure supply of raw materials. The research projects could also be major contributors to the energy transition. Surplus electricity generated from wind and solar energy can provide power for the production of hydrogen which in turn can be used to produce synthetic gas as a method of storing energy.

The funding programme is primarily directed at the chemical industry which is a major consumer of primary energy and primary materials. Measures taken to increase energy efficiency can create significant leverage. Alongside biotechnology, the chemical industry is the only sector which can generate added value through the use of CO_2 in product production. Because the chemical industry often is at the beginning of the value-added chain, it can act as a problem solver for many other industries and help manage the challenges of climate change.

The funding programme supports the sciences and industry through joint development of innovative technologies and techniques and promotion of structural change in industry for long term. The goal is the transformation of the industrial resource base from oil and coal to renewable and alternative resources to ensure future sustainability. Both, in approach and scope, it is Europe's largest CO_2 utilization initiative. Germany is breaking new ground by using CO_2 as a chemical feedstock.

BMBF is providing roughly € 100 million of funding for 33 Research and Development (R&D) projects between 2010 and 2016. The projects were selected from among the 89 proposals which were submitted. 86 industry partners are taking part in the projects including 23 small and medium-enterprises. 71 research institutions and universities are also actively involved.

What is being funded?

BMBF supports 33 consortium projects which bring together science and industry to drive development in the following areas:

- **Migration or extension of the raw material base through utilization of CO_2 as a feedstock for the synthesis of basic chemicals**
- **Utilization of CO_2 for chemical energy storage**
- **Chemical activation of CO_2**
- **Innovation in CO_2 extraction, e.g. from power station gas emissions**
- **Reduction in greenhouse gas emissions in production through increased energy efficiency and the use of functional solvents**


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CO_2 Utilization

Carbon dioxide – greenhouse gas or feedstock?

Carbon dioxide – CO_2 – is a waste byproduct emitted by coal-fired power stations or in general by any combustion of fossil fuels, and it is regarded as the major contributor to climate change. Annual worldwide emissions of the greenhouse gas now exceed 30 billion tonnes.

Chemists are looking for ways of re-using the harmful gas as a feedstock, for example in the production of plastics and other high-value products. In this context, CO_2 is viewed as a carbon building block which could at least partially replace fossil resources such as oil and gas as a source of carbon. Carbon is a key basic resource for the majority of products produced by the chemical industry. Each year, the chemical industry worldwide produces more than one billion tonnes of chemical products which contain carbon including basic chemicals, plastics, tensides, colorants, washing and cleansing agents, etc. Mineral oil is the predominant source of carbon in Germany. Carbon is also obtained from natural gas and coal. Combustion waste gas from coal-fired power stations or other industrial facilities contains large amounts of CO_2, so the gas is readily available as a possible alternative.

CO_2 - an alternative to oil?

The depletion of fossil resources and the difficulties which are likely to be encountered in accessing new deposits are driving prices up. These factors create big question marks around future security of supply. To ensure an affordable supply of carbon sufficient to meet the needs of the chemical industry, alternatives to fossil fuels will have to be found. Besides biomass, utilization of the greenhouse gas CO_2 is one possibility. CO_2 extracted from the waste gas emitted by power stations, cement factories, some chemical plants, etc. can be processed for use as a feedstock in the chemical industry. The list of target products includes plastics to make lightweight automotive parts, mattresses, upholstered furniture, housing materials, insulation, solvents and fine chemicals. Many chemists view CO_2 as a potentially valuable resource with a broad applications profile. CO_2 is a low-energy compound which is relatively inert. This is a big disadvantage, because it means that reactions involving CO_2 consume a lot of energy. Within the framework of the programme “Technologies for Sustainability and Climate Protection - Chemical Processes and Use of CO_2”, scientists are searching for suitable catalysts which overcome the low reactivity of CO_2 and act as a “turbo” in reactions with other substances.

The engineers involved in the projects are making CO_2-based production as energy efficient as possible. Analyses of the material and energy flows are also carried out to ensure that the new processes actually do have a reduced CO_2 footprint, meaning that they have lower CO_2 emissions than conventional production processes. The fact that CO_2 is used as a feedstock and is incorporated into the target product is a key aspect. The percentage of carbon by weight in some plastic products can be as high as 40% or more, and the consumption of fossil-based substances can be reduced by a substantial amount.

The Projects

- Dream Reactions - CO_2 Utilization
  Dr. Aurel Wolf, Bayer Technology Services GmbH
  E-mail: aurel.wolf@bayer.com
- CO_2 as a Polymer Building Block
  Dr. Uwe Seemann, BASF SE
  E-mail: uwe.seemann@basf.com
- Dream Production – Technical Utilization of CO_2 as a Chemical Synthesis Building Block for Polymers
  Dr. Christoph Gürtler, Bayer MaterialScience AG
  E-mail: christoph.guertler@bayer.com
- Dream Polymers
  Dr. Christoph Gürtler, Bayer MaterialScience AG
  E-mail: christoph.guertler@bayer.com
- New Organocatalysts and Cooperative Catalytic Processes for the Utilization of CO_2 as a Building Block for Chemical Synthesis (OrgCoCat) – Junior Research Group
  Dr. Thomas Werner, Leibniz-Institut für Katalyse e. V.
  E-mail: Thomas.Werner@catalysis.de
- Development of Active and Selective Heterogeneous Photocatalysts for the Reduction of CO_2 to C1 Base Chemicals (PhotoCat) – Junior Research Group
  Dr. Jennifer Strunk, Ruhr-Universität Bochum
  E-mail: jennifer.strunk@techem.rub.de
- Combinatorial Electrocatalytic CO_2 Reduction (ECCO_2) – Junior Research Group
  Dr. Karl J.J. Mayrhofer, Max-Planck-Institut für Eisenforschung GmbH
  E-mail: mayrhofer@mpie.de
- Energy-Efficient Synthesis of Aliphatic Aldehydes from Alkenes and CO_2: Valeraldehyde from Butane and CO_2 (Valery)
  Dr. Daniela Kruse, Evonik Industries AG
  E-mail: daniela.kruse@evonik.com
- Acrylic Acid from CO_2 and Ethene (ACER)
  Dr. Michael Limbach, BASF SE
  E-mail: michael.limbach@basf.com
- CO_2-Based Acetone Fermentation (COOBAF)
  Dr. Jörg-Joachim Nitz, Evonik Industries AG
  E-mail: joerg-joachim.nitz@evonik.com
- Integrated Dimethylether Synthesis Based on Methane and CO_2 (DMEexCO_2)
  Dr. Ekkehard Schwab, BASF SE
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- Solid and Liquid Products from Gas
  Dr. Dirk Klingler, BASF SE
  E-mail: dirk.klingler@basf.com

Example Project 1: Dream Production

1. Challenges and Goals

Carbon dioxide is currently regarded as a waste byproduct which has a detrimental effect on the climate. Working in partnership with RWE and RWTH Aachen, Bayer plans to develop useful applications for CO_2 and convert it into high-grade products. The company is looking specifically at polyurethane which is found in many everyday items such as upholstered furniture, sporting goods and auto parts. The goal is to conserve the world's limited oil resources and avoid CO_2 emissions. Both aspects are being investigated as part of a lifecycle analysis. If things go well, the first CO_2-based products should be ready for market introduction in 2015.

2. Scope and Emphasis

The CO_2 used in Dream Production comes from a lignite-fired power station near Cologne. The facility is operated by RWE - another partner of the consortium. The gas is extracted, purified, liquefied and filled at the power station. At a pilot plant which went into operation in 2011 and is located in Leverkusen not far from the power station, Bayer uses the CO_2 to produce a key chemical building block, namely a polyol which is used in polyurethane production. The polyol is normally 100% oil-based. A portion of the oil, which is a scarce resource, is replaced with CO_2 which also contains the key element carbon.

By mixing the novel CO_2-based polyether polycarbonate polyol with other substances (isocyanate), Bayer produces polyurethane foam samples which are subjected to intensive testing. The initial results look very promising. The properties of the material which contains CO_2 are just as good as those of material which is produced the conventional way. If the new process continues to yield good results, Bayer plans to begin industrial production of polyols using CO_2 in 2015. Mattresses will be the first end product made of CO_2-based polyurethane which will be placed on the market. There is a lot of interest in the new foam in many parts of the industry.

The process is now feasible because researchers at Bayer have discovered a suitable catalyst and are working on continued development in collaboration with

Figure 1: Pilot plant in Leverkusen

Figure 2: CO_2-based polyurethane foam

the CAT Catalytic Center in Aachen, which is another partner in the Dream Production project. The relatively inert CO_2 can be made to react efficiently with the aid of the catalyst. The CAT Catalytic Center is a joint research institution which receives funding from Bayer and RWTH Aachen.

Figure 3: Researcher Dr. Christoph Gürtler with CO_2-based polyurethane foam

3. Application, Exploitation of the Results, Economic and Ecological Benefits

Overall, the new process can facilitate migration of the resource base to alternative resources. The fact that CO_2 emissions are reduced during power generation and the energy-intensive oil refining process will enhance sustainability over the long term.

Researchers at RWTH Aachen are carrying out an in-depth eco balance assessment. The initial results indicate that the balance is likely to be positive, as expected. This means that there will be an overall reduction in CO_2.

Example Project 2: ACER

1. Challenges and Goals

Acrylic acid is the principle building block for sodium acrylate, an important base material for high-performance polymers which are used for example as super absorbers in baby diapers. Annual worldwide production now exceeds 2 million tonnes, making acrylic acid one of the chemical industry's big products.

Acrylic acid is currently made in a two-stage reaction from propene, a byproduct of straight run gasoline. The technology, which is fossil-based (oil), has been optimized over a period of many years, and it is the yardstick against which a potential new process as envisioned in the ACER project will be measured.

2. Scope and Emphasis

Since January 2011, researchers at the Catalysis Research Laboratory (CaRLa) which is supported by BASF, hte AG which is part of BASF, TUM in Munich and the University of Stuttgart have been working together on the ACER project (Acrylates ex Renewables) to make CO_2 useable on an industrial scale for the production of sodium acrylate. The process must be viable from both the economic and ecological standpoint. Acrylic acid will be made from CO_2, ethene and a base. The reaction sequence is shown in Figure 4.

The project represents a major scientific challenge. Making sodium acrylate from CO_2, ethene and a base involves a "dream reaction". A reaction of this type has the potential to shake up the existing value-added chains (and the associated markets as well). Unfortunately, nature has created a major technical obstacle. The reaction did not exist at the start of the project, and there were serious doubts whether it would ever be feasible. A potential catalyst which would promote a "marriage" between ethene and the relatively inert CO_2 only existed in the dreams of industry and university researchers.

After only a year of intensive research, the team which includes catalyst researchers and theoretical and technical chemists has achieved a major breakthrough. Sodium acrylate has been produced for the first time from CO_2, ethene and a base through chemical synthesis. It only took a year to do what was previously thought to be impossible.

hte's state-of-the-art high-throughput technology platform expedited the research by quickly providing a broad base of information. Through parallel testing, the team was able to quickly identify the most promising candidate catalyst materials. This effective, time-saving technique earned hte a nomination for the 2011 German Future Award.

Earlier than planned, the researchers have been able to optimize the chosen catalyst system, evaluate different process options and evaluate those options during ongoing lab analysis, giving them a solid basis for process development.

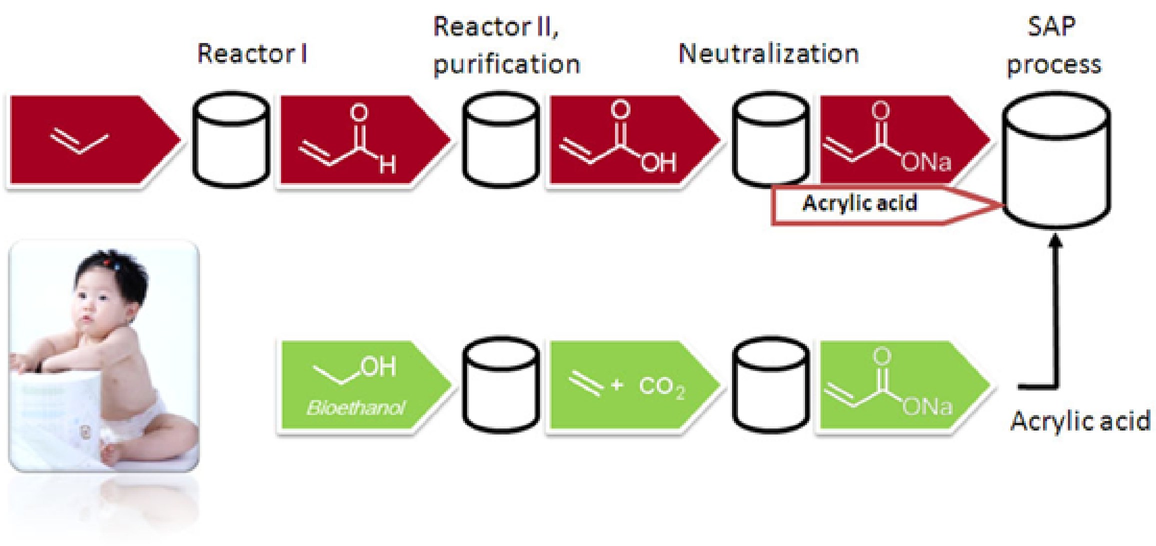

Figure 4: Schematic representation of the acrylic acid production process under investigation on the ACER project

Figure 5: Catalyst screening system

BMBF is providing 2.2 million euros in funding for the project. BASF and hte are contributing an additional 1.7 million euros over a period of three years.

Figure 6: Autoclave stations used for catalyst testing

3. Application, Exploitation of the Results, Economic and Ecological Benefits

If proven successful, the underlying concept of the ACER project will provide a pathway for total conversion of acrylate synthesis to renewable resources and CO_2. The ethene used in the reaction with CO_2 can be produced from bioethanol.

Chemical Energy Storage

The Challenges Posed by the Energy Transition

When the German government decided to phase out nuclear power, increased energy efficiency (e.g. heat insulation in buildings) and the expansion of renewable power generation began to play an even bigger role in national energy policy. Electricity from renewable resources is expected to cover at least 35% of demand by 2020. The figure currently stands at 17%.

The energy transition has wide-ranging consequences. The availability of wind and photovoltaic power is not uniform and is susceptible to significant fluctuations depending on time of day or weather-related and seasonal conditions. Households and industrial users need power even when it is raining or there is a lull in the wind. On the other hand, when the wind is blowing, electricity has to be fed into the grid, a situation which the electricity grids have difficulty coping with.

In regions with undeveloped infrastructure, operators are sometimes forced to disconnect generators from the grid to avoid overload conditions because there is not enough transmission capacity to deliver the electricity where it is needed. The number of forced shutdowns at German wind parks has more than tripled in recent years. 400 gigawatt hours were lost in 2011, which is enough electricity to supply 90,000 households for an entire year.

Chemical Energy Storage – a Possible Solution

What is needed are technologies for storing energy when it is produced and making it available again when there is demand. Large storage facilities such as pumped storage hydroelectric power stations exist, but there is no possibility of further expansion. One possible solution is chemical energy storage, for example in the form of synthetic methane gas. In the programme “Technologies for Sustainability and Climate Protection - Chemical Processes and Use of CO_2”, BMBF is providing funding for strategic projects which are designed specifically to achieve this goal (see box).

The researchers on these projects are developing techniques for using excess electricity from wind and PV power to produce methane from the greenhouse gas CO_2. Methane is a main constituent of natural gas and provides a vehicle for chemical energy storage. It can be fed into the gas grid and held at natural gas storage

facilities. When needed, it can be used to generate electricity or for other purposes such as home heating, vehicle fuel, etc.

The process consists of two stages. In the first step, electricity is used to extract hydrogen from water using electrolysis. Oxygen is produced as a byproduct. The hydrogen and CO_2 are then converted into methane gas and water. The CO_2 can be supplied from industrial waste gas, a coal-fired power station or a biogas plant.

The goal of the subsidized projects is to make this process for producing methane with electric power as efficient as possible, in other words minimize conversion losses.

The Projects

- **Integrated Carbon Capture, Conversion and Cycling (iC4)**
  Prof. Dr. Dr.h.c Bernhard Rieger, Technische Universität München
  E-mail: rieger@tum.de
- **Storage of Electrical Energy from Renewable Resources in the Gas Grid (SEE)**
  Dipl.-Ing. Dominic Buchholz, DVGW-Forschungsstelle
  E-mail: buchholz@dvgw-ebi.de
- **New Catalysts and Technologies for Solar-Chemical Hydrogen Production (HyCats)**
  Dr. Sven Albrecht, H.C. Starck GmbH
  E-mail: sven.albrecht@hcstarck.com
- **Utilization of CO_2 as a Carbon Building Block Mainly using Renewable Energy (CO_2RRECT)**
  Dr. Oliver F.-K. Schlüter, Bayer Technology Services
  E-mail: oliver-fk.schlueter@bayer.com
- **Solar-Thermal Synthesis of Chemical Products from H_2O and CO_2 (Solar STEP)**
  Dr. Michael Göbel, BASF SE
  E-mail: michael.goebel@basf.com
- **Synthesis of Fuels using CO_2 and Water using Renewable Energy (SunFire)**
  Christian von Olshausen, Sunfire GmbH
  E-mail: christian.vonolshausen@sunfire.de

Example Project 1: Integrated Carbon Capture, Conversion and Cycling (iC4)–CO_2 as a Building Block for Efficient, Sustainable Energy Storage Technology

1. Challenges and Goals

The troublesome greenhouse gas CO_2 of all things could actually help solve the energy storage problem by acting as a "shipping container" for renewable primary energy. By converting CO_2 into methane which is a main constituent of natural gas, electricity production could be teamed up with the immense storage capacity of the global natural gas network (chemical energy) making it possible to compensate for lulls in the wind lasting up to several weeks. BMBF is providing 6.3 million euros in funding for the project "iC4: Integrated Carbon Capture, Conversion and Cycling".

Figure 7: Pilot methanation reactor (COOMeth sub-project)

The goal is to efficiently extract CO_2 from a variety of sources including biogas plants, power stations and the iron & steel and cement industries (carbon capture) and synthesize the gas into methane or other chemical building blocks such as formic acid, methanol, higher oxygenates and hydrocarbons (conversion). The technologies developed during the project could make a very substantial carbon-neutral contribution to re-use of CO_2 in the energy and material streams (cycling). A first-rate interdisciplinary consortium which includes high-profile companies and scientists at TUM has been formed to work intensively on a set of inter-related projects.

2. Scope and Emphasis

The development of improved techniques for capturing CO_2 from industrial emissions is a central and mission-critical aspect of the project. The researchers are looking for ways to optimize energy utilization without impairing process efficiency. The new technology includes the use of new solid and fluid sorbents (iC4 AdCOO sub-project) and innovative membranes (iC4 COOMem sub-project).

Compared to existing techniques, the new carbon capture technology is more economical and efficient, and there will be two recycling routes: the methane pathway to store chemical energy in the gas grid which can then be used to generate electricity on demand and utilization of CO_2 as a source of carbon for the processing of basic chemicals. Methanation of CO_2 is already taking place under industrially-relevant conditions in the iC4 COOMeth sub-project. The emphasis is on development and extensive testing of enhanced, rugged catalysts in combination with a suitable reactor design for cost-efficient hydrogenation of CO_2 into methane in conformance with specifications. The goal is to achieve quick technical implementation which, if successful, would make a major contribution to climate protection in the power generation industry once carbon cycling has been established.

The fourth segment of the iC4 project cluster looks further out into the future. It involves direct photochemical conversion of CO_2 and hydrogen into useful products (iC4 PhotoCOO sub-project). Using sunlight as an energy source, newly developed materials with photo-catalytic action will release hydrogen from water and (in the best case scenario within the same system) initiate a reaction between the hydrogen and CO_2.

3. Application, Exploitation of the Results, Economic and Ecological Benefits

Under the best ecological and most advantageous economic conditions, emitted CO_2 would be recycled

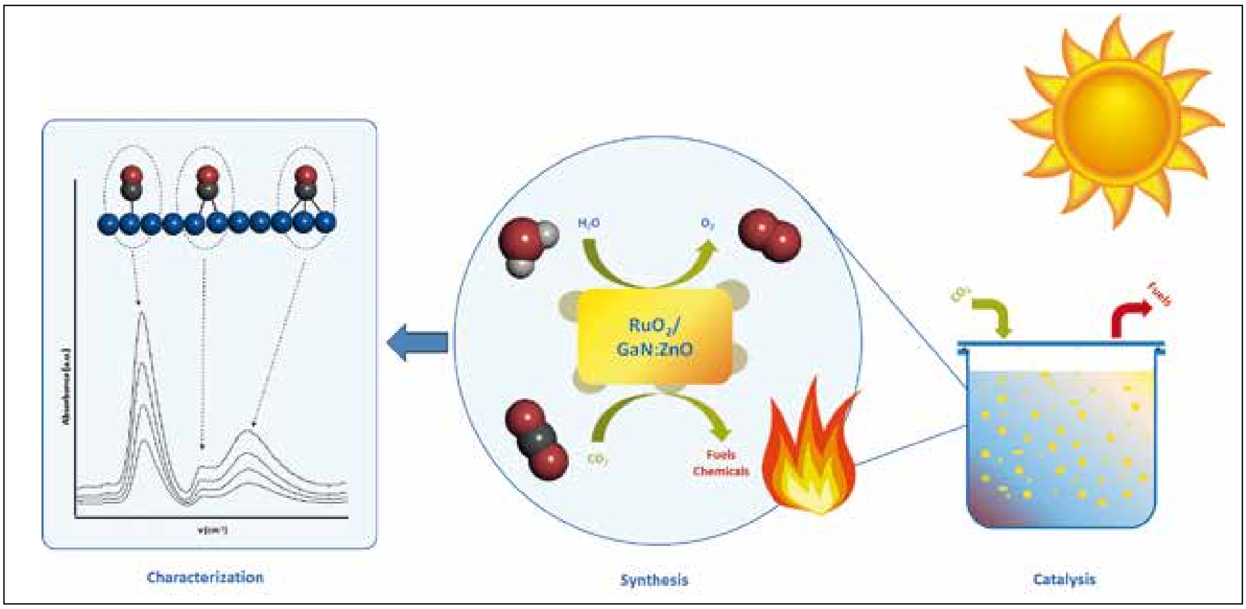

Figure 8: PhotoCOO schematic diagram – synthesis, characterization and potential application for direct conversion of CO_2 into chemicals and fuel using renewable hydrogen and sunlight.

via adsorption and chemical conversion. The technology would make effective use of solar energy and also not only capture (and store) most of the human-emitted greenhouse gas CO_2 but also use a part of it as a material and energy resource. This approach protects the environment and creates a perfect symbiosis between the energy and chemical industries.

Example Project 2: Storage of Electrical Energy from Renewable Resources in the Natural Gas Grid – Water Electrolysis and Gas Component Synthesis (SEE)

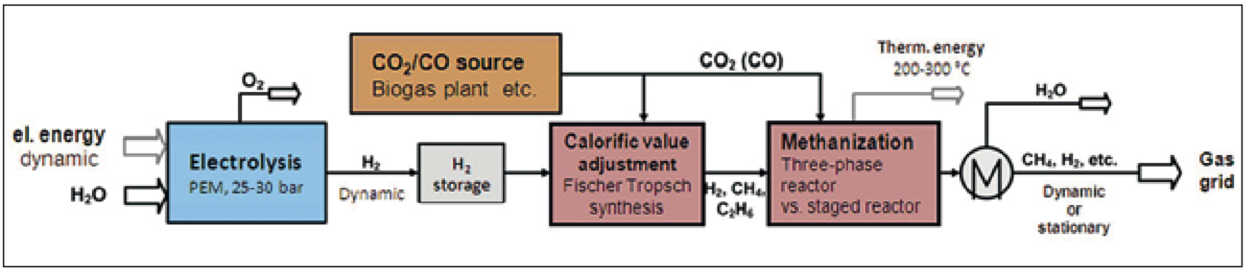

Figure 9: PtG (Power to Gas) process flow for production of SNG from excess electricity and CO_2

1. Challenges and Goals

The goal of this consortium project is to develop chemical storage technology to help manage the fluctuating supply of electricity from wind and solar power based on the production of SNG (Substitute Natural Gas). CO_2 will act as the source of carbon.

Germany has an excellent natural gas storage and distribution infrastructure. Huge porous and cavern reservoirs are already available in the country. Additional storage facilities are under construction or are in the planning pipeline, and they will provide capacity roughly equivalent to eight times the electricity produced from wind power in 2008.

2. Scope and Emphasis

As shown in Figure 9, the project includes all of the steps in the syngas production sequence. The first step is to extract hydrogen in a high-pressure electrolyzer. Electrolyzing water under pressure has the advantage that the hydrogen extracted is already pressurized and the use of an energy-intensive compressor is not needed prior to the subsequent process steps. A polymer electrolyte membrane (PEM) is the key element in the design. The membrane is impermeable to the gas and is coated with a catalyst, making production of hydrogen highly efficient. The membrane's plastic matrix is permeable to H+ ions and functions as a solid electrolyte to conduct electricity.

Hydrogen and CO_2 are directly converted to methane, the main constituent of natural gas. The methanation process also requires a catalyst and takes place in a special reactor.

Figure 10: EL 30 PEM Electrolyzer made by H-TEC SYSTEMS

Fixed-bed reactors with catalysts in a static bed are currently state-of-the-art. The input gases and products flow through the catalyst bed. The SEE project is investigating an alternative type of reactor which looks very promising, namely a slurry reactor where the reaction also takes place at a solid catalyst which, however, is finely distributed in a fluid. Bubble columns form producing intensive contact between the gases which are fed into the reactor and the catalyst in the fluid. The fluid efficiently dissipates the heat generated by the reaction which would otherwise impede the reaction. The researchers are looking in particular at ionic liquids which have high heat capacity and contribute to stable dynamic operation, i.e. are very tolerant to fluctuating inflow of the reaction partners. Development work is also taking place on conventional fixed-bed reactors with particular emphasis being placed on economical operation in small to medium-size systems.

Before the syngas is fed into the German gas network, it needs to be conditioned so that the calorific value is compatible with the natural gas in the grid. Higher hydrocarbons (i.e. with more than one carbon atom) have to be added. Fossil-based liquefied gas is used for this purpose at biogas plants. The process developed on the SEE project is, however, intended to be totally independent of fossil-based resources. The Fischer-Tropsch process is included as an additional step to produce hydrocarbons with between two and four carbon atoms from hydrogen and CO_2 or CO. These hydrocarbons are then used as additives for the syngas.

Figure 11: Pilot system for methanation in a slurry reactor

A consortium made up of experts from various branches of the industrial and research community has taken on the challenge of designing a PtG process which is technically and economically viable. H-TEC SYSTEMS is supplying a PEM electrolyzer. Fraunhofer ISE is carrying out dynamic operational control analysis in order to optimize the system. The DVGW Research Center at the Engler Bunte Institute which is part of Karlsruhe Institute of Technology (KIT) is carrying out investigations on methanation in a slurry reactor and is also in charge of the project. IOLITEC Ionic Liquids Technologies is responsible for development and syntheses of the IL. Outotec is responsible for methanation in a staged reactor, and the Chemical Energy Storage team at the Engler Bunte Institute at KIT is in charge of syngas conditioning to adjust the calorific value. The three research institutes have joint responsibility for the dynamic performance of the overall system. EnBW Energie Baden-Württemberg, a potential user, is evaluating the economic viability and is looking at possible locations for demonstrators.

3. Application, Exploitation of the Results, Economic and Ecological Benefits

By using electricity which would otherwise be wasted, natural gas from fossil-based resources can be replaced with syngas produced with renewables, reducing net CO_2 emissions. Utilization of the reaction heat in the overall process creates additional opportunities to reduce the release of CO_2.

The process technology developed for the PtG process flow could potentially be used in other processes. Temperature-stable ionic liquids developed during the project could be deployed elsewhere. The same is true for the new synthesis technology which could be used in thermal gasification of biomass, or new conditioning techniques for adjusting the calorific value using Fischer-Tropsch products prior to release into the natural gas grid.

Example Project 3: New Catalysts and Technologies for Solar Chemical Hydrogen Production (HyCats)

1. Challenges and Goals

Hydrogen gas could become a climate-friendly alternative to natural gas in the future if it can be produced using renewable resources such as solar energy. For solar chemical hydrogen production, photocatalysts are placed in the water. In the presence of sunlight, the water is converted to hydrogen. Solar energy could be stored as hydrogen, providing a renewable energy source which is not dependent on sunlight at any point in time. However the efficiency of current photocatalysts is much too low, and the purpose of the HyCats project is to help achieve a significant efficiency increase.

What is a photocatalyst?

A photocatalyst uses light energy to increase the rate of a chemical reaction. To do that, it has to absorb light energy (photons), bond to the reaction partner(s) and transfer the energy to it/them. Photocatalytic splitting of water is modeled on natural photosynthesis.

Initial photocatalytic splitting of water used titanium dioxide as the catalytic material in the presence of UV light. Researchers are currently searching for photocatalysts that work in the visible range of the light spectrum.

2. Scope and Emphasis

Researchers on the HyCats project synthesize a large number of photocatalysts and evaluate their activity for solar chemical hydrogen production. To expedite the search for better photocatalysts, the research team is also performing theoretical calculations and investigations to better understand the mechanisms of photocatalysis. The scope of the project also includes the development of industrial production techniques for the photocatalysts and solar reactor trials to provide an efficient means of splitting water.

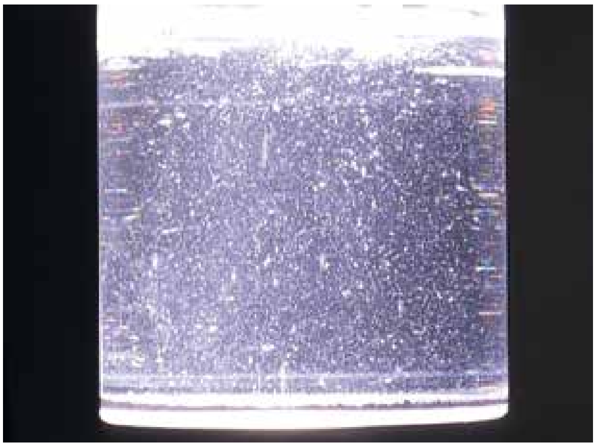

Figure 12: Rising hydrogen bubbles in the photocatalyst lab test

3. Application, Exploitation of the Results, Economic and Ecological Benefits

Hydrogen produced using renewable resources can make a major contribution to climate protection in a wide range of applications such as conversion of CO_2 to hydrocarbons, fuel for domestic energy supply or vehicle fuel cells. Compared to other known renewable-based techniques, solar chemical production of hydrogen has the advantage of much simpler process technology, because water is split in a single low-temperature reactor. This can be an advantage in distributed applications. Hydrogen for domestic heating systems or fuel cells could be supplied under ideal conditions with simplified infrastructure. Hydrogen produced on a large scale at industrial solar parks could be stored and distributed as an alternative to natural gas.

Figure 13: Solar reactor at DLR in Cologne

Example Project 4: Utilization of CO_2 as a Carbon Building Block Mainly Using Renewable Energy (CO_2RRECT)

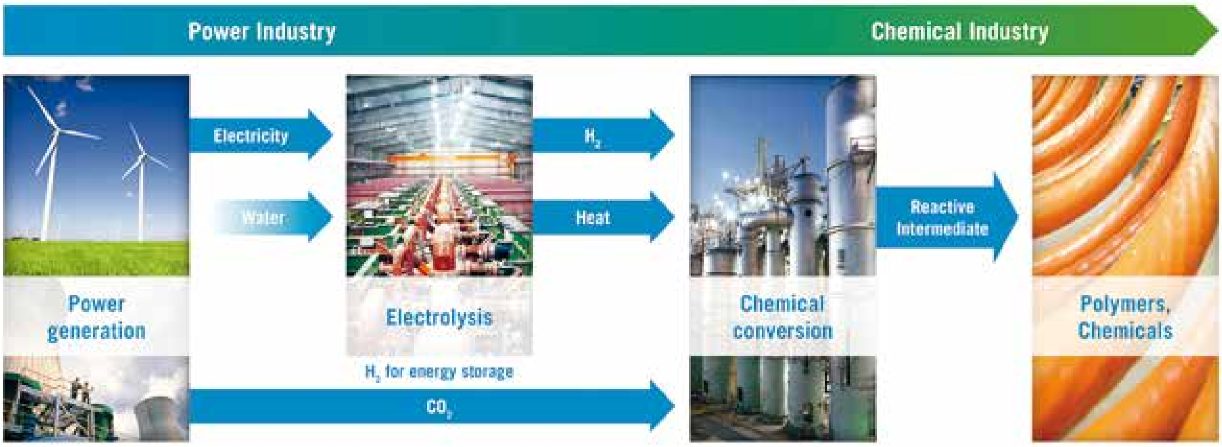

Figure 14: Using hydrogen produced from renewable resources, CO_2 can be converted to useful products in the chemical industry

1. Challenges and Goals

Conventional power stations are demand-driven whereas production from alternative resources fluctuates depending on weather conditions (e.g. wind and sunlight). Continued expansion of power generation from renewables creates the need for additional energy storage to manage demand. Pumped-storage power stations and underground caverns are commonly used for this purpose. However, electricity can also be stored as chemical energy, for example as hydrogen. Energy produced with hydrogen can then be used to produce valuable basic chemicals from the relatively inert greenhouse gas CO_2. A research alliance which brings together Bayer, RWE, Siemens and ten academic partners is working on a new idea, namely to use green electricity to convert the harmful greenhouse gas CO_2 into useful chemical building blocks. This approach makes a contribution to sustainability in two different ways.

2. Scope and Emphasis

Similar to the Dream Production project, the CO_2 is supplied from a lignite-fired power station near Cologne. The facility is operated by RWE which is involved in the project. The gas is extracted, liquefied and filled at the power station. The second feedstock, hydrogen, is produced through water electrolysis which is designed to react to power fluctuations within fractions of a second. The electrolysis system was developed by Siemens.

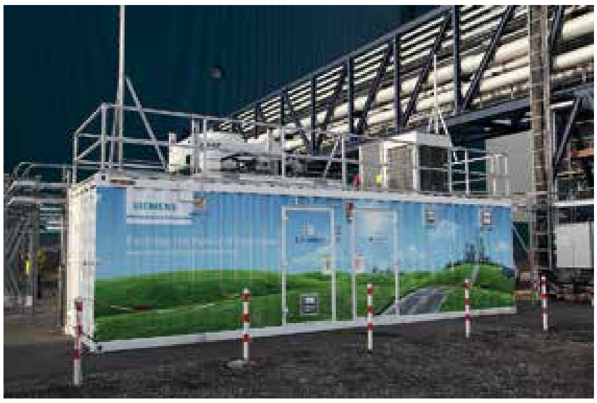

Figure 15: Prototype Siemens 0.3 MW electrolyzer at the RWE Niederaußem facility near Cologne

In a catalytic process, Bayer will then use the hydrogen and CO_2 supplied from the power station to produce a reactive intermediate. A pilot system developed for this purpose will go into operation in Leverkusen in 2013.

A special catalyst is needed to activate the CO_2. Other project partners are contributing their expertise in catalyst research, process technology, reactor optimization and holistic process analysis. The consortium includes the universities in Aachen, Bochum, Dortmund, Dresden and Stuttgart, the Max Planck Society, the Leibniz Institute for Catalysis at the University of Rostock, the Karlsruhe Institute of Technology and the INVITE research center.

Figure 16: Homogeneously catalyzed hydrogenation of CO_2 on a mini plant scale

In addition to the engineering and economic aspects, the researchers are also evaluating the potential for further reductions in greenhouse gas emissions compared to current process technology.

3. Application, Exploitation of the Results, Economic and Ecological Benefits

All of this is currently still a vision which will not become reality before 2020. However, the plans are in place and the roles have been clearly allocated. Meaningful use can be made of excess electricity from wind power, and CO_2 which is otherwise treated as a waste product can be used as a feedstock without dependence on the oil industry.

High-performance plastic polycarbonate can be made from the intermediate which is synthesized from CO_2 for the production of DVDs, LEDs, flexible solar modules, eyeglasses and other items. Isocyanate, an important constituent of polyurethane foam, can also be produced. The foam is found in many everyday products such as furniture, cars and insulation material.

Energy-Efficient Processes and Avoidance of CO_2 Emissions

Energy conservation - the most effective way of reducing CO_2 emissions

Use of CO_2 as described above is one way of recycling this waste product as a useful substance. This approach however cannot prevent climate change. Humans generate more than 30 billion tonnes of CO_2 emissions a year. That is between 100 and 1,000 times more than could be used as a feedstock by the chemical industry. The most effective strategy for reducing CO_2 emissions is to avoid creating the gas in the first place. Energy conservation is the key. Power generation in Germany is largely reliant on combustion of coal and gas which generates large amounts of CO_2. The German government has set a goal of reducing greenhouse gas emissions by 40% by 2020 and by at least 80% by 2050 compared to the 1990 level. The intention is to reduce demand for primary energy by 50% by 2050. Every segment of society will have to take action to save energy. This involves increasing the energy efficiency of buildings and making industrial production and production equipment as energy-efficient as possible.

Energy conservation in the chemical industry

The chemical industry is a very energy-intensive sector of the economy. The global chemical industry accounts for 10% of worldwide energy consumption (30% of industrial consumption) and 5.5% of worldwide CO_2 emissions (17% of industrial CO_2 emissions). Energy conservation and the associated reduction in CO_2 emissions is naturally an important additional aspect of the programme “Technologies for Sustainability and Climate Protection - Chemical Processes and Use of CO_2”. Funding is provided for projects which are aimed at increased energy efficiency based on improvements to process, equipment and systems technology in the chemical industry. There are many ways of saving energy and many projects are underway to explore that potential (see box). Studies on the use of new solvents which have special properties that reduce greenhouse gas emissions are another facet of the programme. Ionic fluids are salts which are present in the liquid state at room temperature or at temperatures below 100°C and could be used as auxiliary agents for chemical synthesis, pre-processing and production.

The Projects: Equipment/Systems/Processes

- **Development of Novel, Resource-Conserving Technologies using Supported Ionic Liquid Phase (SILP) Catalysts (Hy-SILP)**
  Prof. Dr. Robert Franke, Evonik Industries AG
  E-mail: robert.franke@evonik.com
- **Organophilic Nanofiltration for Energy-Efficient Processes (OPHINA)**
  Dr. Christian Schnitzer, Evonik Industries AG
  E-mail: christian.schnitzer@evonik.com
- **Energy Efficiency Management and Benchmarking for the Process Industry**
  Dr. Christian Drumm, Bayer Technology Services GmbH
  E-mail: christian.drumm@bayer.com
- **Innovative Equipment and System Design For Enhanced Production Process Efficiency (InnovA^2)**
  Prof. Dr.-Ing. Stephan Scholl, Technische Universität Braunschweig
  E-mail s.scholl@tu-braunschweig.de
- **Development of a Miniaturized Oil-Free CO_2 Compressor with Built-In CO_2-Cooled Electric Motor Drive for Large CO_2-Heat Pumps**
  Dr. Gerd Janson, KSB AG
  E-mail: gerd.janson@ksb.com
- **Energy-Efficient Polymer Heat Exchangers**
  Prof. Dr. Hans-Joerg Bart, TU Kaiserslautern
  E-mail: bart@mv.uni-kl.de
- **Mixed-Matrix Membranes for Gas Separation**
  Dipl.-Ing. Torsten Brinkmann Ph. D., Helmholtz-Zentrum Geesthacht
  E-mail: torsten.brinkmann@hzg.de
- **Multi-Scale Modelling of Multi-Phase Reactors (Multi-Phase)**
  Dr. Marc Becker, Evonik Industries AG
  E-mail: marc.becker@evonik.com
- **Integrated Resource Efficiency Analysis to Reduce the Climate Impact of Chemical Plants (InReff)**
  Dr. Tobias Viere, ifu Hamburg GmbH
  E-mail: t.viere@ifu.com

The Projects: Ionic Liquids

- Utilization of Low-Caloric Industrial Waste Heat by Means of Sorption Heat Pump Systems using Ionic Liquids and Thermochemical Accumulators (SIT)
  Dr. Matthias Seiler, Evonik Industries AG
  E-mail: matthias.seiler@evonik.com
- Development of Ionic Liquid Based Lubricants for Wind Turbines (IL Wind)
  Prof. Dr. Peter Wasserscheid, Universität Erlangen-Nürnberg
  E-mail: wasserscheid@crt.cbi.uni-erlangen.de
- New Absorbents for More Efficient CO_2 Separation (EffiCO_2)
  Dipl.-Ing. Alexander Schraven, Evonik Industries AG
  E-mail: alexander.schraven@evonik.com
- Utilization of Low-Temperature Heat with Absorption Loops to Generate Cooling Power and Heat Transformation - New Material Pairings
  Dipl.-Ing. Nina Merkel, Karlsruher Institut für Technologie (KIT)
  E-mail: nina.merkel@kit.edu
- Process for Extracting Lignin, Cellulose and Hemicellulose with the Aid of New Ionic Liquids (Licil)
  Prof. Dr. Willi Kantlehner, Hochschule Aalen
  E-mail: willi.kantlehner@htw-aalen.de

Example Project 1: Organophilic Nanofiltration for Energy-Efficient Processes (OPHINA)

1. Challenges and Goals

Solvents which are commonly used in the chemical industry often have to be recovered later on in the process. Thermal separation is the most common method of recovering the solvents and that consumes a lot of energy (normally in the form of heat). The heat is generally supplied from steam which is generated with fossil fuels. More efficient separation technology could potentially conserve fossil fuel and significantly reduce CO_2 emissions.

Organophilic nanofiltration is one such technology, because in contrast to thermal separation it works without the use of heat. Membranes, which remain stable in a number of organic solvents and deliver good separation performance for the specific mixture, are needed for organophilic filtration.

2. Scope and Emphasis

The goal of the OPHINA project is to conduct research and trials for the development of polymer-based membranes which meet the requirements profile. The approach taken by the researchers is based on multi-layer composite membranes, with each layer performing a specific function. The materials in some of the layers have been newly synthesized, whereas existing materials in altered form are used in other layers. In an iterative cycle, the researchers use standard procedures and commercial process systems to assess performance. They then proceed to an optimization step or test possible new solutions. Modeling is also used for theoretical analysis of material transport through the complex system to provide a method for predicting the properties of the membranes.

Figure 17: Spiral-wound membrane module for organophilic nanofiltration

The membranes are enclosed in spiral-wound modules for industrial applications (see Figure 17). During the course of the project, the research team assesses the suitability of the membrane modules for organophilic nanofiltration in a variety of chemical processes.

3. Application, Exploitation of the Results, Economic and Ecological Benefits

A successful outcome will provide a means of significantly reducing CO_2 emissions and costs in solvent recovery. Following successful completion of the project and additional application-specific optimization, Evonik Industries plans to market the special membranes and modules. The objective of OPHINA is twofold, namely to strengthen Germany's technology base and develop a very sophisticated special product, and also to open up new fields of application for organophilic nanofiltration. By enhancing process cost efficiency, the project will help companies to attain a competitive cost advantage while reducing the environmental impact.

Besides lower process costs and CO_2 emissions, organophilic nanofiltration has other benefits such as higher product purity, lower thermal stress on the product and enhanced product quality.

Figure 18: The OPHINA project partners: Evonik Industries (coordinator), Bayer Technology Services, Cognis and RWTH Aachen.

Example Project 2: Innovative Equipment and System Design for Increased Production Process Efficiency (InnovA²)

1. Challenges and Goals

The dilemma which companies face at market introduction has been described by one industry insider as follows: "Everyone wants to be first to be the second to develop an application." References cannot be provided for the new application from a process which reflects actual industrial conditions, and as a result the first user runs a greater technological and business risk. On the other hand, new equipment designs or an improved cost-benefit ratio achieved for example by enhancing the operational efficiency of the equipment provide the only means of exploiting previously unused potential for increasing process-integrated energy efficiency. With financial support from BMBF, a consortium which brings together 17 partners including 12 industrial companies and five university institutes is working on "Innovative Equipment and System Design for Increased Production Process Efficiency InnovA²". Partners involved in the project and in every step of the value-added chain are: system suppliers, equipment manufacturers, engineering service providers, users, plant operators and research institutes.

2. Scope and Emphasis

Optimal heat integration can make a major contribution to improve energy efficiency in a production process. This involves utilization of waste heat generated in various process steps to supply heat for other steps in the process. The InnovA² consortium project is looking at new system designs for enhanced heat integration, for example structured pipe, thermo-sheet plate systems with packs of cushion-shaped plates and multi-stream plate heat exchangers.

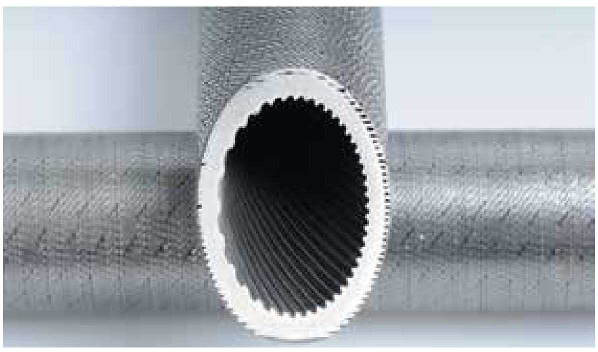

Figure 19: Structured pipe

In the initial phase, the university partners will use model material systems and lab investigations to characterize the thermal and fluid dynamic behavior of the equipment and identify applications where the systems appear to offer the greatest potential benefits.

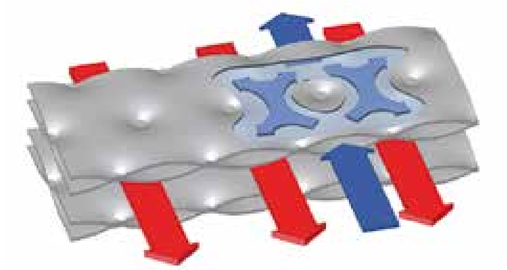

Figure 20: Thermo-sheet heat exchanger

Two parallel pathways are being provided to scale-up and transfer the lab results to real-world engineering applications. Pilot-scale equipment will be used to assess the feasibility of making the transition from bench top to industrial production. Material transferability will be assessed using actual substance mixtures in side-streams on target production systems. This will enable the researchers to identify fouling problems and deploy suitable test systems to replicate the problems during the evaluations. Based on the lab and pilot-scale results, the team will create design dimensioning guidelines and build them into commercial engineering programmes. This will facilitate subsequent use of the project results in industrial applications. An eco-balance will be generated to evaluate the equipment and process technology, identify significant energy efficiency potential and quantify the environmental benefits.

3. Application, Exploitation of the Results, Economic and Ecological Benefits

The design and operation of energy-efficient processes are core engineering responsibilities throughout the material conversion industry including petrochemical, chemical, pharmaceutical and paper production as well as food processing. The InnovA² consortium can make a contribution to increase energy efficiency in all of these sectors of industry. The project is scheduled to run for three years and will receive a total of 3.8 million euros in funding.

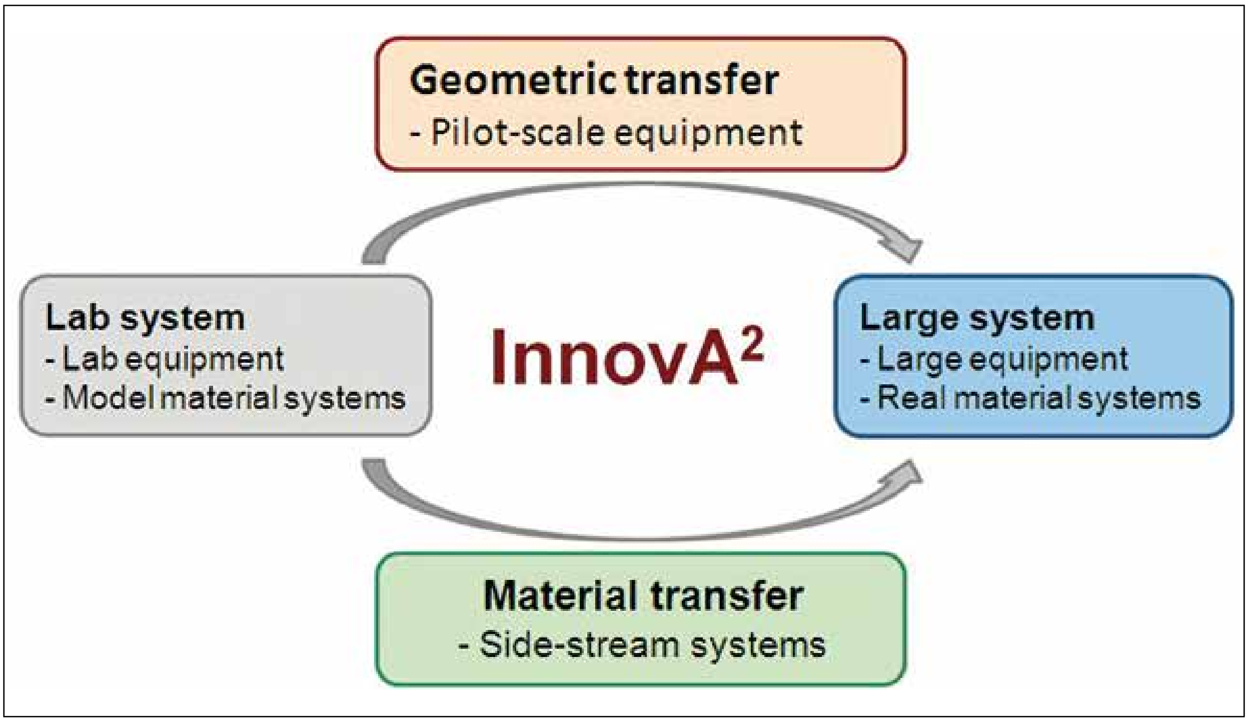

Figure 21: InnovA² research methodology

Example Project 3: Utilization of Low-Calorific Industrial Heat by Means of Sorption Heat Pump Systems using Ionic Liquids and Thermochemical Accumulators (SIT)

1. Challenges and Goals

Large volumes of heat are constantly being released into the environment by industry without being used. In recent years, heat integration technology has been deployed to increase the energy efficiency of the production process in the chemical industry. The point has now been reached where further improvement will not be possible without the introduction of innovative technology.

Additional heat flows can only be utilized by bringing them up to a useable temperature with the aid of a heat pump. High-density chemical heat storage can be used to store the higher-temperature heat and make it available on demand in the form of thermal energy, significantly reducing primary energy consumption and greenhouse gas emissions.

2. Scope and Emphasis

In order to utilize low-grade industrial waste heat, a complete process is being developed which is based on an absorption heat pump and thermochemical storage.

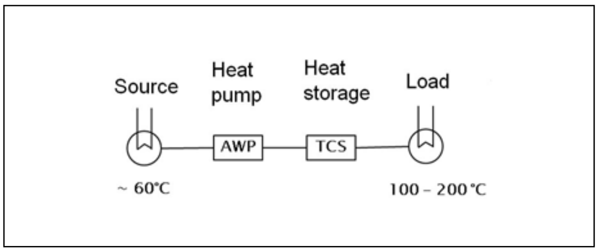

Figure 22: Scenario for utilization of low-calorific industrial heat (AWP: absorption heat pump, TCS: thermo-chemical storage)

New working fluid pairs based on ionic liquids are being developed for absorption heat pumps. By tailoring suitable working fluid pairs, it is possible to enhance overall performance and create advantages compared to conventional working fluid pairs. Process engineering assessment and validation are carried out using pilot-scale heat pumps as well as commercially available heat pumps.

The researchers working on the development of a thermo-chemical heat storage system with high energy storage density identify and evaluate suitable reaction systems. A reactor design optimized for these materials and suitable for this heat pump - heat storage combination is also being developed. Production of a pilot-scale heat storage system will provide the basis for commercial upscaling at a later date.

A techno-economic assessment of the overall concept will be carried out. The reduction in primary energy consumption and greenhouse gas emissions will be validated with the aid of a lifecycle analysis.

In an absorption heat pump, one fluid is absorbed by another fluid and then separated from it again. The substance which is absorbed (coolant) and the absorbent are called the working fluid pair.

Figure 23: View of the test bed used to validate new working fluid pairs for absorption heat pumps

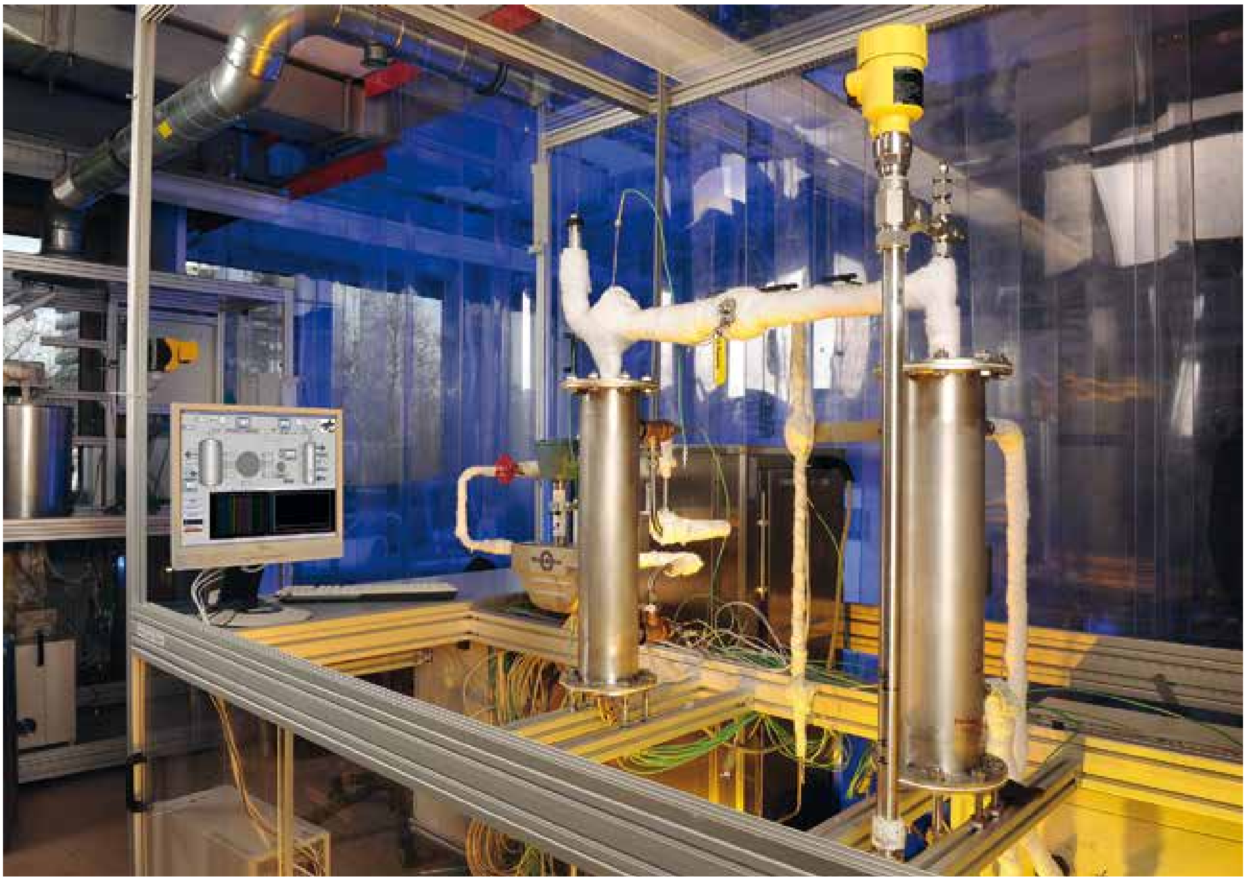

Figure 24: Test system for thermochemical heat storage systems

3. Application, Exploitation of the Results, Economic and Ecological Benefits

406 TWh of waste heat potential is available each year at industrial sites in Germany alone. If this potential is exploited, it would be possible to reduce primary energy consumption and greenhouse gas emissions and also save money. That would give Germany a competitive advantage as a business location and generate long-term growth in the country.

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