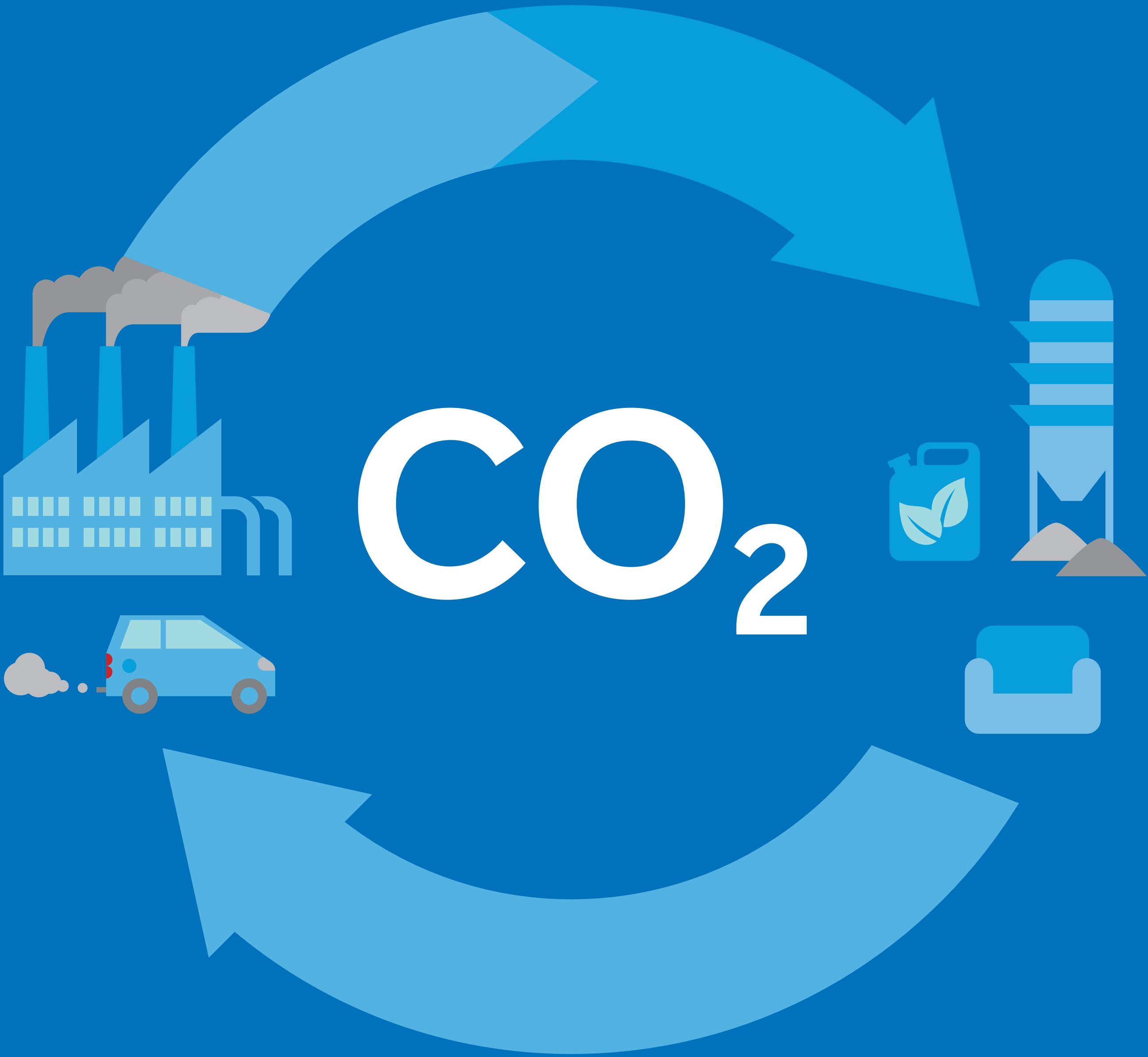
CO_2 Utilisation Today

Report 2017



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CO_2 Utilisation Today

Report 2017

Arno Zimmermann, Marvin Kant

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Editors

Arno Zimmermann
Department of Reaction Engineering
Technische Universität Berlin, Germany

Marvin Kant
Department of Entrepreneurship and Innovation Management
Technische Universität Berlin, Germany

Contact information:
Department of Reaction Engineering – Technische Universität Berlin,
Sekr. TC 8, Straße des 17. Juni 124, 10623 Berlin, Germany
Phone: +49 (0)30 314-262 84
E-mail: co2report@chem.tu-berlin.de

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Foreword

Dr. Evangelos Tzimas

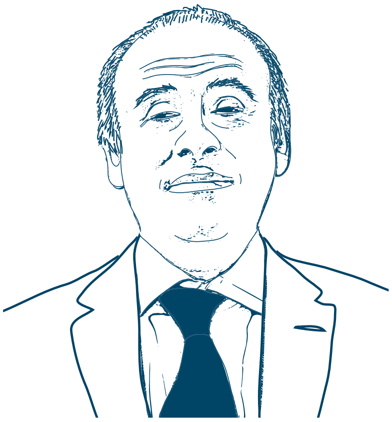
The utilisation of CO_2 for the production of fuels, energy storage media, chemicals or aggregates is attracting growing interest from industry and policy makers. CO_2 utilisation is seen as a promising option for the mitigation of CO_2 emissions of the European transport and industrial sectors that will also create new business opportunities. The use of CO_2 as a carbon source, captured typically from large emission sources such as power plants, steel plants or refineries, allows, in principal, the synthesis of useful products with a lower carbon footprint than those produced by conventional processes which use fossil fuels. In essence, the utilisation of captured CO_2 from fossil fuels which have already been used negates the extraction and use of additional fossil fuels to obtain carbon for the synthesis of these products, hence the CO_2 emissions avoided.

The potential role of CO_2 utilisation in the decarbonisation of our society has, however, raised questions. Key issues that still need to be addressed include large-scale hydrogen availability, cost competitiveness and, most importantly, the carbon balance for various CO_2 utilisation processes that take into account direct and indirect CO_2 emissions. The overall contribution of CO_2 utilisation to Europe's CO_2 emissions reduction objectives will obviously depend on the rate of penetration of CO_2-derived products in the market, but the current consensus is that the potential is rather limited.

Should Europe pursue this option? The CO_2 utilisation can be part of the portfolio of options for a future decarbonised economy as it could bring significant benefits to Europe. It could be an additional driver for the continuous development and deployment of CO_2 capture technologies and transport infrastructure, which would create export opportunities for European industry and facilitate the cost-efficient deployment of carbon capture and storage for those countries that decide to follow this decarbonisation path. More importantly, CO_2 utilisation could be a significant opportunity for innovative industrial processes, as has already been demonstrated by the plethora of recent initiatives in, for example, the European chemical and cement industries. The deployment of CO_2 utilisation could facilitate industrial symbiosis in the form of regional CO_2 hubs, which could act as centres for innovation creating high value jobs.

Accepting the narrative that CO_2 utilisation can be an option, one may argue that CO_2 utilisation requires actions along three directions: Firstly, continuous research and innovation is needed. The European Strategic Energy Technology Plan, which aims to develop low-carbon energy technologies through common R&D agendas between interested Member States and industry with support from the EU, addresses CO_2 utilisation through one of its ten priority actions. Research and innovation targets have already been set and an implementation plan is currently under development. Secondly, transparent methodologies are needed for the calculation of carbon balances that would address the issue of CO_2 avoidance without ambiguity. Finally, the scientific, industrial and policy-making communities need to continue discussing the pathways to the decarbonisation of the energy system and debate the various technological options such as CO_2 utilisation.

This publication is an important contribution to the ongoing debate about the role of CO_2 utilisation in the decarbonisation of the European economy.



Dr. Evangelos Tzimas

Deputy Head of the "Knowledge for the Energy Union" unit at the Energy, Transport and Climate Directorate of the European Commission's Joint Research Centre (JRC).

Introduction

Carbon dioxide (CO_2) has been converted to valuable products for billions of years in nature, such as the formation of sugar from photosynthesis. Mankind has used CO_2 to produce goods for over a century, for example, making urea. However, current CO_2 emissions far outweigh utilisation by over a factor of 100. Given today's conditions of climate change, researchers, entrepreneurs and politicians are working at turning this problem into a solution: They are developing new ways of using CO_2 to make products.

Carbon dioxide emissions occur within the life cycle of goods when, for example, concrete or polymers are produced, fuel is combusted in a car, or a product is discarded and incinerated. The emission of CO_2 is the one-way street of our carbon-based economy today. This begs the question: how can CO_2 be reused?

Almost every source of CO_2 is impure. The gas needs to be separated and purified; this step is called CO_2 capture. The latter can occur either at a specific location, so-called point sources, for example, factories or power plants, or even from ambient air. After the capture step, CO_2 is chemically converted together with other inputs into commercial products by various processes; this step is called CO_2 utilisation. In combination with the CO_2 emission step, the two steps, CO_2 capture and utilisation, complete the economic carbon cycle. Closing this cycle could enable an increase of resource efficiency and a decrease of CO_2 emissions in the future (see figure 1).

As definitions of the term CO_2 utilisation vary in the literature, the definition for this report is as follows:

> *"CO_2 utilisation describes a range of technologies that consume CO_2 chemically [...] to provide products or services with the main objective of an economic benefit, ideally with additional environmental and social benefits."*[1]

This report focuses mainly on the CO_2 utilisation step, but some contributions include the capture step, referring to the term carbon capture and utilisation (CCU). The entire economic carbon cycle is often referred to as CO_2 recycling.

Carbon dioxide utilisation is an umbrella term for different technological applications. A common categorisation distinguishes different types of products. The most prominent categories are minerals, chemicals and fuels. Regarding minerals, CO_2 is applied mainly to silicate

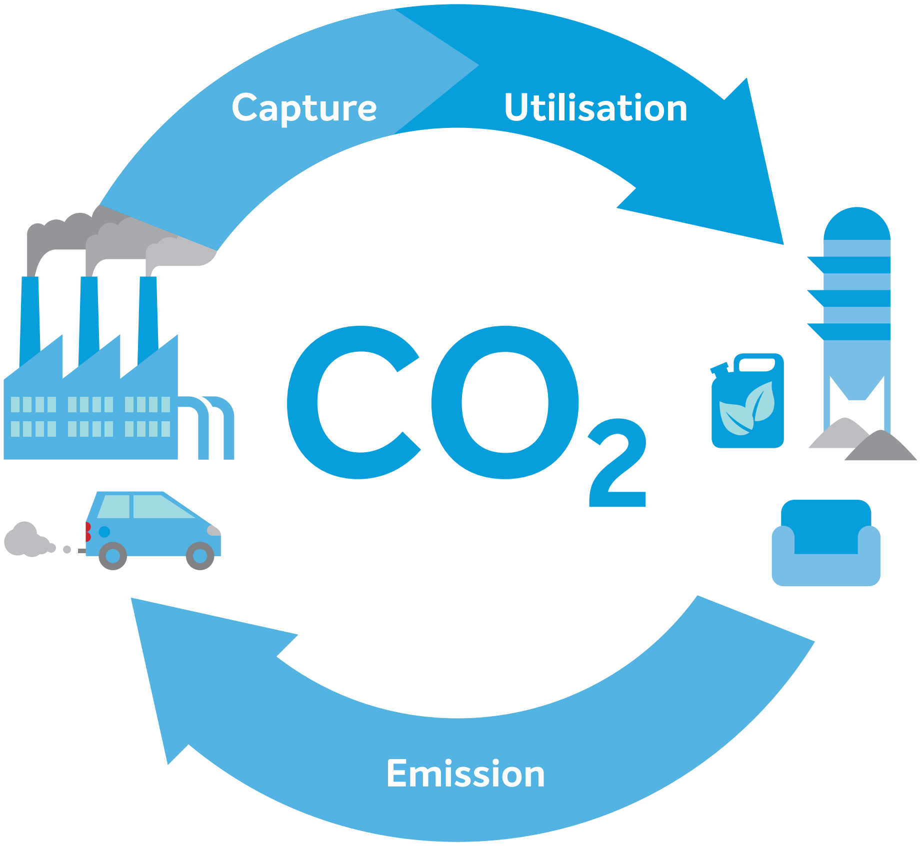


Figure 1: *Economic carbon cycle: economic sources and routes of CO_2.*

minerals and alkaline industrial waste, resulting in construction materials, such as aggregates or fillers. Regarding chemicals, CO_2 is converted to a range of base, intermediate or fine chemicals. The production of syngas (see Opus12's company profile) or polyols (see Covestro's company profile) are good examples. Regarding fuels, CO_2 is transformed into liquid or gaseous fuels. The production of diesel or methanol (see ANTECY's company profile) are typical examples.

Where the energy required for reactions and processes comes from is a central question in the research and development of CO_2 utilisation (see the interviews with Prof. Arlt and Prof. Styring). Energy is a major factor, especially for fuels and chemicals, that determines not only the economics, but also the environmental and social impact. Energy can be added to a chemical process in the form of high-energy

Figure 2: *Emissions over a city*

co-reactants, such as hydrogen, or in the form of heat, light or electricity. The latter electrochemical technologies are also referred to as Power-to-X. These technologies play a key role in the large-scale implementation of renewable energies, as they enable the long-term storage of excess energy (see the interview with Prof. Leitner).

The assessment of CO_2 utilisation technologies from different perspectives plays a crucial role in research and development, providing information for decision-making. Common types of assessment are techno-economic analysis (TEA), value chain analysis, life cycle assessment (LCA), and social perception or impact studies. The TEAs evaluate the economic potential and feasibility of CO_2 utilisation technologies. Value chain analyses study the interplay of sources, transport and sinks. The LCAs evaluate the environmental impact throughout the entire life cycle of a product. Social perception or impact studies assess the effects of technology implementation on societies (see the chapter on Economics, Environmental and Public Perception). Sustainability is composed of three pillars: economy, environment and society (triple bottom line). It is, therefore, essential to put the results of these different assessments into context to better understand trade-offs between the research areas and the overall sustainability of a technology.

Research and development projects are at very different development stages due to the many fields involved in CO_2 utilisation. The technological maturity is especially relevant for the right policy and funding tools for CO_2 utilisation. A common way to describe the maturity of a technology is by Technology Readiness Levels (TRLs). The TRLs define a scale of nine levels spanning from basic research (TRL 1) over pilot systems and demonstration systems to full-scale production systems (TRL 9). The TRL scale from the US Department of Energy is used in this report.

The EIT Climate-KIC EnCO_2re innovation programme addresses four preconditions for the successful development and implementation of CO_2 utilisation:

1. Technology and innovation: CO_2 technologies reach industrial scale.
2. Market development: demand for CO_2-based products is steadily growing.
3. Society and public impact: society accepts and embraces CO_2-based products.
4. Policy and regulation: policy-makers prepare for prosperous market conditions.

The current state of these preconditions and the potential of CO_2 utilisation are discussed in the subsequent chapters of this report.

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http://enco2re.climate-kic.org/co2-re-use/

Current State of Research & Development

“We see a great potential in the use of CO_2 as a building-block for chemicals to contribute to the principles of ‘Green Chemistry’.”

Interview with Prof. Walter Leitner

What is your current research interest in CO_2 utilisation?

We follow two major research lines: one is the use of CO_2 as a building-block for chemicals, ranging from polymers to fine chemicals and pharmaceuticals. We see a great potential there to contribute to the principles of “Green Chemistry”. The second, closely related aspect is to use the combination of CO_2 and H_2 for the production of tailor-made fuels or fuel components.

What is the overall motivation to work on this concept?

The use of CO_2 can help to reduce the carbon footprint of chemical production by replacing carbon derived from fossil feedstocks. In cases where additional energy input is required, technologies based on renewable energy sources could be employed. This opens up new opportunities to “harvest” renewable energy and carbon at the interface of the energy and material value chain.

Director of the Institute of Technical and Macromolecular Chemistry at RWTH Aachen and an external scientific member of the Max-Planck Institute for Coal Research, which focuses on energy- and resource-saving chemical reactions.

What is the current state of this research field and what have been the major breakthroughs so far?

The use of CO_2 as chemical feedstock has a long tradition in catalysis research and the field has seen a remarkable dynamic in recent years. The synthesis of polymeric materials (polycarbonates and polyurethanes) using CO_2 as the raw material has now reached industrial reality, especially through the developments at Covestro

(Germany) and Novomer (USA). New catalysts and catalytic transformations based on CO_2/H_2 have been emerging recently which enable the generation of molecular diversity based on these simple components.

What are the largest challenges in this research field currently and how could they be overcome?

It is a truly interdisciplinary challenge and requires the creativity and systematic work of teams comprising synthetic chemists, catalyst experts, reaction engineers and systems process engineers.

How far apart do you think the emerging CO_2 utilisation products are from current products in the industry?

When will we see the first large-scale CO_2 utilisation on the market?

It is happening already, as indicated above. For applications in the chemical industry, there can already be business cases resulting from reduced raw material costs and/or novel synthetic pathways in today's framework. Other concepts are ready in terms of technology, but require regulatory recognition as ways to reduce our carbon footprint to become cost-competitive. There is an exciting longer term perspective if we can use CO_2 not only as a substitute carbon source to generate the same petrochemical-based molecules, but also as an opportunity to generate better products.

“There are market niches for CO_2-based products, but large-scale CO_2 utilisation is limited.”

Interview with Prof. Wolfgang Arlt

What was your research interest in CO_2 utilisation?

I worked on the separation of CO_2 from flue gas emitted by fossil-fuelled power stations. I was among the first who worked on this topic mainly because it was a thrilling scientific goal for me to see whether the separation was achievable. But my conclusion was that it is not thermodynamically reasonable to recover CO_2 from flue gas, because it would use up too much energy. Therefore, I abandoned the research.

Chair of Separation Science and Technology at the University of Erlangen and founder of the Energie Campus Nürnberg (EnCN), a platform for renewable energy research.

What application areas for CO_2 utilisation do you see?

My research team and I found that there are market niches for CO_2-based products, such as epoxy materials for adhesives or polymers, but we also found that large-scale CO_2 utilisation is limited by three factors: added energy, market size discrepancy and cost of CO_2 supply.

Firstly, let us consider that emitted CO_2 is mostly a result of energy from combustion, which is used for driving cars or for producing electricity in a power station. In combustion, a high-energy level fuel – we say high enthalpy in thermodynamics – is used for driving or producing electricity, leaving the CO_2 and water with lower energy levels behind. While the combustion releases large amounts of energy, thermodynamics tells us that a reversed combustion requires the insertion of these very same large amounts of energy and more. This is the case not only for reversed combustion, but also for many other CO_2-utilising reactions: large amounts of electrical or chemical energy have to be added to produce something from CO_2, for example, in the form of hydrogen. As prices for electricity or hydrogen are higher than many base chemicals, there are not many economically viable options to utilise CO_2. The latter's utilisation is only viable in niche markets.

Secondly, I see a discrepancy between CO_2 emission and product markets. Germany emitted roughly 790 million tonnes of CO_2 in 2014. If someone would produce a solid product from all the CO_2 emitted, let us say polymers or minerals, with at least double the molecular weight, this would then result in over 1.5 billion tonnes of solid product. By comparison, the German markets for such solids have been significantly smaller in recent years: 0.55 billion tonnes of minerals and only 0.018 billion tonnes of polymers were produced. Obviously, CO_2 utilisation cannot be the only tool for emission mitigation.

Thirdly, we should keep in mind that CO_2 does not come free of charge. Most utilising technologies use pure CO_2, but as this is not available in large quantities, the costs for separation also need to be considered.

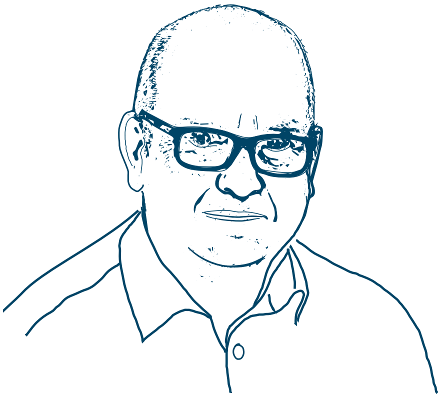
Are there alternatives to CO_2 utilisation?

Yes. For example, I am currently researching the long-term storage and transport of electrical energy. We produce hydrogen from renewable sources and then store it in aromatic compounds. The hydrogen can be released when needed to produce electrical energy again. Consequently, renewable electricity can be stored and transported more efficiently, unlocking further potentials of renewable energies. This process is replacing electricity production from fossil fuels without emitting CO_2.

My example shows that the mitigation of CO_2 can also be achieved by other routes than utilisation. My advice would be to focus on avoiding CO_2 emissions, so that you do not have to recycle them.

"Thermodynamics tells you it is not going to be easy, but kinetics and catalysis will show you that it can be done"

Interview with Prof. Peter Styring



Professor of Chemical Engineering and Chemistry at the University of Sheffield and chair of the CO_2Chem Network, which brings together academics, industrialists and policy-makers to consider CO_2 utilisation.

What is your current research interest in CO_2 utilisation?

My research interests span the whole spectrum of CO_2 utilisation, from capturing CO_2 to the utilisation of CO_2 that does not need capture or can tolerate impurities. We develop catalysts and processes for polymers, minerals and chemicals. Another huge topic is Power-to-X, converting CO_2 into fuels. My team and I are not only focusing on the technological aspect, but also on the socio-political aspect. We advise governments both in the UK and globally.

What do you recommend to politicians?

Companies and governments around the world are becoming interested in this topic nowadays. The field is growing exponentially if you look at the number of publications in recent years and the number of companies adopting the technologies. I see the greatest challenges in persuading industries and governments. It is necessary to demonstrate that CO_2 utilisation can be converted into a commercially viable field, while showing that it also makes environmental sense.

When it comes to recommending breakthrough technologies, mineralisation is showing the greatest promise. This is especially true for mineralisation using waste to make products, rather than to put it into landfill. The company Carbon8 is an excellent example of how this can be achieved. This technology can make a big impact due to the enormous amount of waste worldwide.

How can CO_2 be lifted out of its thermodynamic valley?

People say CO_2 is at the bottom of the thermodynamic valley – it is not. When talking about mineralisation, carbonates have an even lower energy level than CO_2. Energy is released in an accelerated mineralisation process.

Another big misconception is about the energy required. In the case of Power-to-X, using fossil energy does not make sense, as we would convert chemical energy into electrical energy and this electrical energy back to chemical energy again. One downside of using mostly renewable energy is that the energy is not always produced when needed. It is generally difficult to store electricity over long periods; batteries can only be used as short-time storage. Here, CO_2 utilisation can be an alternative: CO_2 can be transformed into fuels as seasonal energy storage by Power-to-X technologies. Using renewables, electricity for Power-to-X makes sense, as overcapacities of electrical energy can be utilised that could have not been accessed previously.

You cannot simply take thermodynamics on its own. There are many processes that have shown that CO_2 utilisation works. That is because effective catalysts have been developed to make processes, such as ammonia production, work and this is a multibillion Euro industry today. Thermodynamics is just one piece in the puzzle of the whole system.

What is the role of CO_2 utilisation when addressing global greenhouse gas emissions?

The CO_2 utilisation will be a part of the solution. Predictions say between 10 and 20% of emissions can be utilised. However, there will be other things that need to be considered, such as energy efficiency and increasing the usage of renewable energies. The major benefit of utilisation is that new fossil carbon can, at least in part, be eliminated from the supply chain.

How far apart do you think the emerging CO_2 utilisation products are from current products in industry?

When will we see the first large-scale CO_2 utilisation on the market?

The first large-scale CO_2 utilisation was in 1923 with the Bosch-Meiser process for urea. That is still the biggest utilisation process. When it comes to the new technologies, they are beginning to emerge. I think when looking at the technology development in many sectors, you are probably looking at 10 to 20 years before truly large-scale production comes along.

Economics, Environment and Public Perception

Public Perception and Acceptance of CO_2 Capture and Utilisation

Dr. Katrin Arning and Prof. Martina Ziefle

Why is public perception and acceptance important for the success of CO_2 capture and utilisation?

So far, the CO_2 utilisation community has focused mainly on aspects of technical feasibility, however, a successful technological development requires more than that: the perception of the public and the acceptance of potential customers are decisive factors for success or failure. Therefore, it is indispensable to include public perceptions into the research agenda to derive guidelines and recommendations for a successful rollout.

This text includes not only the utilisation, but also the capture of CO_2. Both areas are described in the term "carbon capture and utilisation" (CCU).

How do we study public perception and acceptance of CO_2 capture and utilisation?

The perception and acceptance of CCU are complex phenomena that vary depending on individual characteristics, context and framing media coverage. Acceptance-relevant patterns of the public can be captured and analysed by using empirical social science methodology.

When studying the perceptions and acceptance of a technology, we include not only experts, who provide objective facts regarding the risks and benefits of a technology, but also integrate potential customers, usually laypeople, with a low level of information and knowledge. This perspective might be dispensable for experts, especially if the laypeople mention incorrect assumptions or misjudgements. However, these perceptions reveal central acceptance-relevant factors which are used as decision criteria for or against the approval of a technology. The understanding of laypeople's (sometimes incorrect) assumptions can be used to develop tailored information and communication strategies.

Insights into CO_2 capture and utilisation perception and acceptance

Overall, the general perception of CCU technology and products is positive. People welcome the idea of a green, sustainable technology approach which contributes to efforts in reducing CO_2-emissions. Nevertheless, people also have a lot of questions and doubts about it, which mostly come from misconceptions and inadequate assumptions. Less than 5 % of all our respondents knew about

CCU and its products. Considering the low level of awareness and information, it becomes even more important that the public receives adequate information to raise interest and foster a positive perception.

The major benefit of CCU in the public is environmental relief (see figure 1). However, the ideas about the type of relief differ considerably. Laypeople imagine the environmental relief as significant savings of CO_2 emissions in terms of the global emissions budget.

> *"... But if CO_2 is removed from the environment, then even a small percentage is already good, because in this way the environment is relieved. Of course, the more the better!"*
> *(female, 54, layperson)*

In the experts' view of CCU, the environmental relief is saving a significant amount of fossil resources (about 20 %) compared to the production of conventional products.

> *"I mean, how many billion tonnes of CO_2 exist? These are such large amounts – there are estimates that a maximum of 1 % of emissions can be converted into products. If you provided all of Germany with gasoline based on CO_2, for example ..."*
> *(male, 33, expert)*

Although acknowledging the green potential of the technology, some people have doubts regarding its sustainability and judge it as a wrong approach to reach climate protection targets. Regarding CCU, experts often relate the amount of CO_2 savings to the amount of global CO_2 emissions, with the resulting impression that it would be too inefficient to be worth the investments. Greenwashing objections are also present: CCU is assumed to be a pretext for continuing the operation of coal power stations and hampering research and investments in renewable energies.

> *"The use of CO_2 for plastic product manufacture is not a long-term and sustainable solution – the real issue is only delayed. What happens if the products are no longer needed? Then, emissions accumulate again ..."*
> *(male, 30, layperson)*

> *"It may be a tiny contribution, but it will not help combat climate change directly. Other measures must be tackled, such as reconstruction of the electricity sector."*
> *(male, 31, expert)*

Here, it would be useful to communicate that CCU is an integral part of a holistic energy policy strategy to combat climate change, instead of considering it as a short-term technology.

The most important barrier associated by laypeople with CCU were hazards to health and the environment (see figure 1). Laypeople especially fear bodily contact with products derived from CCU, which can be explained by the laypersons' mental model of CO_2: it is not perceived as a part of the natural life cycle, but as a toxic or pollutant substance.

> *"CO_2 is harmful to human health! I do not want to come into contact with products manufactured by CO_2."*
> *(female, 79, layperson)*

> *"I ask myself how a CO_2 product will change the air if I store it in my apartment. Is it able to cause allergies? ..."*
> *(male, 60, layperson)*

Even though factually incorrect, it is important to address laypeople's health fears. Information and communication strategies should, therefore, explain how CO_2 is used. This applies particularly to products which are close to the body, for example, mattresses and clothes.

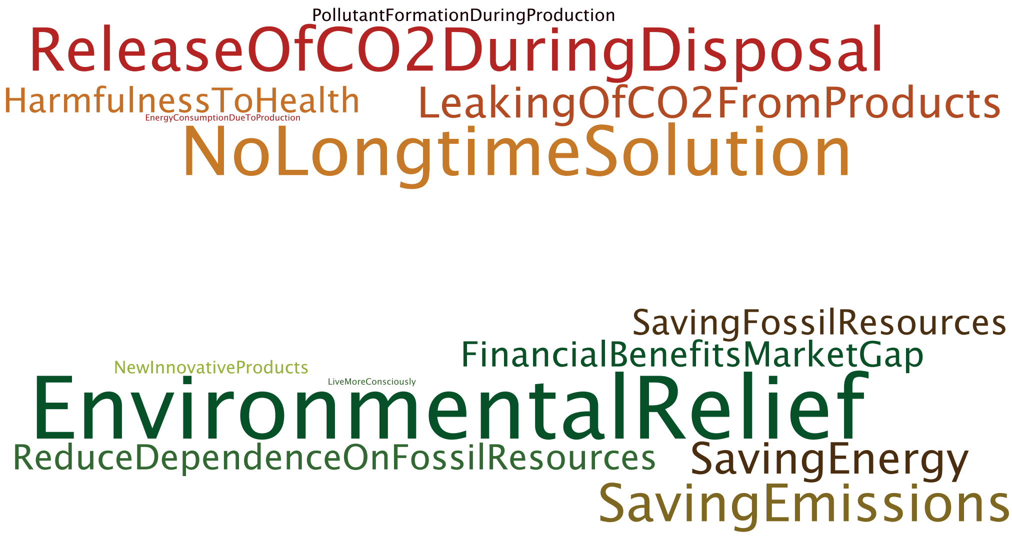


Figure 1: *Barriers and benefits of CCU perceived by laypeople*

Regarding product quality, future customers expect high-quality standards when considering using products derived from CCU. People do not acknowledge the green background per se, instead, they set the same expectations as those for conventional products. Future customers are not willing to pay higher prices for a green CCU product, but expect to benefit from savings in the production process.

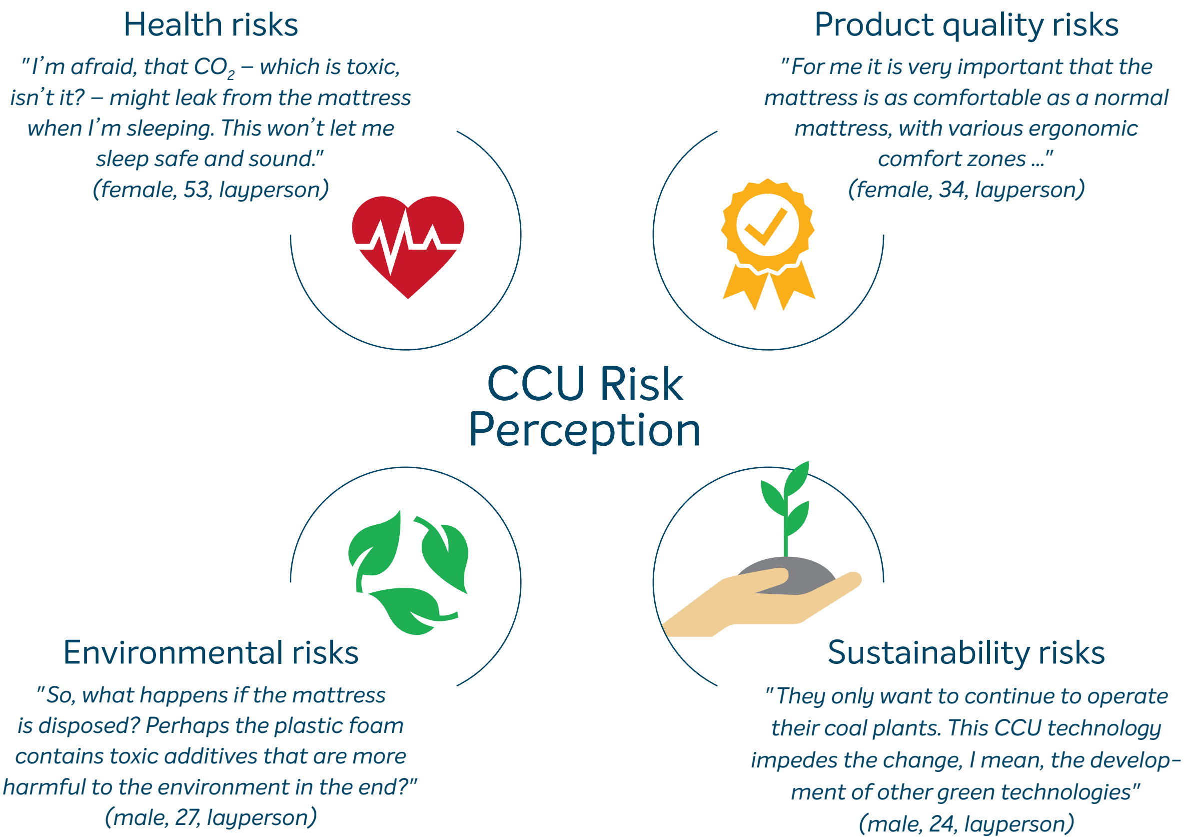


Figure 2: *Risks caused by CCU technology perceived by the public*

We have so far looked at the perception and acceptance of CCU in general. However, individuals' attitudes, experiences and knowledge differ enormously. We identified three consumer groups regarding a CCU mattress based on a survey: approvers, the cautious and rejecters.

The approvers (32 %) are not attracted by green benefits, such as CO_2 reduction or fossil resource savings. They like the mattress produced from CCU, because it is an innovative product with potentially improved technical characteristics (improved breathability or comfort). Communication strategies for the approvers' consumer group should not rely on a green argument. Instead, the innovative character of such a mattress (e.g. improved material properties, technical or practical functionalities) should be emphasised.

For the cautious (57 %, older, mainly female and working in a non-technical profession), health fears and environmental concerns are the main reason for the reluctant attitude towards mattresses produced from CCU. This group is the greenest, with a high environmental awareness. Communication strategies for the cautious consumer group should be directed at the contributions of CCU to climate-protection targets. Health concerns stemming from inadequate mental models and little knowledge about CO_2 should also be addressed.

The rejecters (11 %, mainly male and technically experienced) do not believe in the contribution of CCU to climate-protection activities. Even though they are interested in environmental topics and sustainability issues, they doubt the sustainability of CCU. Addressing the rejecters consumer group is difficult, since they hold a firmly sceptical opinion towards CCU that is not based on irrational fears or concerns, but rather on objectified arguments.

Future steps in acceptance research for CO_2 capture and utilisation

One big topic is the issue of appropriate information or communication strategies, especially for laypeople, since public knowledge and awareness of CCU is at a very low level. There have been many misconceptions about CO_2 prevailing, most of them with negative associations ("toxic CO_2"). Therefore, we need a tailored, target group-specific design of information (such as technical and economic feasibility, sustainability and greenwashing issues, and mental models of CO_2).

Another large topic is the broad variety of the CCU product family. We have used the mattress as an exemplary product so far. Future research should shed light on a broader range of product features and related usage contexts, such as fuels, chemical intermediates, construction materials or even tangible consumer products.

A third topic refers to measures to enhance trust in products from CCU. It is important to investigate to what extent trust is relevant for product acceptance and, if so, which measures are adequate to foster trust in CCU (e.g. transparent labelling of CCU products).

A further promising research direction refers to cross-cultural acceptance aspects. All our studies were conducted in Germany; therefore, we suggest comparative studies in different countries.

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Environmental Assessment of CO_2 Utilisation

Raoul Meys, Arne Kätelhön and Prof. André Bardow

Our motivation: Guide researchers, engineers and politicians on the pathway towards a sustainable industry

The capture of CO_2 and its utilisation as alternative feedstock for valuable products aims at the reduction of greenhouse gas emission and savings of fossil resources. Thus, CO_2 utilisation is contributing to closing the carbon cycle by offering an alternative non-fossil carbon source. Indeed, our studies show that CO_2 utilisation technologies can reduce greenhouse gas emissions and fossil depletion. However, obtaining environmental benefits by CO_2 utilisation is not as intuitive as it may seem at first sight. Imagine you would like to determine the environmental benefits of a CO_2 utilisation technology; would you agree with the following statements?

(i) Utilisation of 1 kg of CO_2 lowers the emissions to the environment by 1 kg of CO_2.
(ii) The production of methanol from CO_2 and hydrogen (H_2) is always a sustainable process (Methanol is a large bulk chemical; production in 2010 reached 60 million tonnes).

If you did not fully agree with the two statements above, you are right! Even though it may seem intuitive, utilised CO_2 cannot be treated as negative greenhouse gas emission. The capture process of CO_2 requires energy (e.g. heat and electricity) and auxiliary materials (e.g. chemicals or process water). Thus, the environmental benefit of CO_2 utilisation technologies cannot be taken for granted. As a matter of fact, in some cases, CO_2 utilisation technologies can even be environmentally more harmful than the processes used currently in industry. Our studies show, for example, that the production of methanol from CO_2 and H_2 increases greenhouse gas emissions compared to conventional methanol production if H_2 is produced from fossil resources. Consequently, when assessing the environmental impact of CO_2 utilisation technologies, it is of the utmost importance to use a holistic and reliable method to arrive at sound conclusions. The method of Life Cycle Assessment has been developed for this purpose and we use it for the environmental assessment of CO_2 technologies.

Our methodology: Life Cycle Assessment for the environmental evaluation of CO_2 utilisation technologies

Life Cycle Assessment is a standardised method to evaluate environmental impacts of processes and products by including all life cycle steps from the cradle to the grave.[1,2] In other words, Life Cycle Assessment takes into account the extraction of all raw materials, the transport between life cycle steps, the production of the product itself and its packaging, the use phase and, finally, the recycling or disposal of waste. Life Cycle Assessment consists of four steps:

1. Goal and Scope Definition
2. Life Cycle Inventory
3. Life Cycle Impact Assessment
4. Interpretation

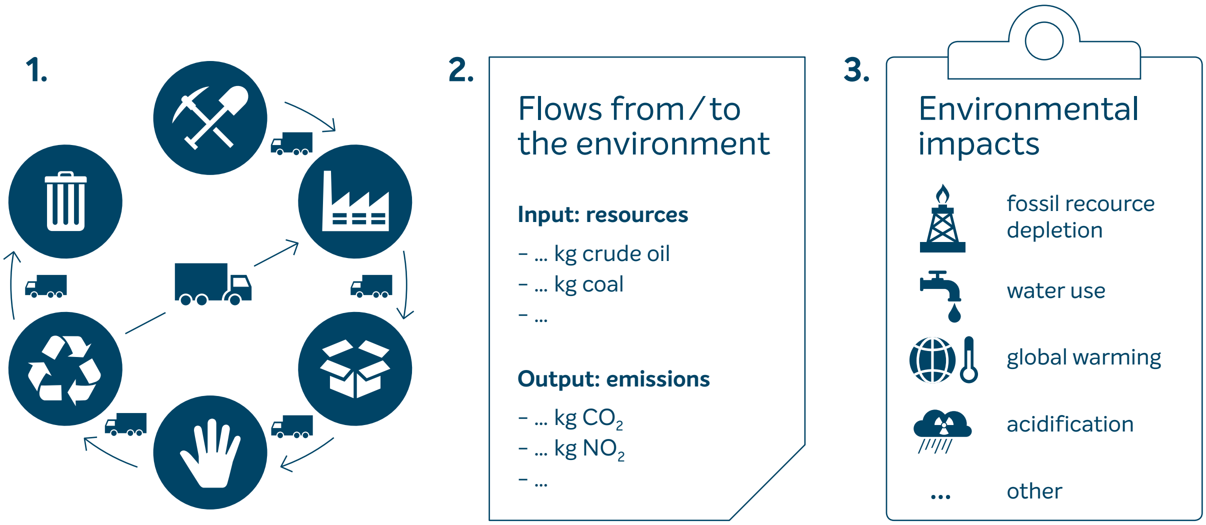

Figure 1: *The general concept of Life Cycle Assessment* [3]

The first step, the so-called Goal and Scope Definition, defines the reason for conducting the Life Cycle Assessment ("why?"), the system and/or product that is studied ("what?"), and which environmental aspects and data will be used for the environmental evaluation ("how?"). The second step, the Life Cycle Inventory Analysis, quantifies all in- and outputs of mass and energy for each life cycle stage (e.g. extraction of raw materials) and all emissions to the environment. In the third step, the Life Cycle Impact Assessment, flows that are exchanged with the environment are assessed regarding environmental impact categories, such as "climate change" or "fossil resource depletion". The last and fourth step includes the interpretation of the results and critically evaluates their suitability to answer the question posed in the Goal and Scope Definition (e.g. in terms of data quality and reliability).

Life Cycle Assessment is a comprehensive environmental assessment method that allows the determination of promising CO_2 utilisation technologies and enables us to avoid the shifting of environmental problems between various environmental impacts (e.g. good for the climate, but bad for acidification of rivers) and different life cycle stages (e.g. save emissions in production, but increase end-of-life emissions). Figure 1 shows all life cycle stages (left), from the extraction of the raw materials to the final disposal or recycling of waste. All flows exchanged from and to the environment are then collected (centre) and transformed into environmental impacts (right).

Our result: Identify the best setting for environmentally beneficial CO_2 utilisation technologies

We explained previously that the production of methanol by utilising CO_2 can be environmentally more harmful than the fossil-based process if a poor H_2 source is used. However, CO_2 utilisation for methanol can also be environmentally beneficial – under the right setting. Hydrogen, for example, could be produced by electrolysis using electricity only from wind turbines. If this H_2 is reacted with CO_2 captured from ambient air, the impact on climate change from the production of methanol is reduced by more than 50 % compared to the conventional production of methanol. This example highlights that it is very beneficial to combine renewable energies with CO_2 utilisation technologies.

The capture of CO_2 from ambient air requires the separation of low concentration CO_2, which needs a substantial amount of energy. The production of this energy again creates CO_2 emissions. Thus, captured CO_2 cannot be treated as negative greenhouse gas emission, and the energy required to capture CO_2 has to be considered.

Figure 2 maps the locations of various large-scale CO_2 sources in Europe, each with annual emissions higher than 0.1 million tonnes of CO_2. We showed that easier sources requiring less energy for CO_2 capture are available at the production facilities of chemicals, steel and iron, as well as coal-fired power plants. Using CO_2 from these sources instead of CO_2 from ambient air would further decrease the climate change impact in our methanol example. Thus, maximal climate benefits are only obtained by using the right carbon sources.

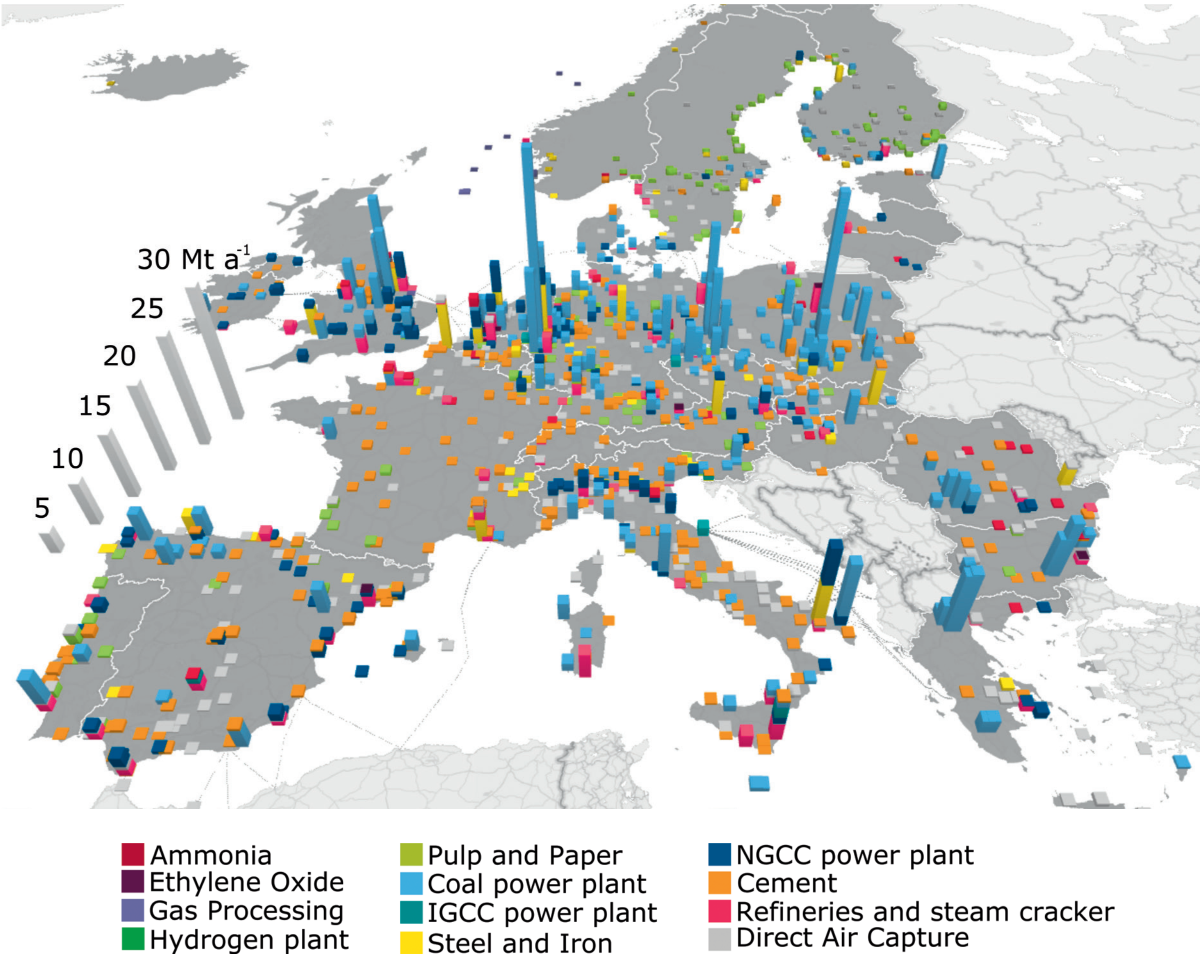

Figure 2: *Large-scale CO_2 sources in Europe* [4]

However, the main environmental benefit of CO_2 utilisation may not even come from the capture of CO_2, but from the substitution of energy- and emission-intensive chemicals within the production chain. If CO_2 substitutes for such chemicals, energy demands and emissions are reduced as well as our dependence on fossil resources. One recent example is the production of polyols, which are used to produce mattresses. By substituting up to 40 % of fossil-based energy- and emission-intensive chemicals, called epoxides, utilising 1 kg of captured CO_2 reduces the greenhouse gas emissions by 3 kg CO_2-eq. (the impact on climate change is expressed in kg CO_2 equivalents) compared to conventional polyol production.

Future perspectives for guiding CO_2 research by Life Cycle Assessment

We have shown the environmental potential of CO_2 utilisation technologies based on Life Cycle Assessment. However, the field of CO_2 utilisation is relatively new and fast growing. Many technologies are at early development stages and the data is not yet available for a full Life Cycle Assessment. In other words, the environmental impact of many CO_2 utilisation technologies is still unknown. Thus, there is a risk that the most beneficial options have not yet been identified.

We have developed tools to conduct large-scale screenings of new CO_2 utilisation technologies based on short-cut Life Cycle Assessment calculations to expand our current knowledge on new CO_2 utilisation technologies. The most promising CO_2 utilisation technologies identified in the screening should then be studied in more detail, leading to a full Life Cycle Assessment. This rapid screening is another contribution to exploit the full potential of CO_2 utilisation and to guide the pathway towards a more sustainable industry and future.

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N. von der Assen, A. M. L. Lafuente, M. Peters, A. Bardow in *Carbon Dioxide Utilization – Closing the Carbon Cycle*

Value Chains of CO_2 Capture and Utilisation

Dr. Arturo Castillo Castillo

Providing a systemic view of CO_2 capture and utilisation value chains

There is significant research being performed on individual technologies for carbon capture and utilisation (CCU). Most of it ranges from upstream work on novel forms of catalysis through to research on entrepreneurship, but is mostly limited to a specific solution or segment of the CCU value chain. In addition to analysing those components, there is a need to research the requirements and success factors that would enable their consolidation into value chains. This wider view helps stakeholders identify suitable partners along the value chain, which reduces the risk and effort involved in developing CCU schemes. Recent international activity has already incorporated some collaboration between scientific and governmental stakeholders in a few isolated studies, for example, in the southern United States. However, they focus mostly on locating CO_2 sources and, in a few cases, on locating uptake routes for CO_2 in their region. Therefore, there is still an important void to fill in terms of research that also includes transport logistics and can take a regional, pan-European – and broader – perspective.

Identifying suitable CO_2 sources and utilisation options

Stakeholders must be able to evaluate viable options for collaboration in early planning stages to develop regional CCU schemes. This evaluation is complex, as characteristics of CCU processes vary widely. Algae production, for example, only works with a significant amount of sunlight, Power-to-Chemicals technologies need regional capacities of renewable energy and mineralisation plants require a constant supply of ash. Our work on Value Chain Analysis provides a systematic way to identify compatible sources for consolidation, complementary uptake routes and synergistic transport means. These elements must be analysed locally and in a replicable way to uncover the best CCU opportunities.

Consequently, we developed a four-step approach based on material flow analysis and industrial ecology principles. Firstly, we generated an emission source classification with CCU-relevant boundaries for different scales and purities. Secondly, we integrated these categories into a cartographical visualisation tool to locate truly relevant sources.[1] Thirdly, we developed the ClusterCO_2re method to evaluate CO_2 utilisation processes regionally.[2] The method helps to assess the availability of the auxiliary inputs needed even when a compatible source and an uptake route are present. This last step is often neglected in other preliminary analyses. Fourthly, we developed a framework to calculate the economically viable distances between sources and uptake locations based on the purity of the emissions, dimension of the flow and transport means. By combining these steps, we can match sources with promising utilisation processes and appropriate auxiliary inputs, such as excess hydrogen or nutrient-rich wastewater effluents.

CO_2 value chains in European regions

Deploying our approach at a European level, we can identify regions with significant critical mass of CO_2-receiving processes. Figure 1 shows that regions in Scandinavia, the Benelux countries, western Germany and eastern Spain exhibit a potential for CO_2 uptake of between 1 and 2 million tonnes per annum based on a subset of their economic activities. Combining the mapping of classified sources with information on uptake potential, the areas where relevant sources are located can be prioritised to further evaluate CCU opportunities.

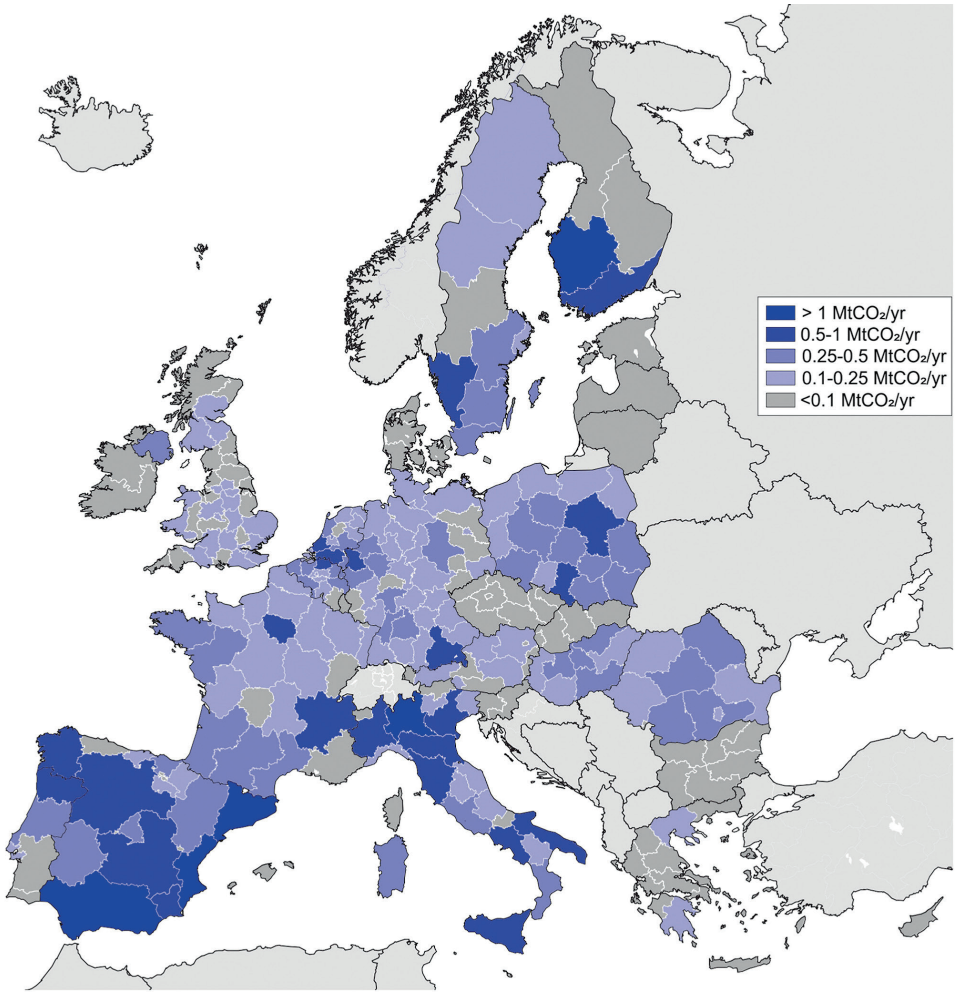

Figure 1: *Prioritisation of regions for CCU* [2]

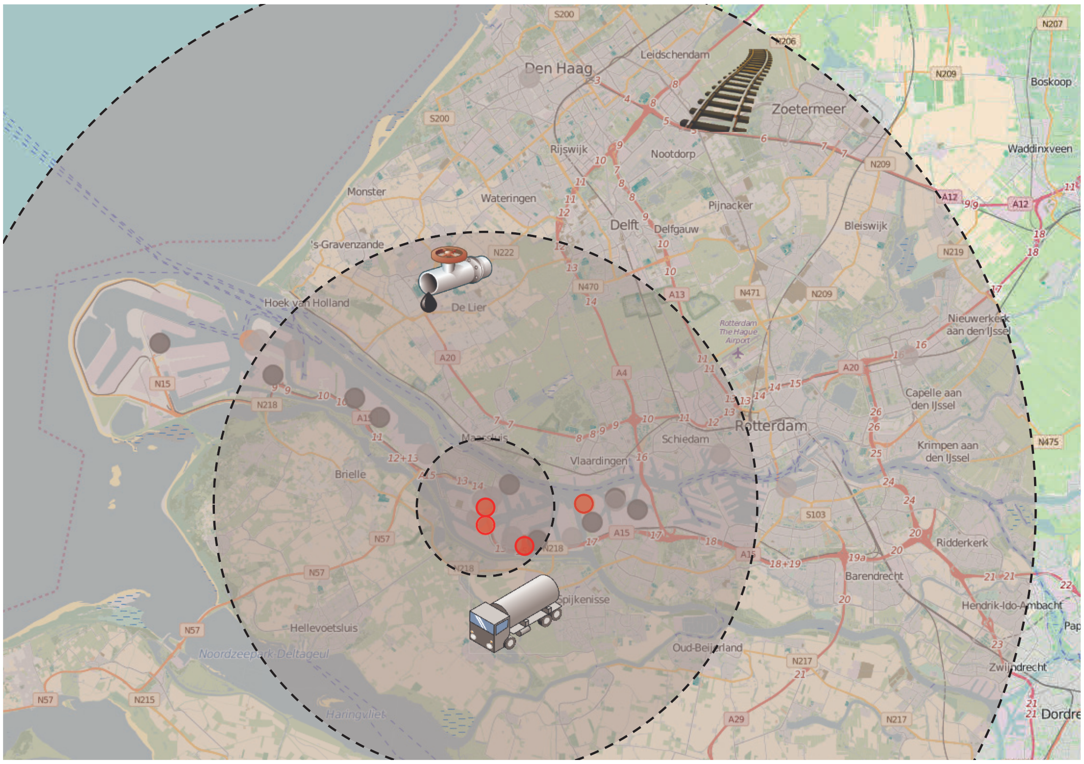

Figure 2: *Logistics calculation framework* [3]

Logistical options to join up the value chain

When building a viable CO_2 value chain, sources must first be matched with sources of compatible purity that can be consolidated to reduce costs and share infrastructure, and the same logic is used for CO_2-receiving processes. It is then necessary to establish how far an emitter or a receiver can search for partners under local logistical constraints. Our calculation framework, based on chemical engineering and supply chain logistics principles, can determine optimal distances under different local circumstances.[3] Key variables considered in the framework include:

- concentration of CO_2 in the flue gas,
- annual volume of emissions,
- transport means (e.g. pipelines versus trucks),
- transport costs,
- cost of emitting CO_2 (e.g. carbon taxes or emission certificates) and
- market prices of bulk CO_2.

We considered multiple permutations for the most common sources, such as cement plants, power plants and steel mills. The transport means included were on- and off-shore pipelines, trucks, rail and marine shipping. Figure 2 shows an example of the logistical ranges calculated with the framework.

Regional case studies

We have carried out two regional case studies in which stakeholders explored the feasibility of CCU value chains. After assessing potential uptake routes and matching them with the sources and auxiliary inputs present, convergence points for new mineralisation, horticultural and methanol applications were identified. The next steps in regional research focus on the non-technical barriers that can emerge under those specific conditions and in light of our policy-related findings.

Policies for bridging the "valleys of death"

The European debates about CCU policies in recent years has focused mostly on large emitters and a small number of non-technical barriers. Our work aims to find out how policy could further support CCU, addressing current gaps and highlighting additional options to provide incentives. This research entails comprehensive analysis of EU policies directly or indirectly relevant to CCU rather than focusing on single components of the value chain or stages of the innovation cycle.

The well-known term "valley of death" refers to projects faced with funding challenges as they struggle to move forward along the innovation cycle, for example, from research and development to pilot-plants or from pilot to commercial plants. Based on innovation policy analysis, we found that policies bridging these valleys of death, such as financial support for pilot plants, have been underestimated and must be reinforced immediately. One of the mechanisms that can benefit several CCU technologies is the inclusion of local CCU objectives in the EU Smart Specialisation Strategies for key industrial regions.

Open questions

The main open questions from a comprehensive, value chain perspective belong to three categories: the integration into regional development strategies, aligning existing policy incentives and identifying appropriate regions for implementation.

From the regional development standpoint, CCU offers several benefits. In addition to emissions mitigation, it contributes to increasing fossil resource efficiency, improving the exploitation of renewable energy, reducing waste, creating jobs and developing infrastructure. However, its regional implementation is only possible if the concept can attain the political priority required. This can be accomplished by embedding it within the context of regional development strategies that form the basis from which EU structural funds and other kinds of European and national support can be justified and requested. An important first step is to ensure that elements of carbon capture and utilisation, such as infrastructure, are included in the European Smart Specialisation Strategies following the guidance of the Directorate-General for Regional and Urban Policy.[4]

The broad adoption of CCU can be further accelerated by aligning existing policies to also include CCU. Firstly, national support must be designed to integrate and supplement European incentives. This support can, for example, address market adoption by public procurement. One example of such an initiative is the Dutch CO_2 performance ladder.[5] Furthermore, national tax incentives can target investments in infrastructure, logistics and demonstration activities. Nevertheless, one of the most important political debates is on whether and how to account for CO_2 emissions that are converted into products or services within the EU Emissions Trading Scheme.

When searching for regions suitable for CCU, the question is less whether there are "right" CCU technologies and more whether there are appropriate local contexts in which to deploy them. Since all the major related infrastructures, such as energy, water, transport, waste management and food production, are determined at a regional level, techno-economic and industrial ecology analysis should be performed, potentially with the tools mentioned above, to identify promising clusters in appropriate regions. It is worth realising that even small-scale projects can have an influential effect on public acceptance and urban planning regulations, which are crucial non-technical enablers.

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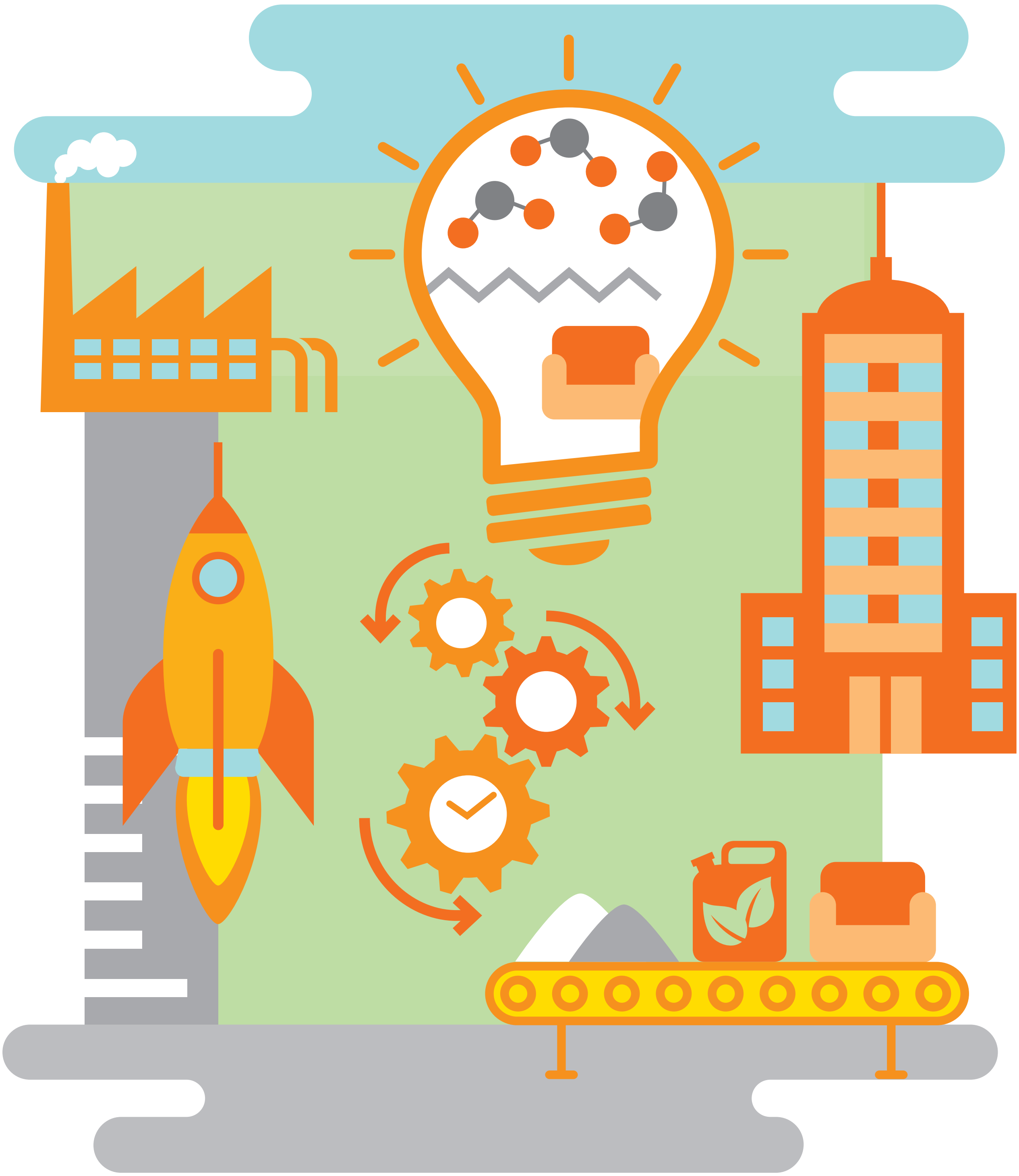
Insights from Industry & Start-ups



OPUS12

Opus 12, Inc.
Nicholas Flanders, CEO

Type of CO_2 utilisation:
Chemicals (various)
Technology Readiness Level: TRL 3–4 (Analytical and experimental critical function and/or characteristic proof of concept)
Founding year: 2015
Location of headquarters: Berkeley, CA, USA
Number of employees: 7
Revenue: n/a

Opus 12 has developed a device that recycles CO_2 into cost-competitive chemicals and fuels. The technology bolts onto any source of CO_2 emissions, and with only water and electricity as inputs, transforms that CO_2 into some of the world's most critical chemical products: a $ 300 billion global opportunity.

Problem being solved

Industry discards large volumes of CO_2 simply because it has no other use for it. Opus 12 provides a profitable alternative: converting those emissions into higher value base chemicals, using only water and electricity as inputs.

CO_2 utilisation technology and its impact

Opus 12 is developing a platform technology that integrates into existing electrolyser hardware, which is deployed at a wide range of scales. Opus 12 will deploy CO_2 conversion and will offer a spectrum of catalysts to convert CO_2 into a variety of different molecules, depending on customer need. Products will include syngas, ethylene, ethanol and bio-methane. Therefore, Opus 12's platform technology could be the foundation of the next generation of the petrochemical industry: forming products from recycled emissions and renewable electrons instead of from fossil fuels. It could offset 1.5 billion tonnes of CO_2 emissions annually. In the immediate future, Opus 12 has identified a billion-dollar niche application where it can solve a critical customer pain point for 10 times lower cost and higher safety than existing solutions.

Biggest achievements

Opus 12's biggest achievement so far were the development of a high-performance prototype and the acquisition of funding. The company was founded at Stanford University in 2015 and was selected as one of six companies nationwide to form the first cohort of the Cyclotron Road accelerator at the Lawrence Berkeley National Lab, where it is currently scaling up its technology. Opus 12 is the 2016 recipient of a Shell GameChanger grant, the 2016 winner of SBIR grants from NASA, DOE, ARPA-e and NSF, and is the 2015 winner of the DOE's Transformational Idea Award. Nicholas Flanders (CEO) is among Forbes'30 under 30 in energy for 2016, Kendra Kuhl (CTO) is among the MIT Technology Review's TR35 Innovators for 2016, and Etosha Cave (CSO) and Nicholas are 2016 Echoing Green fellows.

Biggest challenges

Opus 12's technology development entails major challenges. Opus 12 is developing a brand-new technology, therefore, its core focus has been on rapid iteration to move from concept, to proof of concept, to high-performance prototype, to scale-up.

Future goals and favourable conditions

Opus 12 aims to launch its first commercial unit in late 2017. Since its process utilises electricity as an input, the continued deployment of low-cost, low-carbon power sources will increase the impact of our technology. Opus 12 aims to build a business that is profitable independent of subsidies, so that any carbon legislation is additive, but not necessary to its existence.

Opus 12 co-founders Kendra Kuhl, Nicholas Flanders, and Etosha Cave

ANTECY

FUEL THE FUTURE

Type of CO_2 utilisation: Fuels and Chemicals (methanol)
Technology Readiness Level: TRL 6–7 (Engineering/pilot scale, similar system validation in a relevant environment)
Founding year: 2010
Location of headquarters: Hoevelaken, The Netherlands
Number of employees: 5
Revenue: n/a

ANTECY provides a technology for the economically viable production of methanol. The key innovation is a low-cost processing unit for capturing CO_2 from ambient air. The cost of capturing CO_2 from air is decreased by using low-cost materials and low-value heat.

ANTECY, B.V.

Saša Marinić, Managing Director

Problem being solved

Solar-derived methanol fuels (solar methanol) combine the benefits of a clean fuel with a high-energy density, similar to fuels on the market today. That is why solar methanol is suited as a drop-in fuel or fuel additive for cars. Furthermore, it can even serve as a seasonal energy storage and is also well-suited as a substitute for fossil feedstocks in the chemical industry.

The production processes of solar methanol are well-understood and the solar energy required can be supplied in large quantities. However, the key challenge for industrial-scale production is an economically viable technology for supplying CO_2. Even though CO_2 is available in billion tonne quantities in industrial flue gases or the atmosphere, its economic capture and compression currently pose a crucial challenge for the solar methanol industry.

CO_2 utilisation technology and its impact

The Carbon from Air (CAIR™) technology developed by ANTECY can concentrate CO_2 out of any source using low-value waste heat. The CO_2 and solar-derived H_2 are then processed to fuels and chemicals, such as solar methanol (see figure 2), using the energy storage and transformation (ETL) technology.

The core of ANTECY'S CAIR™ capturing solution is a solid carbonate sorbent (see figure 1). Unique characteristics of the technology are:

- low desorption temperature, reducing energy cost,
- highly stable sorbent material, reducing processing cost, and
- an overall environmentally friendly process.

ANTECY's CAIR™ technology can be used to provide CO_2 at low (> 10 %) and high concentrations (> 99.5 %). The price for air capture is estimated at 50 \$/t and for flue gas capture at 25 \$/t, being significantly lower than other options available on the market today. The low price of capture and a variable processing approach allow not only an economically viable production of solar methanol, but also many further applications in a variety of processing industries, such as algae production or greenhouses.

Biggest achievements

A total of ten patents have been granted regarding ANTECY's technologies. The CAIR™ process has been demonstrated over an eight-month trial period. The overall process for production of solar methanol on a large scale is currently validated by Shell Global Solutions. A future involvement of Shell Global Solutions is planned in following development steps.

Biggest challenges

The key technology challenge was to identify the low-cost and environmentally friendly materials that can desorb CO_2 at low temperatures. This matter was solved in close collaboration with University of Twente.

The biggest business challenge was the funding for the upscaling activities, where a €3 million investment round had to be closed, financing the coming two years of research and development. Further challenges posed were the high cost of electricity for H_2 production.

Future goals and favourable conditions

The most important goal for the future is a pilot plant on a semi-commercial scale. Such a plant is essential for ANTECY to provide verifiable data on process stability and product quality. These data are required for a partnership with a launching customer.

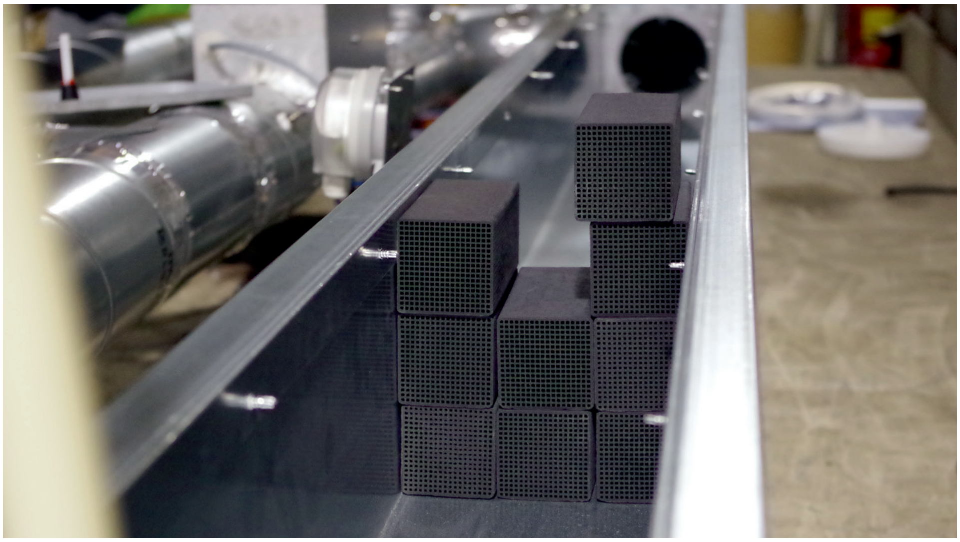


Figure 1: *Loaded sorbent of ANTECY's CAIR™ technology*

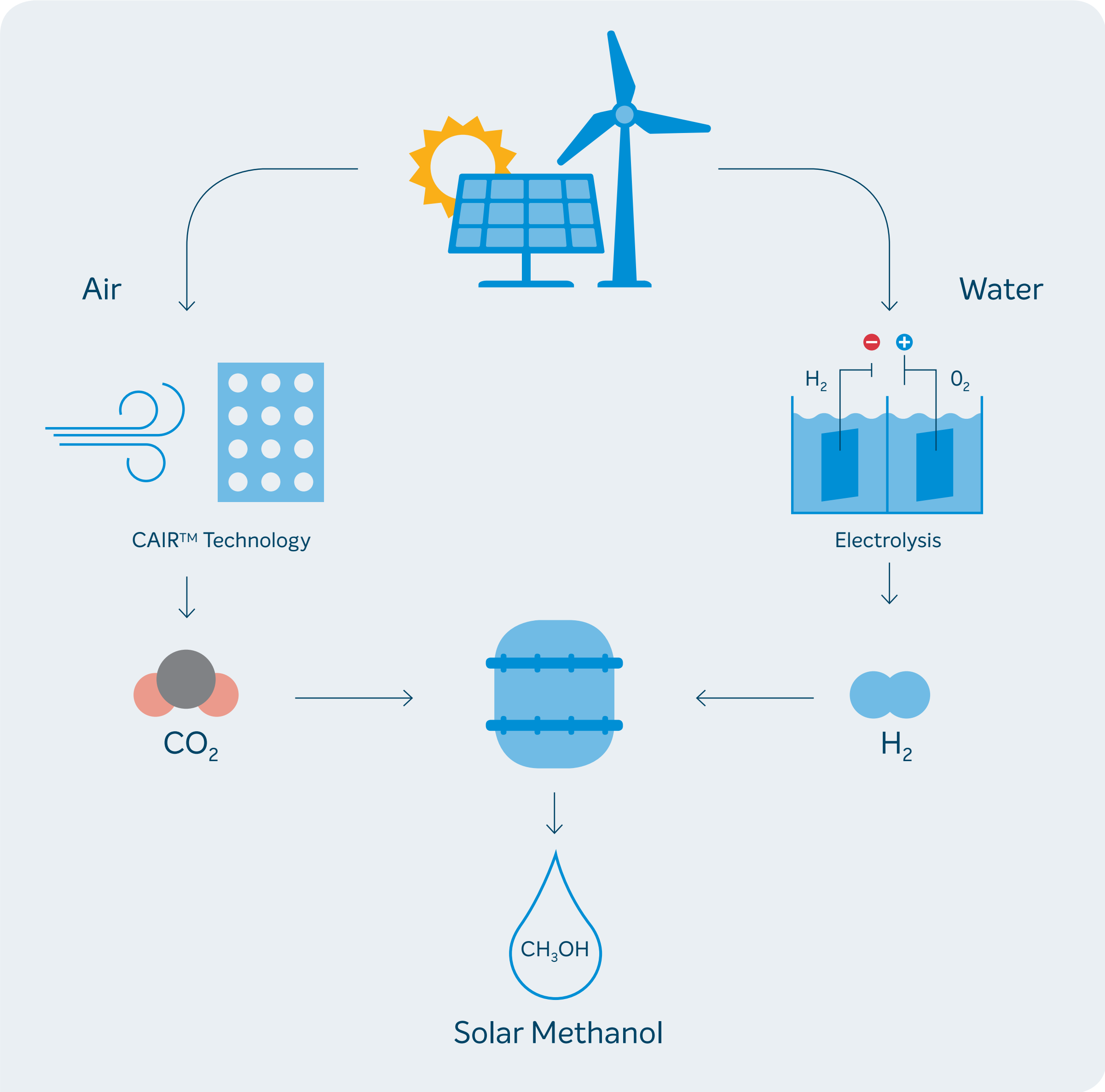


Figure 2: *Process flow of ANTECY'S technology*

Covestro AG
Stefan-Paul Mechnig, Communications

Problem being solved

Covestro succeeded in using CO_2 as a new raw material to produce plastics, thus, saving traditional fossil-based raw materials, such as crude oil, and contributing to resource efficiency.

CO_2 utilisation technology and its impact

Researchers at Covestro have been working together with partners on converting the low energy level waste product CO_2 into a valuable new raw material since 2008. They found an effective catalyst and developed a process that made it possible to integrate CO_2 into components for flexible foams and other plastics. Covestro has just recently started the industrial production of a foam precursor with a CO_2 weight content of around 20 %. Scientists at Covestro are now working on including CO_2 in other plastic raw materials and increasing the CO_2 amount that can be used. Precursors for elastomers and rigid foams are promising projects currently.

Biggest challenges

The biggest challenge for Covestro was to find a way to use CO_2 in a sustainable way. It normally takes a lot of energy to make the CO_2 molecule react with other molecules because its own energy level is very low. If too much energy is needed, the reaction would not be worthwhile, either ecologically or economically. However, Covestro and its partners have succeeded in finding an effective catalyst, allowing an energy-efficient reaction.

Type of CO_2 utilisation:
Chemicals (polymers)
Technology Readiness Level: TRL 9 (Actual system operated over the full range of expected mission conditions.)
Founding year: 2015
Location of headquarters: Leverkusen, Germany
Number of employees: 15,800
Revenue 2015: € 12.1 billion

Covestro is a world-leading supplier of high-tech polymer materials for key industries. The company's products and solutions range from raw materials for flexible and rigid foam to high-tech plastics, to raw materials for coatings, adhesives and sealants.

Future goals and favourable conditions

In addition to having dedicated experts within Covestro, collaboration with partners from academia and industry and the right framework conditions are crucial to making further progress in introducing CO_2 as a new and alternative raw material in plastics production.

Covestro is very happy to be able to rely on third-party expertise and to obtain public funding for a lot of its research projects now and in the future. It is fortunate that the German government acknowledges the potential especially of CO_2-based production processes. This positive attention towards CO_2 needs to be maintained and expanded to make industrial-scale CO_2 utilisation a reality.

Figure: *The newly opened plant for foam precursor production in Dormagen, Germany with a capacity of 5,000 tonnes per year*

Conclusion

This report provides perspectives on CO_2 utilisation from a variety of angles: interviews with scientists, essays on business, environment and social impact, as well as stories from CO_2-utilising companies. While the authors' views differ on whether and how CO_2 utilisation could be done, all agree that large-scale CO_2 utilisation would have a significant impact: It could not only change the way fossil resources and renewable energies are used, but CO_2 utilisation could even lead to market changes in chemicals, fuels and materials and to new value chains. Such a fundamental societal change requires favourable preconditions in the four fields of technology, market, societal impact and policy, according to the theory of change framework. The arguments presented in this report will be summarised along these four categories.

Technology and innovation

A lot is happening in terms of technology and innovation. A broad portfolio of CO_2-utilising technologies is emerging: chemicals, fuels, and even building materials are being developed. While the research featured in this report might focus on substituting current products, some researchers believe that yet completely new products are possible. Novel catalysts for CO_2 and hydrogen "enable the generation of molecular diversity" stated Prof. Leitner. These new products could also lead to new business cases for the chemical industry. However, making CO_2 utilisation work is not an easy challenge: Prof. Arlt pointed out the thermodynamic limitations: in many cases, substantial amounts of added energy or pure CO_2 streams are required, which lead to extra burdens in the form of added cost and increased emissions. What fields show promising results? Prof. Styring underlined the potential of mineralisation and Power-to-X technologies, where these limitations play a minor role or can be overcome by the integration of renewable energies.

Market development and demand

While research occurs mainly inside a lab, commercialisation happens outside in markets; the major requirements for market development and demand mentioned throughout the report are:

- good product-market fits, in a market with suitable size;
- sustainable product design: proving viability in economics, environment and social impact;
- successful technology scale-ups of chemical technologies in demonstration and pilot plants; and
- regional CO_2-utilisation clusters, where infrastructure can be shared for a lower cost.

Reaching these requirements is not easy for companies. Proving a good product-market fit in early development stages is challenging, for example, because multiple products can be produced with platform technologies (valid for all companies in this report). However, such platforms also provide opportunities for pivoting to different markets. Another challenge is designing sustainable CO_2-based products in an environment where laypeople do not expect to pay higher prices, but benefit from savings, as described by Dr. Arning and Prof. Ziefle. Furthermore, commercialisation of new chemicals and technologies requires multi-million Euro investments and can take decades until full market adoption, translating into substantial risk for investors. However, our examples show that it can be done: the chemistry start-ups Opus 12 and ANTECY have raised millions of Euros for scale-up, and polymer producer Covestro constructed a pilot plant in 2016, reaching a capacity of 5,000 tonnes of CO_2-based products per year.

Companies cannot reach these requirements themselves. Governmental organisations need to bring the different actors of the CO_2 value chain together to create regional lighthouse projects. The price for CO_2, for example, varies widely depending on the region, but pooling CO_2 emission from multiple sources would allow for sharing infrastructure and costs. Dr. Castillo Castillo identified four suitable regions in Europe and calls for an integration of CO_2 utilisation into regional policy strategies.

Society and public impact

The major societal impact of CO_2 utilisation discussed in this report is emissions mitigation, others are storage of renewable energy, increased resource efficiency and lower dependency on fossil fuel imports, regional value and job creation, and other factors of environmental impact.

Meys and colleagues discussed whether a certain CO_2-utilisation technology is reducing emissions, and concluded that the answer is specific to the technology. They showed both, examples of methanol production with decreased as well as with increased emissions. The emissions reduction in the polymer case presented did not result primarily from CO_2 utilisation per se, but from the substitution of an emission-intensive fossil ingredient. Meys and colleagues claim that systematic assessment of environmental impact over the whole life cycle of the product (LCA) is crucial before a judgement can be made.

Furthermore, social acceptance is essential for the successful implementation of new technologies, especially when people mention incorrect assumptions or misjudgements, as described by Dr. Arning and Prof. Ziefle. One important example is the emissions mitigation technology carbon capture and storage: the implementation was slowed down or even stopped due to public resistance in Germany, the UK and elsewhere. While people are usually receptive of green technologies, they also show doubts about sustainability and greenwashing. Dr. Arning and Prof. Ziefle call for tailored communication for effective knowledge transfer to overcome misconceptions and negative associations by the public.

Policy and regulation

Governments in the United States, Europe, China and elsewhere have funded CO_2-utilisation research and development over the last few years. Various articles in this report point out that continued funding for research and development is necessary, while additional measures for commercial demonstration and pilot plants must be added. One example is support for chemistry start-ups in the form of incubation programmes, such as INKULAB at the TU Berlin, or programmes for partnering with large industrial companies. Furthermore, Dr. Castillo Castillo calls for the inclusion of CO_2 utilisation into regulatory frameworks for emissions trading and industrial subsidies among others. Regional strategies can help to create lighthouses in CO_2 utilisation.

A common misconception is that CO_2 utilisation is the ultimate answer to emissions mitigation: its mitigation potential is estimated to be one order of magnitude smaller than current man-made CO_2 emissions, which means that the reduction and not the mitigation of emissions should be addressed first and and CO_2 utilisation can only be applied together with additional emissions mitigation technologies.

Outlook

The ultimate impact of CO_2 utilisation remains to be decided, but is increasingly on the agenda of technologists, governments, and businesses. Whether utilisation markets will be niche or large-scale is debated and dependent on the right requirements in technology, markets, society and policy. In addition to emissions mitigation, CO_2 utilisation holds many more advantages. It has the potential to revolutionise many of today's products and services. The fact that not only governments, but also private venture capital firms and large industrial players with commercial interest are funding R&D shows that confidence in the commercial potential of CO_2 utilisation already exists today.

About EIT Climate-KIC EnCO$_2$re Flagship Programme

EnCO$_2$re is an innovation and market development programme for CO_2 re-use, pursuing the vision of a balanced and prosperous market for re-used CO_2, beginning with a focus on polymers and chemical intermediates. EnCO$_2$re's ambition is large-scale CO_2 re-use through the establishment of a CO_2 value chain.

EnCO$_2$re was co-initiated by Climate-KIC and the chemicals producer Covestro, forming a consortium of 12 European partners from industry and research sectors. The programme has a comprehensive approach towards CO_2 re-use and comprises activities in technology development, product development, technology acceptance, ecological assessments and market development.

EnCO$_2$re is pronounced like the French word *encore*, meaning "again," in reference to the re-use of CO_2 the programme aims to enable.

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