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Carbon2Chem—Innovative Research for the Energy Transition

Torsten Müller

Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Carbon Utilization and Synfuels, Oberhausen, Germany

Correspondence: Torsten Müller (torsten.mueller@umsicht.fraunhofer.de)

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ABSTRACT

Since 2016, the publicly funded project Carbon2Chem has been demonstrating that energy transition solutions can be successfully developed within an interdisciplinary network involving science and industry. In concrete terms, the project is developing technical carbon capture and utilization (CCU) solutions. The key application is the use of metallurgical gases containing CO₂ from steel production to manufacture chemical products, such as methanol. Despite the constant changes in the project's framework conditions, the project, now in its third funding phase, is set to achieve its goals by the end of 2028. The project has a number of unique selling points.

1 | Introduction

The defossilization of the basic materials industry is one of the biggest technological and systemic challenges of the energy transition. The processes within steel, lime, and cement production, and thermal waste treatment generate gases containing CO₂ that cannot be completely avoided in the future, even with boosts in efficiency and process changes.

This is precisely where Carbon2Chem comes in: with carbon capture and utilization (CCU) concepts, carbon dioxide is not viewed as waste but as a raw material that makes carbon cycles possible within the technosphere (see [1]). The aim is to use process gases from the basic materials industry as feedstock and thus reduce both CO₂ emissions and the input of fossil carbon into the technosphere.

Since the project was launched in 2016, partners from industry and science have been working to make the entire process

chain—from gas purification and conditioning to the supply of renewable hydrogen and catalytic synthesis—available at a technical center and pilot scale and bring it into industrial use. Unique infrastructures were created for research and development with the commissioning of the Carbon2Chem technical center (Figure 1) next to the steelworks in Duisburg and the project's own laboratory in Oberhausen [2]. For over 10 years, the partners have managed to keep to the original timetable up to the end of 2028, despite dynamic framework conditions. Carbon2Chem thus not only delivers results from a technical perspective.

2 | Project Description

Carbon2Chem adopts a modular, cross-sectoral approach to the use of CO and CO₂-containing process gases from point sources as feedstock in the basic materials industry (e.g., steel, cement, lime industry, and thermal waste treatment) (Figure 2). Key elements

Abbreviations: CCS, carbon (dioxide) capture and storage; CCU, carbon (dioxide) capture and utilization; CDA, carbon direct avoidance; DAC, direct air capture; DRI, direct reduced iron; ETS, emissions trading system; LCA, life cycle assessment; L-KK, subproject coordination and communication; SAFs, sustainable aviation fuels.

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FIGURE 1 | View of the Carbon2Chem technical center in Duisburg.

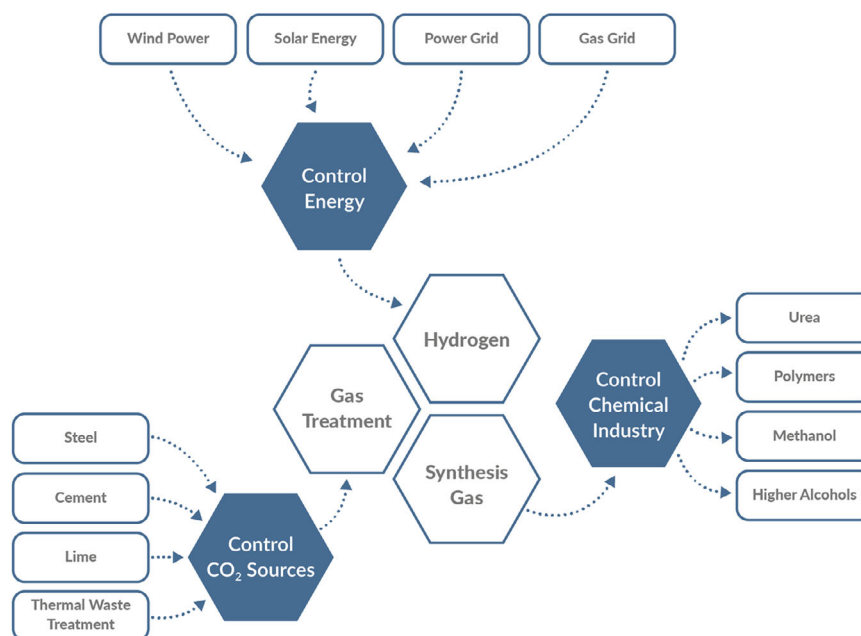


FIGURE 2 | Systemic approach of Carbon2Chem.

include the analysis, capture, purification, and conditioning of the process gases, the flexible supply of green hydrogen, and the downstream synthesis of basic chemicals. The modular character allows for adjustment to changing gas compositions and process conditions in various sectors and locations. The main example of the research and development activities within the project is steel production with its various process gases. The work within the project follows three guiding principles:

1. Raw material development: Process gases containing CO and CO₂ are viewed as sources of chemical raw materials, not as pure waste or energy sources.
2. Contribution to the energy transition: The energy required should be fed into the system from renewable sources, above all hydrogen produced using renewable energy (Power-to-X). Work within Carbon2Chem also looks at the contribution towards network stability as part of the energy transition.
3. System integration: The process chains and technological building blocks are designed in such a way that they can be integrated technically, energetically, and economically into existing industrial structures, taking into account environmental criteria.

The process gases from the integrated metallurgical plant of thyssenkrupp Steel in Duisburg provide the basis for work within the project. At the start of the project, the three dominating gas streams—coke oven gas, blast furnace gas, and converter gas—were recorded and analyzed. In the project's own laboratory in Oberhausen and partner laboratories, initial investigations are carried out on gas purification and treatment methods as well as synthesis routes using synthetic metallurgical gases supplied as pure gases in accordance with the data obtained.

As the project progressed, experiments using real gases from the metallurgical plant in the project's technical center were also carried out directly in the steel mill in Duisburg from 2018 onwards. The project's infrastructure laid the foundations for interdisciplinary cooperation within the project and continuous scaling throughout the project duration. The fundamental approach can be divided into the following points:

1. Supply and blending of the process gases: Coke oven, blast furnace, and converter gases occur in an integrated metallurgical plant. They differ in terms of their composition and heating value. Carbon2Chem is investigating how these streams can be captured, stored temporarily, and supplied in mixing ratios suitable for the respective target product. In addition, a transfer to other industrial point sources and a possible CO₂ infrastructure are being considered.
2. Gas treatment: Process gases that are generated in practice contain dust, sulfur, and nitrogen compounds, as well as a large number of other trace substances. In addition, their composition and quantity vary over time. Modular gas purification stages are being developed (dust removal, desulfurization, dehumidification, and CO₂ separation) that allow defined syngas qualities to be supplied for the subsequent synthesis steps [3]. The design of gas treatment is optimized in combination with the subsequent synthesis step, with the aim of achieving the required product quality.
3. Synthesis of valuable products: After adding hydrogen in catalytic processes, the treated gases are converted into carbon-based chemicals and energy sources. The focus is on methanol, ammonia, polymers, higher alcohols, and OME, as well as their derivatives. The processes are adapted to the specific constraints of the process gases (residual impurities, pressure and temperature profiles, and fluctuations in composition).
4. Embedding into energy systems: The process chains are designed in such a way that they can be adapted as flexibly as possible to the respective framework conditions (e.g., fluctuating energy prices) and can act as variable loads in the energy system. The use of waste heat and byproduct streams (e.g., oxygen from water electrolysis) is systematically planned. For example, a suitable storage option for green hydrogen is being designed [4].

In this way, the Carbon2Chem project exceeds the classic framework of isolated CCU procedures in many development projects and addresses the challenge of a cross-sectoral system solution.

The project is funded by the Federal Ministry of Research, Technology, and Space. This funding is provided in three phases and is continuing despite the ministry undergoing its fifth change of leadership. The project and its results have been evaluated at the end of each funding phase to date and measured against the original schedule and project plan from 2016. The three funding phases focus on different areas and can generally be divided into the phases of feasibility, scaling, and implementation.

Although the fundamental feasibility of the CCU approach was assessed in Phase 1 with a focus on fundamental research, Phase 2 looked at scaling the approaches identified as feasible. In

Phase 3, work is now continuing on the transition from applied research to industrial application. Efforts have increasingly been consolidated here, and the potential product spectrum of five possible products (methanol, higher alcohols, polymers, urea, and oxymethylene ethers) has focused on the synthesis of methanol and its subsequent applications in Phase 1.

The funding will reach €200 million by the end of 2028, and the total budget for the project will come to over €400 million. Research and development not only aim at implementing the developed technological building blocks as part of CCU solutions in Europe but should also enable the export of German technologies for global transformation projects. The project is thus not only about technological development but also adopts a sustainable approach that takes into account economic and environmental criteria.

Throughout its duration, Carbon2Chem has not deviated from its original direction but has responded to changes in the project's environment. For example, it was not possible to further reduce the carbon footprint within steel production when the work began due to thermodynamic limitations in the conventional blast furnace route, which is why the goal was to use process gases sustainably. Hydrogen-based direct reduction (DRI) of iron ore in steel production did not yet appear suitable for large-scale primary steel production. Today, DRI is an integral part of the transformation within the steel industry, which is why the change in viewpoint has been included in the work by Carbon2Chem [5].

In 2016, the Carbon Management Strategy did not exist, and carbon capture and storage (CCS) was ruled out as a possible transformation pathway. The Carbon Management Strategy of North Rhine-Westphalia [6] from 2021 linked together various concepts—carbon direct avoidance (CDA), CCS, and CCU. The partners within Carbon2Chem incorporated this into the systematic assessment and joined the associated discussion on industrial transformation in the context of the energy transition, including the Carbon Management Strategy at a national level. Part of the systemic assessment is also the project's engagement in dialogue with society, including involvement in a communication project with a nationwide traveling exhibition on the energy transition.

3 | Project Structure

The structure of the project has constantly changed according to the requirements in the individual phases. The overall Carbon2Chem project consists of several subprojects in each phase. A key feature in the first two phases was a strong orientation towards industry requirements, which is why the subprojects were led by industrial partners. The partners of Carbon2Chem come from steel production, the chemicals industry, plant engineering, technology providers from the field of water electrolysis, the lime industry, and thermal waste treatment, as well as university and nonuniversity research institutions.

To enable interaction beyond subproject boundaries, not only are regular project meetings held involving all of the partners, but also specialist communities were formed to exchange information, particularly regarding the systemic assessment. Specialist communities currently exist on process design, simulation, life

cycle assessment (LCA), cost estimates, and the regulatory framework conditions. This structure makes it possible to both work on scientific questions at a high level and take industrial requirements and framework conditions into account at an early stage.

The overall coordination of Carbon2Chem is carried out by the Max Planck Institute for Chemical Energy Conversion on behalf of fundamental research, the Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT on behalf of applied research, and thyssenkrupp Carbon2Chem GmbH on behalf of industry.

During the project, a greater focus was placed on the CCU process for scaling in Phase 2. To address the changes in the steel industry and the transfer to other industrial point sources, the project structure and the consortium were supplemented by a subproject on possible sources of CO₂ and their particular requirements. External communication was reinforced with a dedicated subproject.

With a view to a possible industrial implementation, the work focused on the product methanol and its further use in Phase 3. The individual components of the CCU process were thus brought together in one large subproject to improve coordination. The systemic assessment and external communication are handled in separate subprojects.

4 | Project Results

In addition to commissioning and operating the project's own infrastructure, a key milestone in Phase 1 was the confirmation of the economic and environmental advantages of the identified CCU concepts by the industrial partners.

In Phase 2, the operation of the technical center station was expanded, and the demonstration plant for methanol synthesis was transferred from the laboratory to the technical center in Duisburg. It has since been possible to continuously produce methanol, subject to the technical center's capabilities. A similar result has been achieved in the synthesis of ammonia as a precursor to urea production, albeit only on a laboratory scale. The systemic assessment demonstrated, among other things, that CCU concepts enable defossilization in industry under economic framework conditions and with lower energy costs.

The technical results provided evidence that metallurgical gases can be prepared under real operating conditions in such a way that they can serve as defined syngases for downstream chemical processes. This was shown, in particular, with the following points:

- Successful testing of suitable separation and treatment processes for the process gases.
- Successful development and establishment of measuring procedures to identify traces in the process gases [7].
- Successful generation of a wide range of syngas compositions by combining various metallurgical gas streams with the targeted addition of hydrogen using different technologies.



FIGURE 3 | Successful methanol synthesis in Carbon2Chem.

- It was possible to demonstrate the suitability of the conventional methanol catalyst using various compositions of the syngas (Figure 3).
- Creation of a central requirement for multiproduct capability.
- Verification through process simulations and demonstration tests that a dynamic adjustment of the gas streams is technically feasible for different chemical synthesis routes.
- Verification that an indirect reduction in emissions can be achieved in the chemicals industry by substituting fossil-based chemical production, alongside direct emission avoidance in the metallurgical plant.
- Verification that the flexible operation of water electrolyzers and synthesis plants can smooth out peak loads in the electricity system and support the integration of fluctuating renewable production, as long as corresponding market incentives and regulations are in place.
- Mathematical verification that significant CO₂ reductions are possible with the comprehensive implementation of Carbon2Chem concepts at major steel sites within the national framework. However, specific figures vary significantly depending on the assumptions made (electricity prices, CO₂ prices, and technology costs).
- Establishment of a platform for a comprehensive analysis of scenarios [8].

In light of these obvious successes, however, other achievements tend to be overlooked. Within 4 years, it was possible to form a project consortium of partners from industry and science at the start of the project. The partners collaborate on current research and development tasks every day. When it comes to industrial partners, it has even been possible to bring competitors on board together. This cooperation has grown within the framework of the project and forms the essential foundation for the results achieved. The collaboration between the Fraunhofer-Gesellschaft and the Max Planck Society in the Carbon2Chem laboratory in Oberhausen for over 10 years is itself an outstanding feature of the project's work.

The "System integration" subproject has not only created a content-related framework to bring together the results from the individual subprojects. With the specialist communities, a systematic approach to developing and assessing CCU process

concepts based on results from the laboratory and technical center has also been created. Beginning with process design, a simulation is conducted over a full year, enabling dynamic effects to also be taken into account. Finally, an assessment is carried out according to environmental, economic, and regulatory criteria. The assessment framework in the form of a basic scenario is reviewed at the beginning of each funding phase and adapted, if necessary, for example, to account for changes in the composition of the electricity mix.

This has led to further achievements as follows:

- Publication of numerous scientific articles, doctoral theses, and conference contributions.
- Training of skilled workers at the intersection of process engineering, energy system analysis, and industrial ecology.
- Development of models, simulation tools, and assessment approaches concerning systemic assessment that can be used beyond the project.

A continuous dialogue with the project executing organization and the funding provider has made it possible to respond to changes in framework conditions within the work schedule and thus keep the ongoing development up to date while still keeping the project on track.

5 | Project Characteristics

As described in the previous section, the project is characterized by a high level of interdisciplinarity and a cross-industrial mindset. Carbon2Chem connects different sectors of industry as well as fundamental and applied research. This wide range of skills makes it possible to address process, catalysis, system, and legal issues among the project partners in an integrated manner and consistently work on them within the systemic approach.

The Carbon2Chem technical center in Duisburg not only represents a unique opportunity for research using real gases in Germany. In combination with the Carbon2Chem laboratory, a learning and transfer cycle has developed that enables continuous research and development from a laboratory level to real-gas operation in a technical center. Typical operational challenges—fluctuations in gas composition, unplanned downtime, and contamination events—can thus be identified immediately in the technical center and integrated into process development. The growing number of visitors to the technical center alone shows how special the establishment created there is.

The cross-sectoral collaboration between the companies makes it possible to

- Address issues relating to chemical engineering, the energy industry, and business administration simultaneously,
- Integrate operator experience and regulatory requirements at an early stage, and
- Take into account the joint development of new business models at the interfaces between sectors as the basis for industrial implementation.

The modular approach within the project—gas purification, H₂ supply, synthesis, product processing, and system integration—enables the solutions and concepts to be adapted to different CO₂ sources and product pathways. Results from the third phase concerning simulation, the use of digital twins, AI methods, and adapted gas analysis methods can offer important foundations for the subsequent implementation of CCU solutions.

The systemic approach also provides insights into how CCU concepts can form part of a comprehensive transformation strategy. This is possible by

- Linking process development and systemic evaluation.
- Considering alternative approaches (DRI, CCS, and electrification) and their interactions.
- Analyzing long-term transformation pathways instead of exclusively short to medium-term optimizations.

Looking beyond the scope of technical development is another feature of the project. Society has little awareness of the solutions being developed in the field of carbon management. The project stands out in attempting to counteract this, including with the traveling exhibition Power2Change (Figure 4). The examination of the project's economic importance also provides vital information at this juncture. The linking of energy-intensive processes with the renewable electricity and H₂ infrastructure as well as storage (e.g., caverns) addresses the volatility of the energy system and uses chemical pathways as an energy sink and carbon store. In this context, practical options for the energy system are also being explored with the proposed hydrogen cavern.

6 | Outlook

The final phase of Carbon2Chem (2025–2028) focuses on industrial verification and transfer into application. The main goal of the experimental work is the application-oriented verification of process stability, adaptation to DRI gases for use in the steel industry, and quality issues concerning methanol and its derivatives, with regard to product standards, blending, and further processing options (e.g., to make fuels and polymers). At the same time, business models and regulatory pathways for applications in the field of sustainable aviation fuels (SAFs) and basic chemicals are being set out in more detail. Methanol samples are made available for research work on derivatives in other projects.

The operational and economic evaluations within the subproject “System integration” take aspects of scaling, investments, and value creation into account. A transfer into large-scale plants requires investments that necessitate appropriate framework conditions. The next steps concern the transfer of selected process chains into larger industrial plants on the basis of modeling and simulation. Investment and operating costs, space requirements, safety aspects, and integration into existing metallurgical plant and chemical infrastructures are important criteria here. The regulatory framework conditions, especially the European Emission Trading system, are also taken into account with regard to implementation.



FIGURE 4 | Providing information to the public with the Power2Change exhibition.

This includes questions regarding the eligibility of CCU products towards climate targets, the design of CO₂ pricing systems, evidence of origin for renewable energy, and the recognition of “recycled carbon” in product regulations and policy frameworks. Carbon2Chem can make important contributions here through scenario and policy analyses. Part of the project in the third phase, however, also concerns identifying suitable partners to enable further scaling. The project will seek increased dialogue with suitable stakeholders here.

The partners continue to work on expanding the CO₂ source base as part of the transfer to other industries. This transfer to industrial point sources alongside the steel industry cannot, however, take place on the same scale. The modular architecture of the building blocks allows for cluster solutions at industrial sites where H₂ production, gas purification, and synthesis interact in a network and market-compatible manner. For decentralized sites, however, a future CO₂ infrastructure could also be a pathway that should be considered as a source of CO₂.

The closure of carbon cycles within sites, such as in the metallurgical plant, and globally via direct air capture (DAC) is part of the project’s further work. Overall, the project will attempt to serve as a reference for integrated CCU systems and create impetus for research, industry, and politics by the end of its term.

7 | Summary

Within the context of comprehensive defossilization, the carbon requirements of the chemicals industry cannot solely be met using mechanical and chemical recycling concepts and biogenic carbon (see Chemistry4Climate study [9]). As a result, CCU concepts will be necessary as conceptual technological building blocks.

Since 2016, Carbon2Chem has convincingly demonstrated that the use of CO/CO₂-containing process gases from steel pro-

duction as feedstock can be integrated into the system and is technically feasible, environmentally beneficial, and economically viable. Key hurdles to CCU implementation—especially gas purification, catalyst stability, and load-flexible H₂ supply—have been addressed through the unique combination of laboratory and technical center infrastructure within the project, pilot testing based on real gas in 24/7 operation, an extensive system analysis, and the interdisciplinary consortium structure. By developing integrated process chains that allow metallurgical gases to be used as feedstock in the chemicals industry and that combine them with renewable hydrogen, the project highlights a concrete path towards reducing greenhouse gas emissions and enabling sector coupling of the steel, chemical, and energy systems.

The results achieved by the network include, among other things, the following:

- Verification of the technical feasibility of a high-quality gas treatment and syngas supply under real conditions.
- The successful demonstration of catalytic process routes (especially for methanol production) with real metallurgical gases.
- Detailed environmental and techno-economic evaluations that transparently highlight the potential and limits of the concepts.
- The establishment of a unique research and demonstration platform, as well as extensive scientific and technical expertise.

The current third phase is intended to drive forward industrial verification, transferability to other CO₂ sources, and market launch. Carbon2Chem is thus a pioneer in a climate-friendly basic materials industry as part of a future industrial carbon management strategy. It enables the transfer of value creation into a defossilized future.

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Data Availability Statement

The data that support the findings of this study are results of the project Carbon2Chem and in parts published in CIT issues of the project (2024, 2022, 2020) and also on the website about the project <https://umsicht.fraunhofer.de/carbon-cycle>.

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