CO₂ REDUCTION
through cross-industrial cooperation between the steel, chemical and energy industries
KEEPING CARBON IN THE LOOP
We have an ambitious goal: By 2030, the emission of greenhouse gases in Germany is to be halved compared to 1990. This poses great challenges for Germany as a production location and especially for the energy-intensive key industries such as steel and chemicals. Research and development will help us tackle this challenge. We see this as a chance for our economy because climate change is a global issue. As pioneers in the field of innovations which protect our climate, we are securing jobs and prosperity in our country and opening up new markets.

Carbon2Chem is such a pioneering project which combines economic success and effective climate protection. It pursues a cross-industry approach and turns harmful greenhouse gases into valuable synthetic fuels, plastics or basic chemicals in a sustainable way. 20 million tons of the German steel industry’s annual CO₂ emissions, that is, 10 percent of the annual CO₂ emissions of Germany’s industrial and manufacturing sectors, will be made commercially usable in the future. That is a climate-relevant savings effect.

To achieve such dimensions in climate protection, the state and the economy must cooperate closely. The Federal Ministry of Education and Research embraces such a culture of cooperation. That is why we are funding Carbon2Chem until 2020 with more than 60 million euros.

I am convinced: Carbon2Chem is a pioneering project that brings together research-oriented global market leaders of various industries and outstanding research institutions – this is how research and development for climate protection works.

Anja Karliczek MdB
Federal Minister of Education and Research
Project structure

L0  System integration | Pilot plant | Laboratory
thyssenkrupp AG, Max Planck Institute for Chemical Energy Conversion, Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Siemens AG

L1  Water electrolysis in non-stationary operation
thyssenkrupp AG, The hydrogen and fuel cell center ZBT GmbH

L2  Sustainable methanol production
Akzo Nobel Industrial Chemicals B.V., Ruhr-University Bochum, Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Max Planck Institute for Chemical Energy Conversion, Fraunhofer Institute for Solar Energy Systems ISE, Clariant Produkte (Deutschland) GmbH, thyssenkrupp AG

L3  Gas purification
Linde AG, Ruhr-University Bochum, Clariant Produkte (Deutschland) GmbH, Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Max Planck Institute for Chemical Energy Conversion, thyssenkrupp AG

L4  Higher alcohols
EVONIK Resource Efficiency GmbH, Ruhr-University Bochum, Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, RWTH Aachen University Institute of Technical and Macromolecular Chemistry (RWTH ITMC), thyssenkrupp AG

L5  Carbon2Polymers
 Covestro Germany AG, Max Planck Institute for Chemical Energy Conversion, RWTH Aachen University Catalytic Center (RWTH-CAT), Max-Planck-Institut für Kohlenforschung, RWTH Aachen University Chair of Fluid Process Engineering, RWTH Aachen University Chair of Technical Thermodynamics, RWTH Aachen University Institute of Technical and Macromolecular Chemistry

L6  Oxymethylene ethers
BASF SE, Volkswagen AG, Linde AG, Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Karlsruhe Institute of Technology | Institute of Catalysis Research and Technology (KIT-IKFT), thyssenkrupp AG
The objective of Carbon2Chem® is to find a big solution that will eventually allow all technology modules to be linked. In line with the modular system to be developed, Carbon2Chem® consists of seven subprojects.

Currently, Europe's integrated steelworks mostly convert their process gases into electrical energy. With Carbon2Chem®, these top gases will be used not only to generate electricity, but also for the production of valuable chemical substances. Using the thyssenkrupp steelworks in Duisburg as an example, the unavoidable CO₂ emissions in industry are to be made economically usable in the future.

What makes this project unique is not only the broad, cross-industry cooperation of a total of 18 project partners from industry and science who want to create a new network of steel production, power generation and chemical production. The steel production industry serves as an example here, as the aim is to develop modular systems from which modules for the implementation of the energy transition can be created. The objective of Carbon2Chem® is to find a big solution that will eventually allow all technology modules to be linked. In line with the modular system to be developed, Carbon2Chem® consists of seven subprojects.

The subprojects L1 - L6 focus on the modules hydrogen, methanol, higher alcohols, polymers, oxymethylene ethers and gas purification. Originating from basic research, applied research brings the results to market maturity in close cooperation with industry. The subproject L0, System Integration, interlinks the results from the other six subprojects in such a way that they can be used either as a whole or as individual modules in an industrial location, in line with company requirements. This principle is what makes Carbon2Chem® unique.

In order to reach the first milestone of this ambitious goal - the implementation on a laboratory and pilot plant scale - the Ministry of Education and Research will provide funding amounting to 60 million euros by the end of 2020. Existing buildings at the Fraunhofer UMSICHT site in Oberhausen were extended with a new laboratory with office space and meeting rooms. This allows scientists from Fraunhofer UMSICHT and the Max Planck Institute for Chemical Energy Conversion to combine basic research with applied research in immediate proximity.

thyssenkrupp has constructed a pilot plant on the outskirts of the steel location Duisburg to be able to work with real top gases from spring 2018 onwards. The teams from all subprojects meet at these locations to conduct research in a network for periods ranging from a few weeks to several months. With Carbon2Chem®, partners focus on sustainable technologies and support the energy transition, with science and industry developing and applying tools that reduce the global carbon footprint. In short, with Carbon2Chem® and its modules, carbon is recycled within the production network.
The coordination group of Carbon2Chem®

Professor Robert Schlögl, Director of the Max Planck Institute for Chemical Energy Conversion in Mülheim an der Ruhr, Dr. Markus Oles, Head of Innovation Strategy & Projects at thyssenkrupp AG and Professor Görge Deerberg, Deputy Director of the Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT in Oberhausen, share the overall leadership of the project and are responsible for the implementation of basic research in combination with applied research at an industrial scale, and to consequently bring the results to market maturity.

PROF. ROBERT SCHLÖGL | Basic research

At the Max Planck Institute for Chemical Energy Conversion, we find ways to efficiently convert energy into storable and usable forms. In this instance we particularly look for suitable catalysts for the chemical reactions required. Industry generally tries to cut CO\(_2\) through avoidance, and industry in Germany is already working with minimal use of carbon. However, complete avoidance is not possible. With Carbon2Chem®, we are developing a modular system for these industries from which modules for implementing the energy transition can be created.

PROF. GÖRGE DEERBERG | Applied research

As an institute whose motto is “production without raw materials”, we fit perfectly into this project. For several years, Fraunhofer UMSICHT has been conducting research in projects that have set themselves the goal of further reducing both CO\(_2\) emissions and the extraction of fossil fuels, and instead work with “waste products” such as the top gases that inevitably arise in steel production, in order to use them for the production of chemicals such as methanol. That is why, with Carbon2Chem®, we want to recycle carbon after it has formed during steel production, so that it is not released but instead is sustainably reused on site.

DR. MARKUS OLES | Industry

Together with the scientific community and other industrial partners, thyssenkrupp is the first industrial enterprise to conduct pioneering work in this field. We are not pursuing a single solution, but rather a set of solutions that can also be used by other smelting works and industries. All technology modules should ultimately be interlinkable. Our first application on an industrial scale is in the steel sector - a very CO\(_2\)-intensive industry. This way we are undertaking preparatory work in the industrial environment, so that we can eventually extend the modules to other industry sectors. Which is something that benefits us as a diversified corporation.
The office of Carbon2Chem® is an independent body that reports directly to the coordination group in an advisory capacity. It is part of the overarching project structure and brings together all the information from the subprojects and the advisory bodies outside the project. The office consists of employees of the Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, the Max Planck Institute for Chemical Energy Conversion and thyssenkrupp AG. The office management is based at the Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT.

Tasks of the office

- Exchange and forwarding of information within the project about the respective status in the subprojects, including laboratory and pilot plant
- Creation and maintenance of the project schedule
- Representation of the project externally
- Participation in project meetings as representation of the coordination group
- Organization or support of overarching project meetings
- Central contact point for the consortium
- Maintenance of the internal data space and provision of information for the subprojects and the overall consortium

- Organization of the coordination and release of documents for the public presentation of the project and of project results
- Coordination of overarching project publications
- Organization of the project conference series

The office supports and reports to the steering committee as well as the project advisory board and the project lead partner.

To present the project and to discuss project results with external professionals, the consortium hosts a conference titled “conference on sustainable chemical conversion in the industry” during each year of the project. This additionally examines central aspects of energy transition and climate protection and creates a link to parallel projects.
## TASKS

The process and plant simulation is carried out in subproject L0. It enables the description of the interaction of different industrial plants in a plant network as a "cross-industrial network", as well as the analysis of their dynamic system behavior. For this purpose, the current state of science and technology as well as the available information and models of the relevant subprocesses will be determined and developed further. Uniform interfaces and transfer points of the submodels are defined for the simulation of the overall model. This allows models to be imported and analyzed on independent simulation platforms.

## OBJECTIVES

The objective of the L0 - System Integration subproject is to create the prerequisites for the parallel development of technologies and subprocesses in the subprojects L1 to L6 and to use them optimally in the integrated steelworks at a later stage. In addition to the evaluation and selection of the sub-processes, the preliminary investigations and simulations for system integration in the integrated steelworks also serve to provide decision support for the technical and economic optimization of the current processes under varying internal and external parameters. A system analysis that determines the advantages offered by flexibly operated systems is carried out for this purpose. Further, the regional potential for the use of fluctuating renewable energies is determined, taking into account the factors of generation, consumption and grid utilization. The status quo of the feed-in data of renewable energies will be used as a basis and the increasing share of renewable energies in a changing generation portfolio, as well as the future added value for society, will also be taken into account.

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**LO | System Integration**

The aim of the Carbon2Chem® project is to use top gases from steel production, including the CO₂ they contain, as a raw material for chemical products. Electricity from renewable energies is to be used for this purpose. This will make an essential contribution to climate protection and the success of the energy transition.
STEEL
Steel Mill Gases

GAS-TREATMENT

ELECTROLYSIS
Hydrogen

Control
ENERGY

Control
CHEMICAL INDUSTRY

UREA
POLYMERS
METHANOL
HIGHER ALCOHOLS
Hydrogen plays a special role in linking the energy, steel and chemical industries, both under energetic as well as material aspects. The core of this subproject is therefore research on dynamic water electrolysis under consideration of the varying supply of top gases and fluctuating, renewable electricity.

**TASKS**

In cooperation with the hydrogen and fuel cell center ZBT GmbH (ZBT), thyssenkrupp is researching the effects of fluctuating load profiles on various electrolysis systems. For this purpose, the systems are dynamically operated and studied at the ZBT. The long-term behavior is then predicted with a simulation model on the basis of these experimental results. The construction of a water electrolyzer in the pilot plant (MW power consumption) as well as several laboratory-scale test rigs (kW power consumption) is also an integral part of the subproject. The performance of an industrially relevant sized plant is predicted by combining the research results from the plants.

The complex, dynamic requirements of the entire Carbon2Chem® production network are used as the basis for the creation of a water electrolysis model, which is then incorporated into the overall simulation of Carbon2Chem®.

**OBJECTIVES**

The objective of the overall Carbon2Chem® project is to link the energy, steel and chemical industries into a cross-industrial production network. In this case the process of water electrolysis plays a key role, as hydrogen is required for almost all subsequent synthesis routes. The availability of this gas must be ensured notwithstanding the use of fluctuating, renewable energies and the varying hydrogen content of the top gases. These requirements inevitably lead to rethinking the previously known mode of operation of electrolyzers. Due to the materials in use, large amounts of carbon-containing process gases are produced in the steelworks, some of which are currently already being used internally in the integrated steelworks.

To make other available gases usable, in particular the climate-relevant CO₂, it must be ensured that the hydrogen produced is pure and that the availability corresponds to the top gas supply.

The objective of this subproject is the simulation-supported evaluation of different electrolysis techniques with regard to the requirements in non-stationary operation, and also the construction of a commercial electrolyzer that has the flexibility required by Carbon2Chem® as well as the necessary system capacity.
L2 | Sustainable methanol production

Methanol is one of the most widely produced organic chemicals. In order to be able to produce it cost-efficiently from top gas, the conventional catalytic converter has to be reviewed and refined. Even the common method requires adaptation. After successful tests in the laboratory and the pilot plant, the next step is the economic and ecological assessment.

**TASKS**

Methanol is produced from synthesis gas, which is composed of hydrogen, carbon monoxide (CO) and carbon dioxide (CO$_2$). This synthesis is currently extracted from fossil fuels such as coal, oil or natural gas. Top gas also contains the required components, in addition to nitrogen and methane. If synthesis gas can be made from top gas instead of fossil fuels, it is possible to make methanol with a significantly lower carbon footprint. To do this, new requirements for its composition, purity and time availability must be defined in the context of Carbon2Chem®. Furthermore, it must be assessed whether, under the given conditions, available catalysts are sufficiently effective and whether they have a cost-efficient service life, taking into account an acceptable investment in the upstream gas purification.

**OBJECTIVES**

The subproject focuses on the development of economically feasible technologies as well as their ecological evaluation. Production of synthesis gases from CO$_2$ using regenerative hydrogen, including during an intermittent operating mode, will be used as a basis to evaluate to what extent CO$_2$-based methanol synthesis is suitable for energy storage. During the development of the technique, the overall process of methanol production is considered and the energy requirements as well as operating and investment costs are determined. Furthermore, the composition of the synthesis gas will be optimized, the integration of renewable energies will be assessed and a cost-efficiency comparison with conventional methanol production will be made. The sustainability assessment is carried out in the form of a life-cycle assessment. Finally, an economic optimum for the entire process chain will be identified. The production of methanol with synthesis gas from top gases replaces fossil raw materials and significantly reduces the carbon footprint.

If synthesis gas can be made from top gas instead of fossil fuels, it is possible to make methanol with a significantly lower carbon footprint.
In addition to gas purification, L3 also addresses the laboratory validation of ammonia synthesis based on top gases.

**L3 | Gas purification**

Each synthesis requires a certain gas quality: Each of the different gas utilization options of Carbon2Chem® requires a customized process chain for the purification of the raw gases. The process steps are adapted, tested and optimized on a pilot scale using top gases in the pilot plant. Innovative approaches are investigated on a laboratory scale.

**TASKS**

In subproject L3, the treatment of converter, blast furnace and coke oven gas is investigated. The focus is on the provision of a synthesis gas for chemical production of the highest possible quality. Key steps to produce pure hydrogen from coke oven gas are catalytic pre-purification and a subsequent fine purification step using pressure swing adsorption. Catalytic pretreatment and amine scrubbing are used to obtain high-purity CO and CO₂ from converter gas. The gas treatment is demonstrated on a scale of 100 Nm³/h in a pilot plant, which is connected to the pipeline network of the Verbund site Duisburg-Schwelgern. Accompanied by laboratory tests on a scale of 1 Nm³/h, novel process steps are tested, such as the (plasma) catalytic oxygen removal or the electrothermal regeneration of adsorbents.

**OBJECTIVES**

The main objective of L3 is to develop the economically and technologically optimal purification process for top gases to present synthesis gases in the required purities. The evaluation in the pilot plant aims to validate and improve towards a commercially feasible basic concept. Further, the laboratory work also allows for process intensification as well as greater flexibility in gas composition, as expected at other smelter sites. Modeling of these process steps and a data export to the subproject L0 are absolutely necessary in order to develop the overall concept, including further synthetic steps, and to evaluate it in detail.
L4 | Higher alcohols

The project aims to develop a process for using blast furnace gases from steelworks to produce C2+ alcohols that are used as fuels and chemical intermediates. Heterogeneous and homogeneous catalytic process concepts are developed and their cost-effectiveness and sustainability are analyzed.

TASKS

The focus of the project is the development of catalysts and processes for the selective conversion of carbon monoxide and carbon dioxide with hydrogen to C2+ alcohols. These investigations are carried out in the context of an overall process for the material and economic utilization of blast furnace gases of steelworks, whilst simultaneously reducing primary raw material consumption and lowering specific CO2 emissions.

The project tasks include the identification of suitable homogeneous and heterogeneous catalysts, their optimization and characterization and the transfer of catalyst production to an industrial scale. Process development and economic analysis are based on catalytic testing, kinetic modeling, reactor and process simulation. The sustainability of the overall process is assessed in a life-cycle analysis.

OBJECTIVES

The objective of the project is the development of a cost-efficient overall process for the catalytic utilization of blast furnace gases processed into synthesis gas from steelworks for the subsequent, direct conversion to C2+ alcohols. The use of the alcohols as fuels and as starting point for other chemical components reduces the consumption of primary raw materials. Firstly, conventional raw material sources such as natural gas are replaced by blast furnace gases for the supply of synthesis gas. Secondly, fixing carbon in the usable products reduces the specific CO2 output of the steelworks. The use of the alcohols produced this way as fuels results in a substitution of the corresponding quantity of conventional fuel, and thus also the corresponding amount of crude oil. In addition to ethanol (C2), which is currently being added to conventional fuels as "E10", the product range that is being developed also includes butanol (C4), which is discussed as a fuel substitute due to its higher energy density and better miscibility with conventional fuel components. Another utilization option is the already established refinement of the alcohols into chemical secondary products (e.g. polyethylene, polypropylene and vinyl acetate).
L5 | Carbon2Polymers

Plastics in every shape, color and size are part of everyday life. They are still mostly produced on the basis of fossil raw materials such as oil. These provide the essential element carbon. But there are alternatives, as shown by a consortium led by Covestro.

TASKS
In subproject L5, the materials manufacturer Covestro together with other partners is investigating how oil can be reduced as a carbon source in plastics production. In focus: CO and CO\(_2\) from smelter gases from steelworks.

First, suitable catalysts for the complex chemical processes are defined and further developed. As catalysts can be very sensitive to even the smallest impurities, the composition of the smelter gases must be closely scrutinized. In a further step, the cost-effectiveness and sustainability of the new routes for plastics production are to be investigated.

OBJECTIVES
Carbon2Polymers aims to show that CO and CO\(_2\) from smelter gases from the steel industry are suitable as raw materials for the production of plastics and can be used sustainably.

CO can serve as a building block for polycarbonate, which is used for example in spectacle lenses or car headlights. Covestro already uses CO\(_2\) on an industrial scale. It can be used for instance to make polyurethane foam for mattresses or upholstered furniture. In the course of the subproject L5, a new production process for a polyurethane polymer module is to be developed.

Once the chemical usability of the smelter gases has been tested and deemed to be economically and environmentally worthwhile, a bridge is built between steel production and chemical production network.

The efficient and sustainable closure of the carbon cycle can facilitate a link between two major industries, where the by-products of one industry serve as raw materials for the processes of the other.
L6 | Oxymethylene ethers

Oxymethylene ethers (OMEs) are a new class of oxygen-containing compounds that may in future replace the fossil hydrocarbons in diesel and petrol fuels. OME burn clean and can be produced environmentally friendly from carbon dioxide (CO$_2$).

**TASKS**

In the L6 subproject, the partners collaborate on developing the essential process steps for the production of OME as well as on their use in fuels. To this end, L6 is divided into the five work packages U1 to U5.

The work packages U1 to U3 deal with the three process steps of OME synthesis. OME shall be produced from synthesis gas via the precursors dimethyl ether and formaldehyde. Alternative production routes will also be conceptually designed and, if successful, developed experimentally in a follow-up project and brought to industrial maturity.

Work package U4 serves to connect the OME synthesis network to steel production in steel mill infrastructure.

Application of OME-containing fuels and related questions, such as e.g. their compatibility with automotive construction materials, are addressed in the work package U5.

**OBJECTIVES**

The objective of subproject L6 is to design a value chain for OME production from steel mill gases and the subsequent use of OME as a component in diesel fuels.

On the basis of mass and energy balances, a concept for processing of steel mill gases is developed that are available at the thyssenkrupp steelworks in Duisburg. The individual synthesis steps to dimethyl ether and formaldehyde, as well as their final synthesis to OME 3 to 5 (3 to 5 units of formaldehyde per OME molecule), are developed theoretically. This includes proposals for synthesis catalysts and suitable process conditions, as well as an estimate of the expected yields.

The technical data is then used for an estimate of the economic efficiency of this OME process.

In the OME application test, the project initially focuses on the compatibility of OME-containing fuels with construction materials used in the automotive industry.
Oxymethylene ether

Diesel
A total of approximately 500 m² of laboratory space and approximately 30 office workstations including meeting rooms are available in the two-storey building. The laboratory building integrates seamlessly into the infrastructure available at the site. At the end of 2017, scientists from the Max Planck Institute for Chemical Energy Conversion and Fraunhofer UMSICHT moved into the space to work together on the objectives of Carbon2Chem®.

The laboratory serves basic research in the field of catalytic production of methanol and higher alcohols from top gases as well as gas purification. The focus of the work is on the behavior of different catalysts in the use of top gases and a dynamic driving style of the processes. The results serve as the basis for the work in the project's pilot plant.

Carbon2Chem® Laboratory

The Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT and the Max Planck Institute for Chemical Energy Conversion operate the project laboratory at Fraunhofer UMSICHT in Oberhausen. The building provides all the consortium partners with laboratory and office space to gather collaborative experimental data.
The pilot plant serves as the first demonstration of a cross-industrial network. As the central location of the project, the sectoral coupling between steel and chemical industry is realized here for the first time. Demonstration on a pilot plant scale is essential for the purification and conditioning of actual top gases and for the water electrolysis required for the provision of additional hydrogen for the chemical syntheses.

The top gas-based synthesis gases are converted in the first pilot plants into methanol, ammonia and higher alcohols. The basics of the necessary technical processes are already known today. For the pilot plant, an interconnection of these methods has now been defined and realized for the first time.

Carbon2Chem® Pilot Plant

In order to ensure the overall objective of Carbon2Chem®, i.e. transfer to industrial applications, it is important to carry out experiments under industrial conditions as soon as possible. For this reason, a pilot plant with access to real top gases was constructed adjacent to the thyssenkrupp Steel Europe site in Duisburg on an area of 3,700 m².

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The consortium

Partners from industry and science work together in the project to achieve the defined objectives. The consortium combines the different competencies of the partners. Together, the consortium contributes to advancing the state of science and technology.
Keeping carbon in the loop - a short sentence that succinctly describes the Carbon2Chem® project. Better climate protection requires a reduction of CO₂ emissions as well as less use of fossil fuels. Cross-industrial networks give the energy and emission-intensive industrial sectors an opportunity to make a sustainable contribution.

In the Carbon2Chem® project, a large consortium from industry and science works on implementing a flexible carbon capture and utilization (CCU) concept for the carbon-based industry. The project is sponsored by the Federal Ministry of Education and Research (BMBF). A special feature of the project is the scale of the solution to be implemented. The modular approach to CO₂ utilization within cross-industrial networks enables the combination of climate protection and competitiveness for large industrial locations in Germany and other parts of the world.

An example is a cross-industrial network of steel industry, chemical industry and energy industry. Top gases from the steel mill which were previously used for energy now serve as raw material for the production of synthetic fuels, plastics and other basic chemicals.