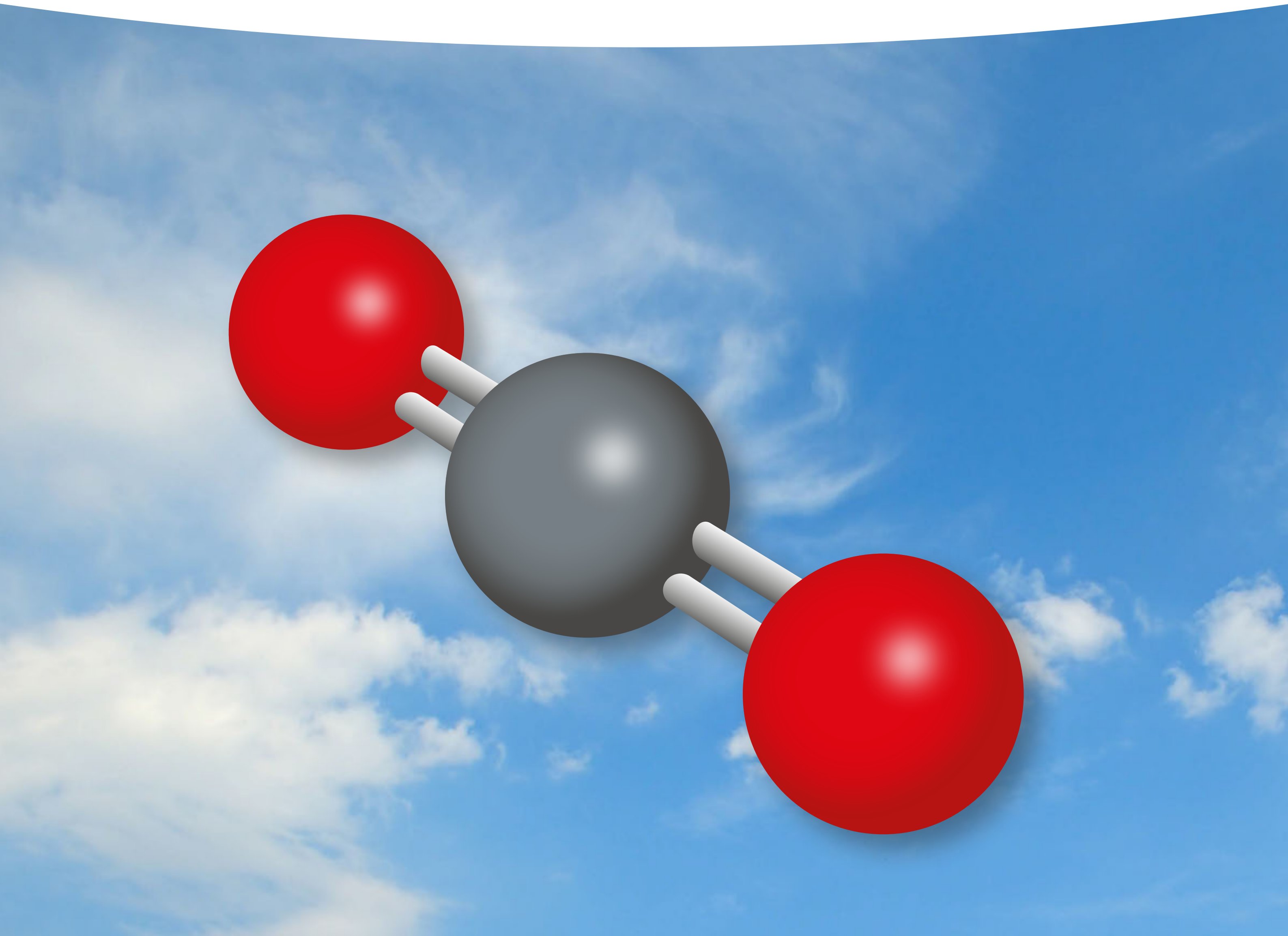
European Commission

SETIS
Information For Decision-making

SETIS magazine
No. 11 – January 2016



Carbon Capture **Utilisation** and Storage

SETIS

Cover photo © iStock

Contents

Editorial

By Loredana Ghinea

A.SPIRE Executive Director

Carbon dioxide – turning an enemy into a valuable friend!

Carbon dioxide is naturally present in the atmosphere as part of the Earth's carbon cycle. However, recently it has been declared the planet's public enemy number one and how to deal with it is a subject of great controversy.

Still, what should not be a controversy is that CO_2 is the only abundant non-fossil carbon resource available in Europe; and, with technological innovation making it possible, starting to actually valorise CO_2 could play a vital role in the decarbonisation of industry and in establishing a truly circular economy in Europe through industrial symbiosis. The SPIRE (Sustainable Process Industry through Resource and Energy Efficiency) Public-Private Partnership has taken on this angle and has built up a comprehensive roadmap showing how to address resource and energy efficiency in the process industry up to 2030, including giving CO_2 a value.

CO_2 conversion technologies can contribute to meeting ambitious EU targets for energy. They can increase the share of energy produced from renewable resources through large-scale energy storage via Power to Gas technologies (producing methane for storage in existing gas networks) and Power to Liquid technologies (producing liquid energy carriers such as methanol). These technologies can also provide advanced sustainable alternative fuels with a CO_2 reduction potential of more than 70%, making a CO_2-based fuel car comparable to an electric vehicle.

Many sectors in SPIRE, including cement, chemicals, engineering and steel, are actively involved in the development of new CO_2 conversion technologies.The steel sector is developing new technologies that combine excess hydrogen with CO_2 rich industrial flue gases via bio-chemical and catalytic conversion to produce valuable hydrocarbons. Already the use of CO_2 as a renewable resource has been demonstrated in the manufacture of polymers with a reduced CO_2 footprint. In the cement sector, innovative processes and products using CO_2 enable the production of a new type of concrete with a reduced CO_2 footprint (up to 70%) as compared to traditional Portland cement.

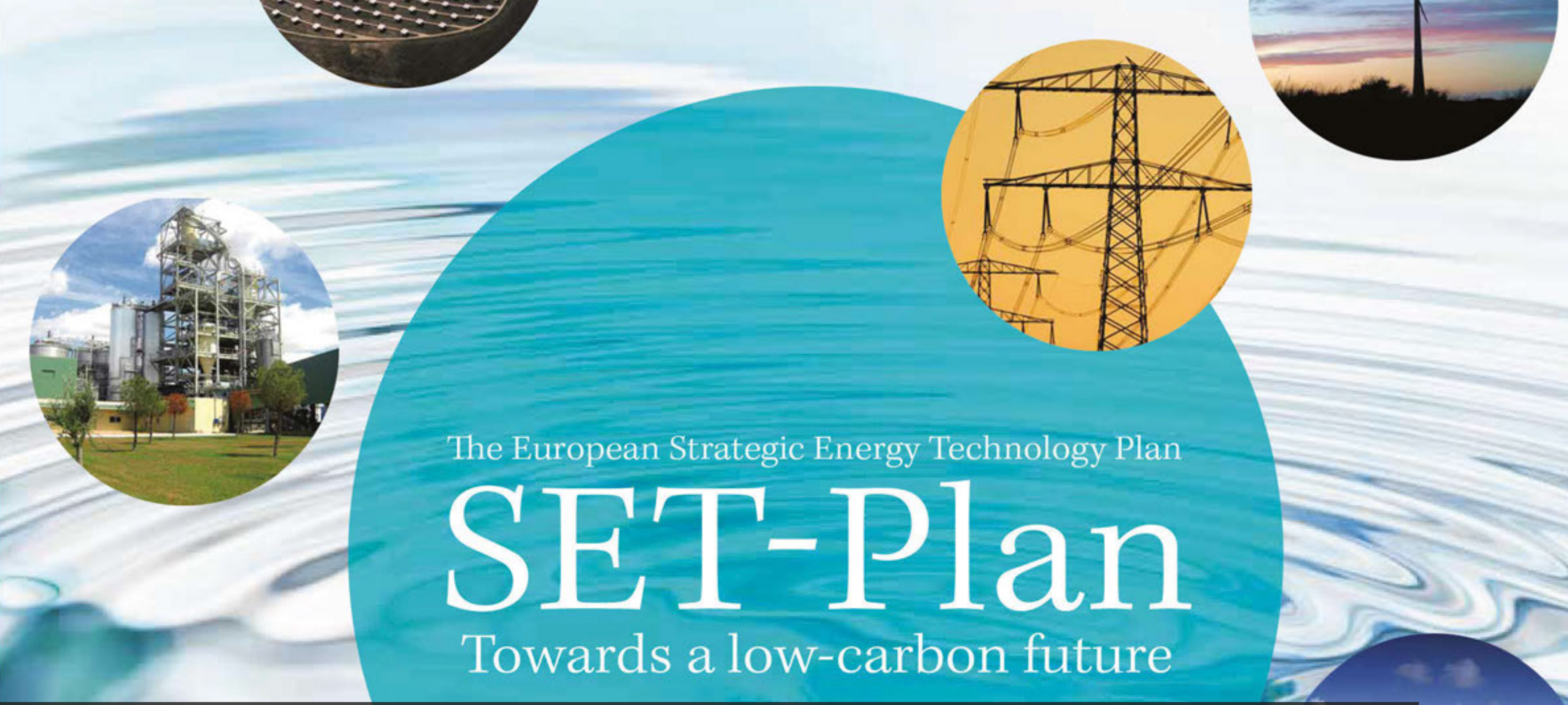
A longer term option is the direct photo-conversion of CO_2 from ambient air via 'artificial photosynthesis'. This would be a major technological breakthrough leading to new CO_2 conversion technologies using only air and sunlight to produce chemicals and fuels.

Achieving widespread uptake of CO_2 as an alternative carbon resource to produce chemicals, materials, fuels and store energy also requires a stable and appropriate policy framework in the areas of energy, transport and circular economy as they are developed at the EU and national levels. It is essential that the legislative system is adapted to define products using CO_2 as a resource, as renewable-based products (such as through the Circular Economy and Energy Union packages). To attract investment and gain the environmental and social benefits there must be no distinction between CO_2 of biological origin and other CO_2 streams. Policies that encourage inter-sectorial use of CO_2 also need to be put in place.

As Executive Director of the A.SPIRE association since 2012, Loredana Ghinea has been leading the ambitious industrial efforts towards the launch and implementation of the contractual Public-Private Partnership SPIRE (Sustainable Process Industry through Resource and energy Efficiency), a multi-billion euro instrument of the Horizon2020 framework programme working across eight major European industry sectors: cement, ceramics, chemicals, engineering, minerals, non-ferrous metals, steel, and water. These sectors together represent over 450 000 individual enterprises making up around 20% of the European economy. They employ 6.8 million people and generate over EUR 1 600 billion turnover annually.

SPIRE's goal is to promote the deployment of the innovative technologies and solutions required to reach long term sustainability in Europe's process industries while boosting their global competitiveness.

www.spire2030.eu



SET-Plan Update

The European Strategic Energy Technology Plan (SET-Plan) aims to transform the way we produce and use energy in the EU with the goal of achieving EU leadership in the development of technological solutions capable of delivering 2020 and 2050 energy and climate targets.

The EU supports Carbon Capture Utilisation and Storage through its Framework Programme for Research and Innovation and other mechanisms, and by creating the legislative and policy framework needed for CCUS implementation. The following is a chronological overview of some of the actions taken to promote CCUS in the EU, in addition to a more general look at recent actions in support of the SET-Plan.

Carbon Capture Use and Storage

- In October 2001, Directive 2001/80/EC of the European Parliament and of the Council on the limitation of emissions of certain pollutants into the air from large combustion plants highlighted the EU's commitment to a reduction of carbon dioxide emissions.
- In October 2003, the European Commission published Directive 2003/87/EC, establishing a scheme for greenhouse gas emission allowance trading within the Community. This was amended in April 2014 by Regulation No 421/2014, in view of the implementation by 2020 of an international agreement applying a single global market-based measure to international aviation emissions. In July 2015, the Commission presented a legislative proposal to revise emissions trading for the period after 2020 - increasing the pace of emissions cuts and introducing more targeted carbon leakage rules.
- The European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) was founded in 2005 as a broad coalition of stakeholders united in their support for CO_2 Capture and Storage (CCS) as a key technology for combating climate change. ZEP serves as advisor to the European Commission on the research, demonstration and deployment of CCS.
- The European Union Emissions Trading System (EU ETS) was launched in 2005 as a cornerstone of the European Union's policy to combat climate change and its key tool for reducing industrial greenhouse gas emissions cost-effectively. The first - and still by far the biggest - international system for trading greenhouse gas emission allowances, the EU ETS covers more than 11 000 power stations and industrial plants in 31 countries, as well as airlines.
- CO_2GeoNet was launched in 2008 under the European Commission's 6th Framework Programme as a Network of Excellence dealing with all aspects of geological storage of CO_2. The aim of this network was to promote research integration within the scientific community to help enable the implementation of CO_2 geological storage.
- In April 2009 the European Commission published Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide (the "CCS Directive"). This directive established a legal framework for the environmentally safe geological storage of CO_2 as a key element of the fight against climate change. The Directive covers all CO_2 storage in geological formations in the EU and the entire lifetime of storage sites. It also contains provisions on the capture and transport components of CCS, though these activities are covered mainly by existing EU environmental legislation, such as the Environmental

Impact Assessment (EIA) Directive or the Industrial Emissions Directive, in conjunction with amendments introduced by the CCS Directive.

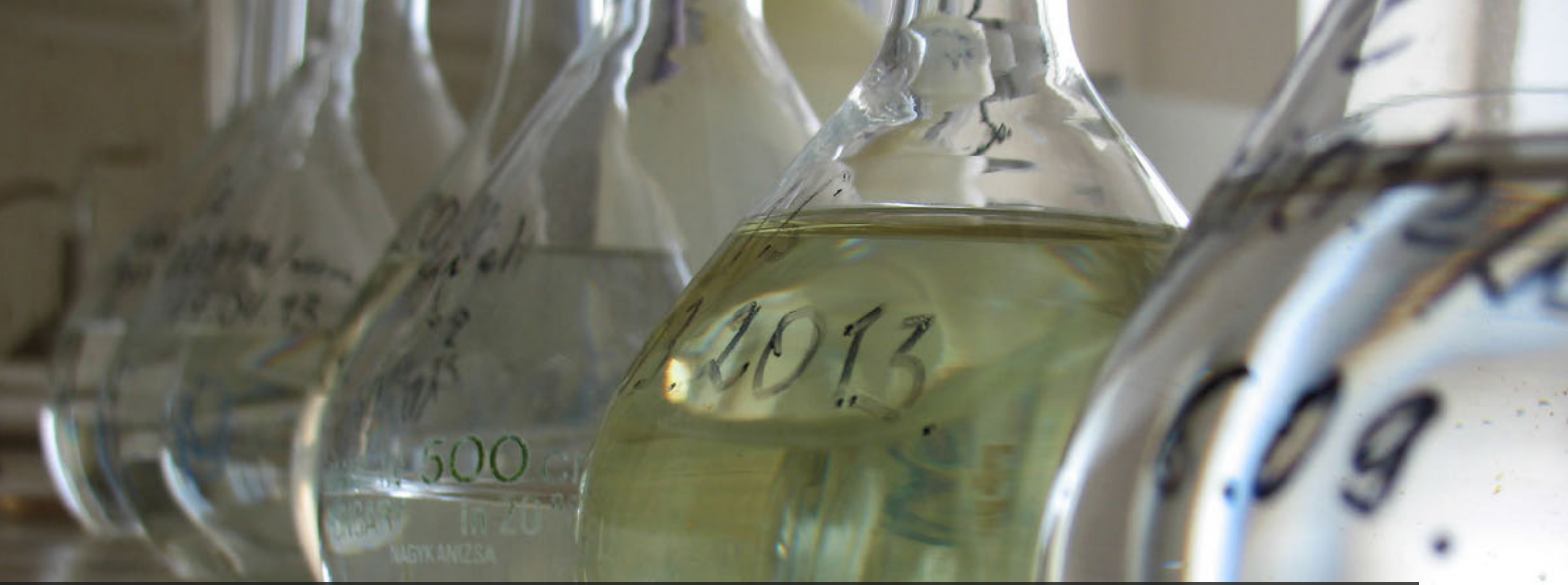
- The European Energy Programme for Recovery (EEPR) was established in 2009 to address both Europe's economic crisis and European energy policy objectives. Almost EUR 4 billion were assigned to co-finance EU energy projects that would boost economic recovery, increase the security of energy supply and contribute to the reduction of greenhouse gas emissions. Within the general framework of the EEPR, the CCS programme was designed to make a significant contribution to the general objective of European energy policy to deliver secure, competitive and sustainable energy supplies.
- The European Industrial Initiative on CCS was launched in June 2010 to demonstrate the commercial viability of CCS technologies in an economic environment driven by the emissions trading scheme. In particular, the EII aimed to enable the cost-competitive deployment of CCS technologies in coal-fired power plants by 2020-2025 and to further develop the technologies to allow for their subsequent wide-spread use in all carbon-intensive industrial sectors.
- The European Energy Research Alliance (EERA) Carbon Capture and Storage Joint Programme was officially launched at the SET-Plan Conference in Brussels in November 2010. The CCS JP coordinates both national and European R&I programmes to maximise synergies, facilitate knowledge sharing and deliver economies of scale to accelerate the development of CCS.
- In March 2013, the European Commission published a Communication on the Future of Carbon Capture and Storage in Europe (COM/2013/180), which concluded that an urgent policy response to the prime challenge of stimulating investment in CCS demonstration is required, to test whether the subsequent deployment and construction of CO_2 infrastructure is feasible.
- The Joint Research Centre (JRC) of the European Commission (Institute for Energy and Transport) and the Directorate General for Climate Action co-hosted a Workshop on CO_2 Reuse Technologies in Brussels in June 2013. The aim of the workshop was to present how the most promising pathways for CO_2 re-use are related to climate and energy technology policies, facilitate a dialogue between stakeholders and address the challenges for a possible large scale roll-out of CO_2 re-use technologies.
- In January 2014, the European Commission published its Communication 'For a European Industrial Renaissance' (COM/2014/14), setting out the Commission's key industrial policy priorities. The Communication recognises the need to speed up investment in breakthrough technologies and sends a clear signal of Europe's commitment to reindustrialisation, the modernisation of Europe's industrial base and the promotion of a competitive framework for EU industry.
- In February 2014, the European Commission produced a report to the European Parliament and the Council on the implementation of the CCS Directive (2009/31/EC) which noted that, as of October 2013, all Member States had notified CCS Directive transposition measures to the Commission and that the majority of Member States had completed transposition of the Directive. The Commission then started to check if the notified measures conformed in substance to the CCS Directive.
- In 2014 a CCS Directive Evaluation study was launched to obtain a comprehensive view of the current state of CCS deployment in Europe and the functioning of the CCS Directive. The project held two stakeholder meetings in Brussels during 2014 to collect inputs to assist in the review of the Directive and published a final report in January 2015 which found that the overall need for CCS (and European CCS regulation) remains genuine and urgent and, given the lack of practical experience, it would not currently be appropriate, and could be counterproductive, to reopen the Directive for significant changes.
- In February 2015, the European Commission published its Energy Union Package - A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy (COM/2015/80). This document called for a forward-looking approach to carbon capture and storage (CCS) and carbon capture and use (CCU) for the power and industrial sectors. According to the Strategy, this will require an enabling policy framework to increase business and investor clarity, which is needed to further develop these technologies.
- The European Commission's Directorate General for Research and Innovation organised a workshop on 'Transforming CO_2 into value for a rejuvenated European economy' in March 2015. This event aimed at opening a discussion on CO_2 conversion and utilisation, gathering a critical mass of interested stakeholders at all levels, from decision makers to industry delegates and European Commission representatives. The event gave a broad overview of the status of CO_2 conversion technologies in Europe, including programmes and projects currently running, and it provided a discussion forum for setting an agenda of shared priorities on the topic at European level, leading potentially to the development of a Europe-wide initiative.
- In its Communication 'Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation' (COM/2015/6317), published in September 2015, the European Commission called for increased research and innovation activities on the application of carbon capture and storage (CCS) and the commercial viability of carbon capture and use (CCU). The Communication pointed out that research and innovation should support carbon and energy intensive industries to explore the feasibility of CCS, focusing primarily on sectors with high-purity sources of CO_2 to minimise capture costs.

- In September 2015, the EERA Joint Programme for CCS organised an expert meeting on Practical Next Steps to CCS Deployment in Europe. The expert meeting brought together 26 key people from national agencies, the EC (DGs Climate, Energy and Research), industry and their associations, national research and energy agencies and NGOs.
- In its Directive 2015/1513 from September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources, the European Parliament empowered the Commission to adopt acts with regard to carbon capture and utilisation for transport purposes.

General SET-Plan related news and activities from JRC/SETIS

- In September 2015, the European Commission adopted its Communication towards an Integrated Strategic Energy Technology Plan (SET-Plan): Accelerating the European Energy System Transformation (COM/2015/6317). This Communication addresses the role of the SET-Plan in defining the new research and innovation (R&I) approach which will accelerate the transformation of the European energy system and ensure the EU's leadership in the development and deployment of low-carbon energy technologies. It also provides the overall framework for encouraging further cooperation and synergies in R&I between the EU, Member States and stakeholders (research and industry).
- In the context of the process towards the Integrated Roadmap, organisations (universities, research institutes, companies, public institutions and associations) involved in research and innovation activities in the energy field are invited to register in the European energy R&I landscape database, which aims at facilitating partnerships and collaboration across Europe. Registration is open to stakeholders from the EU and H2020 associated countries. Organisations are able to indicate their area of activity according to the energy system challenges and themes, as identified in the SET-Plan process towards an Integrated Roadmap and Action Plan. The database is publicly available on the SETIS website.
- The 8th SET-Plan Conference was held on 21-22 September 2015 at the European Convention Centre Luxembourg, launching the European debate on the new SET-Plan and the next steps to implement its actions. The conference focussed on the Communication addressing the European energy system transformation and the role of the SET-Plan, which was adopted in September. The new Integrated SET-Plan Communication defines the new Energy R&I Strategy for the EU for the coming years and provides a framework for promoting strengthened cooperation in energy R&I between the EU, Member States and stakeholders.
- Two SET-Plan Steering Group meetings were held in September - one on September 9 in Brussels, and the second on September 23, in the aftermath the SET-Plan Conference in Luxembourg. The final Steering Group meeting of 2015 was held in Brussels on December 9.

© iStock/Volker Göllner



French National Centre for Scientific Research (CNRS) Research Director

Alessandra Quadrelli

TALKS TO SETIS

© iStock/CarylIN

The world's carbon dependence has overwhelmed the planet's ability to process the resulting carbon dioxide emissions. What solutions exist to restore balance to the carbon cycle?

The first immediate major solution is to decrease the future emission rate, that is - reduce plethoric energetic consumption, since fossil fuel consumption for energy production is the main source of anthropogenic CO_2 emissions. Therefore increasing the efficiency of current fuel consuming processes, and also refraining from frivolous or excessive usages, is of pivotal importance.

The second and intermediary solution is to remove CO_2 from the current emission balance. This could be done by geological storage, which is being explored as an option, and still raises several questions. Removal of CO_2 from the current emission balance can also be achieved by chemically embedding CO_2 in a value-added and long-lasting product. Inorganic carbonates or polymeric polycarbonates are good examples. As a chemist, I immediately recognise the potential and feasibility of transforming CO_2, a molecule usually considered as a waste and a nuisance, into a new molecule: chemistry is the key technology for turning problematic molecules into useful ones.

A third family of solutions consists in replacing fossil fuel with renewable energies as our primary source of energy. One of the hurdles is storing these intermittent sources of energy. Storage in the form of chemical energy is one of the possible solutions. Here too, CO_2 can be the molecule that helps close the loop. It is no coincidence that this molecule, considered to be waste, will be the key to the turnaround just like CO_2 is in nature: being the end-molecule of biomass transformation in the cycle of life, the same molecule has to be the entry molecule in photosynthesis when bridging solar energy to biomass. No long term solution is possible without circularity, and no circularity in global anthropogenic activities is possible without a key role played by CO_2.

What are the main obstacles to the implementation of a viable CCUS system in Europe?

I will focus my attention on CDU (carbon dioxide utilisation). Some CDU solutions are already technically feasible and deployed on very large pilots. The low price of oil coupled with dull incentives or policy blockages (e.g. if CO_2 is labelled as a waste can we sell products made from it?) sometimes make the new solution difficult to deploy. Very well established incumbent technologies, with all the necessary infrastructures already in place, also make replacement more difficult.

Some new solutions are ready to be tested at the pilot level, but which organisations are capable of taking on the risk of the investment needed to perform these very large-scale tests?

As in many instances, a lack of financing at the research level can slow down our capacity to identify and remove lingering obstacles.

What benefits, if any, does CO_2 recycling offer over storage as a method of greenhouse gas (GHG) emission control?

Producing value added and marketable products out of CO_2 is an obvious plus compared to remediation-like technology, where there is an "all cost - no sales" model.

The public perception will also potentially be less negative when the technology yields products that are practically indistinguishable from analogues already marketed, as opposed to technologies that currently raise substantial public concern.

Finally, being able to "discover" a new feedstock, CO_2, which can be "mined" directly in Europe, and build industrial plants here around its chemical transformation, can form a substantial economic asset. When these processes feed into the energy sector and thereby contribute to European energy self-reliance and security, the benefits become even more compelling.

CDU could also be compatible with delocalised smaller-scale models of production and distribution, which are promoted by some as an interesting model to consider for future highly-connected and renewable energy based societies.

What are the most promising conversion routes from CO_2 to marketable carbon derivatives?

It is worth remembering that urea, a chemical produced at the rate of almost two hundred million tonnes a year, is synthetized from CO_2. Other established chemicals can be cited too, one example is acetylsalicylic acid, a precursor of aspirin, whose industrial synthesis from CO_2 is a century-old established process.

Among the novel routes, it will be very interesting to look at the growth of the market share of CO_2-based methanol obtained from renewable energies as compared to fossil based methanol. Methanol is a base chemical with a direct connection to the energy sector and thus has tremendous potential. Several other Power to Fuels conversion processes are also emerging industrially, all of which use CO_2 as the key shuttle molecule between renewable energy and the fuel molecule.

CO_2-containing polyurethanes could also become a "greener" alternative to the existing fossil-based ones, which are omnipresent polymers used, for example, in most foams.

Finally, inorganic carbonates obtained from CO_2 and, for example, ashes and other end of pipe materials, for use in the construction business as a substitute for mined rocks and cementitious materials, are very interesting products.

What projects currently being implemented in Europe offer the most exciting CCUS solutions?

All the examples I just cited are from European-based companies, either spin-offs from well-established large groups, or new ones. State-level projects (such as pledges to reduce, and eventually erase, the share of fossil fuel in electricity production), will de facto boost CDU deployment, since it is a key enabling technology for introducing renewable energy in the current infrastructure. Finally ambitious projects from several funding agencies can lead to exciting further solutions through research.

How do you see CCUS developing in Europe in the medium to long-term?

For all the reasons stated above, which range from the maturity of some technologies and the genuine political commitment to favour renewable energies and reduce our dependency on fossil fuels, to the economic soundness of some processes and the creativity of our research, I see a very positive outlook for CDU development in Europe.

Alessandra Quadrelli

Elsje Alessandra Quadrelli is a Director of Research at CNRS and chair of the Sustainability Chair at the École Supérieure de Chimie Physique Électronique de Lyon (CPE Lyon). In this context, she founded and chairs the "CO_2 Forum", a biyearly international conference on CO_2 utilisation for a circular carbon economy. She graduated from Scuola Normale Superiore di Pisa and holds a PhD in organometallic chemistry from the University of Maryland at College Park.

Spurring innovation in carbon capture and utilisation technologies:

The Horizon Prize for CO_2 reuse

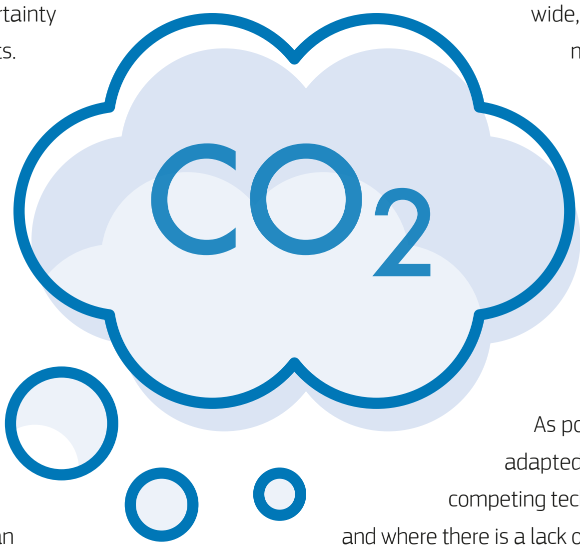
© iStock/Peshkova

Innovative technologies using carbon dioxide as a feedstock for industrial and consumer products can play a role in achieving Europe's ambitious climate change objectives. The *Horizon Prize for CO_2 reuse*, to be launched next year by the European Commission, aims to further support and accelerate emissions-saving innovation in carbon capture and utilisation.

The European Union is committed to reducing its greenhouse gas emissions by 20% by 2020 and by at least 40% domestically by 2030 compared to 1990 levels. It has also adopted a robust set of policies to reach these targets, for instance by promoting renewable energy, energy efficiency and low-carbon technologies such as the capture and geological storage of carbon dioxide (CCS). A promising area for further emissions reductions is carbon capture and utilisation (CCU), which enables the use of carbon dioxide (CO_2) as a feedstock for products such as chemicals, building materials and substitute fuels.

In addition to cutting emissions, CCU technologies can bring multiple economic benefits. They can support the EU's industrial revival and the development of a circular economy. They can contribute to our energy security, to the decarbonisation of the transport sector and to the deployment of wind and solar electricity by providing energy storage. Moreover, innovation in CCU will also support the further development of carbon capture and storage, as it helps advance capture technologies and create demand for the CO_2 captured. Mutual benefits could be drawn by developing hubs and clusters for CO_2 capture, transport, storage and utilisation around sites with emissions-intensive industries.

Many possible pathways for CO_2 utilisation are under consideration, but most of these breakthrough technologies are still at the research and development stage and face many technical, economic and market barriers. Determining their future potential is challenging due to the complexity of the chemical reactions involved, a lack of comparable information about energy and material consumption, and uncertainty over environmental impacts and costs. To provide answers to some of these unknowns, the European Union and its Member States are supporting research to contribute to advancing CCU technologies through the EU Framework Programme for Research and Innovation and national research programmes.



In order to further support and accelerate innovation in carbon capture and utilisation, the European Commission will launch a *Horizon Prize for CO_2* reuse in the third quarter of 2016. The prize, worth EUR 1.5 million, will be awarded in late 2019 to the most innovative product reusing CO_2. The winning product should demonstrate a significant reduction in net CO_2 emissions while overcoming key technical, commercial and financial barriers.

By putting the spotlight on emissions reduction, the prize aims to support the development of CO_2 utilisation technologies that have the potential to make a genuine contribution to the European Union's emission reduction targets. The prize also aims to mobilise private investment in research and innovation, create new partnerships and boost incentives for researchers and innovators to enhance emissions abatement efforts.

The *Horizon Prize for CO_2* Reuse is part of the European Commission's series of 'challenge' or 'inducement' prizes, which offer a cash reward to whoever can most effectively meet a defined challenge. Over the recent years, challenge prizes have become a reliable and tested way to support and accelerate change in many areas. They have become an important driver for innovation in the public, private and philanthropic sectors worldwide, providing a different approach to the more traditional grant-based research support. The race towards the best solution encourages innovators to take risks and forge new partnerships, and the prize money is a booster to industry as a whole to deliver on the objectives of the prize without prescribing how these will be achieved.

As policy tools, these prizes are particularly adapted to circumstances where a number of competing technologies can deliver similar outcomes and where there is a lack of transparency about the real potential of different approaches to achieve significant, commercially-viable and scalable results. This also applies to CCU technologies. Through the *Horizon Prize for CO_2* reuse, the European Commission aims to further stimulate innovation across the relevant industries and contribute to the development of new sustainable products and technologies in line with EU policy objectives in the fields of energy, climate change and industrial innovation.

For more information, please visit:
Horizon Prizes: https://ec.europa.eu/research/horizonprize/

This article was contributed by the European Commission's Directorate-General for Climate Action: http://ec.europa.eu/clima/

Dr Lothar Mennicken

from the German Federal Ministry of Education and Research

TALKS TO SETIS

© iStock/Mirexon

Why is CCU an important technology option for Europe?

Europe is a world leader when it comes to innovative and key enabling technologies. The chemical and biotechnological industries, and also the processing industry, are strong and major drivers of economic growth. CCU technologies will play a major role in the future when it comes to adapting to the changing raw material market – in the energy sector as well as in the chemical sector. CCU can deliver solutions to major challenges: To support the transition of the energy system towards fluctuating renewable energies, CCU technologies can provide the means for large-scale energy storage with minimal land use requirements. It can also support the transition of the transport sector by providing technologies for clean fuel production from non-fossil sources with an extremely low carbon footprint. A major contribution is, however, the provision of an alternative raw material base for the chemical industry. By developing CO_2-based production routes for base chemicals, the dependency on fossil carbon sources of the chemical industry and all subsequent production routes will decrease. Furthermore, as an additional benefit, all these factors also help to mitigate greenhouse gas emissions significantly.

Many see CCU as an enabler to CCS, others as a pathway to new industrial opportunities. What is your opinion?

In Germany, there is no debate about CCS anymore. CCS has a very bad image in Germany and has basically been rejected by the German public and media. Hence, CCU is not seen to have any connection with CCS. On the European level however, CCS is still a topic. I believe though, that the two technologies do not have much in common. First of all, there are the costs: CCS is basically a non-profit technology, where every step is costly. CCU however has the potential to produce value-added products that have a market and can generate a profit. Secondly, the primary aim of CCS is the mitigation of climate change by storing large amounts of carbon dioxide underground. There is no inclination to add value to the captured carbon. In contrast, CCU's major driver is to substitute fossil carbon as a raw material by recycling CO_2. CCU and CCS are related technologies with regard to carbon capture, but CCU should not be limited as being just an enabler for CCS, as it can do so much more than simply deposit carbon dioxide underground.

What are the most promising CCU pathways? What are the main technological barriers to their commercialisation?

For Germany, the most promising pathways are certainly twofold. Firstly, in the chemical sector we have a very promising example from the polymer industry. Covestro is currently commercialising the first CO_2-based polyurethane product, e.g. for mattresses. The mattresses are expected to hit the market in 2016. This is a real chance for the CCU community, as it shows that CO_2-based products are an economically viable route in major market sectors. Secondly, the Power to Liquids (PtL) technology has strong potential. The Dresden based start-up company sunfire opened the world's first PtL-plant of its kind last year in Germany. This plant in particular has a symbolic character as it demonstrates to a broader audience that liquid fuels can be made from CO_2, water, and renewable energy. Considering that there will be demand for liquid fuels in the transportation sector even in the future (aviation, long haul freight transportation), PtL can facilitate the transition of the transportation sector to renewable energy with a very low carbon footprint and in some cases to drop-in-fuels (e.g.

diesel, kerosene, gasoline). With respect to technological hurdles for commercialisation – there are not many unsolved problems left; the major hurdles are more regulatory in nature.

How is research and innovation in CCU supported in Germany?

The Federal Ministry of Education and Research (BMBF) started a major research and development program in CCU in Germany in 2009, ahead of almost every other nation in the world. We strongly believed in the potential that CCU technologies hold for sustainable development and a "green economy". With the first funding measure - "Technologies for Sustainability and Climate Protection: Chemical Processes and Use of CO_2" - 33 collaboration projects between academia and industry were supported with approximately EUR 100 million, to which industry added another EUR 50 million. Projects, like the aforementioned Covestro and sunfire projects were part of the measure. To build-up on this major success, BMBF has recently launched a new funding measure, "CO_2Plus", which focusses on the utilisation of CO_2 as a raw material and also aims to enhance currently underdeveloped fields of research and development in Germany, e.g. photo- and electrocatalysis and direct air capture. Additionally, BMBF has introduced a novel funding instrument, "r+Impuls" - here the transfer of research and development results into the market is tackled and projects with a technology readiness level of at least 5 can receive support for the risky upscaling from pilot plant to the first industrial demonstration plant.

What have been the most significant achievements of CCU research to date?

Again, CCU has already proven that it can contribute to major challenges and is technologically ready to be commercialised in many cases. The success stories show that clean technologies can already have a market, as seen in the polymer sector. In Germany in particular, CCU has brought industries together, like steel (CO_2 as waste) and chemistry (CO_2 as a raw material) that have had no significant overlap in the past. The potential for cross-industry approaches is huge and this can provide an insight into the industry of the future. Another achievement is the speed of the developments: five years ago almost no one believed in the success of CCU technologies, yet worldwide today we have successful examples that are market-ready. There are only a few other technology fields that have developed so quickly.

How can policy and regulation support CCU?

Particularly in the fuel sector, a change in regulation (the renewable energy directive (RED), and fuel quality directive (FQD)) can boost the use of CCU technologies. At present, these fuels are in a kind of "no-man's land" as they are not defined in the EU terminology and if they are included, like in the last amendment of the RED, the definition is not very clear. Andreas Pilzecker of DG CLIMA recently referred to them as "zombies". Policy and regulation should provide a clear definition and course of action.

How does progress with the development of CCU in Europe compare with the rest of the world?

Europe is leading when it comes to CCU technologies. However, there is the danger that technology development and application will move to other countries like the USA or certain Asian countries, in particular China, as they are catching up fast. This has happened to other emerging technology fields (e.g. batteries) before and we have to act now in order avoid this "technology drain". If Europe manages to keep hold of the innovations, there is a huge market opportunity to sell the technologies to non-European markets in future which will be beneficial to the European economy. Industry and politics have to work hand in hand to ensure this promising emerging technology will become a European success story.

Dr Lothar Mennicken

Lothar Mennicken graduated from the Rheinische Friedrich-Wilhelms-University of Bonn in agricultural sciences in 1989. After conducting research work in Malaysia and Berlin he received a doctorate from the Technical University of Berlin. International scientific-technological cooperation was his main topic until 2010. Since then he has acted as senior adviser at the Federal Ministry of Education and Research (BMBF), in the Resources and Sustainability Division, where he is in charge of raw materials, including carbon capture and utilisation.

Chemical valorisation of CO_2 for Europe

© iStock/Hramovnick

The chemical valorisation of CO_2 has the potential to define a new landscape and business opportunities for European industry in the next decades, and contribute to addressing major challenges such as energy security, resource efficiency and growth through breakthrough concepts and new business models in the long run.

The potential value of CO_2

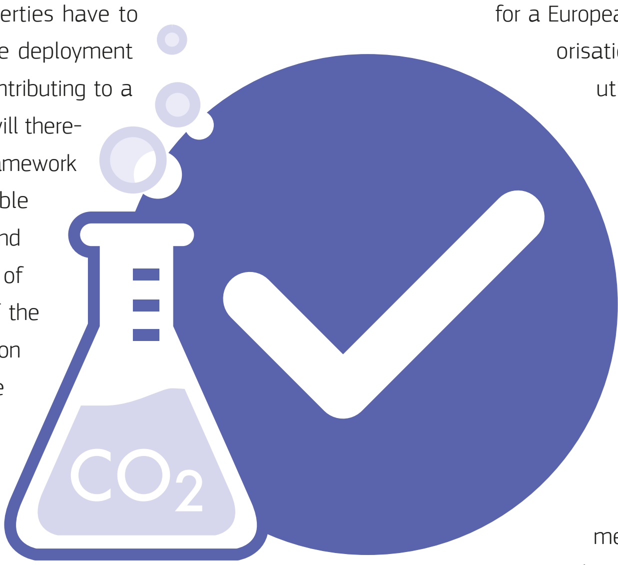
The utilisation of sustainable alternative raw materials by the chemical industry can complement the energy and resource efficiency of chemical processes and contribute to the development of a low-carbon economy. CO_2 is available in abundance in Europe and can be considered as an alternative source of carbon when processed via innovative CO_2 conversion technologies that make it possible to recycle carbon from industrial flue gases. The positive environmental impact of the chemical valorisation of CO_2 is not only determined by the quantity of CO_2 used, but also - and even more-so - by the CO_2 emissions which are avoided by replacing fossil feedstock by this new alternative feedstock. Innovative CO_2 conversion technologies can therefore contribute to reducing the use of fossil carbon sources and import dependency, as well as relieving pressure on biomass, land use and other environmental stressors.

CO_2 conversion also has the potential to increase the share of energy produced from renewable sources via improved management of renewable electricity with large scale chemical energy storage using Power to X technologies. These processes enable the production of methane that can be injected into the existing gas network, in addition to other energy carriers such as methanol. Moreover, CO_2 conversion technologies can provide solutions for the decarbonisation of the transport sector via the production of advanced sustainable alternative fuels (e.g. methanol, gasoline, diesel, dimethyl ether (DME)) using CO_2 as carbon feedstock.

Chemical utilisation of CO_2 in Europe

Many chemical companies are already working on the development of various CO_2 conversion technologies (e.g. catalysts, membranes, process technologies) at different Technology Readiness Levels for various applications: high added value fine chemicals, polymers, high volume basic chemicals and energy vectors. The competitive access to renewable energy and the development of innovative processes to generate renewable hydrogen at lower cost are key factors for the deployment of some of the CO_2 valorisation routes. The optimisation of the purification of flue gases to provide companies with competitive access to the appropriate quality of CO_2 will also play a role in the economic viability of the technologies.

The utilisation of CO_2 as an alternative feedstock would be a major technological transition for the chemical industry and would entail significant investments. These new clean technologies have to compete against established processes which have achieved a high degree of efficiency and competitiveness, and some sustainable materials with new properties have to overcome market penetration. The deployment of CO_2 conversion technologies contributing to a low-carbon and circular economy will therefore require an adequate policy framework (regulation including the Renewable Energy Directive, standardisation and labelling systems) with recognition of the environmental added value of the chemical valorisation of CO_2 based on a consistent approach to life cycle assessment.



Many specific activities related to CO_2 utilisation have already been initiated at national and regional levels in Europe. The conversion of CO_2 is also a priority of SusChem, the European Technology Platform for Sustainable Chemistry. The European Commission is supporting various projects through different funding programmes, and topics addressing CO_2 conversion are included in several work programmes of Horizon 2020 including some SPIRE calls.

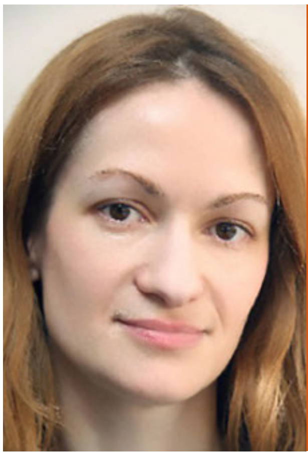
Time for a European integrated approach

However a more coherent and coordinated approach across Europe and across public and private sectors is needed to complement the existing dispersed efforts and create the critical mass and speed needed to compete with other global regions such as the USA and Asia. In this respect, the European chemical industry, together with companies from other industrial sectors, is developing a proposal for a European integrated approach to CO_2 valorisation: Phoenix[1]. Any initiative on the utilisation of CO_2 as a sustainable source of carbon, going beyond a mere financial instrument, should engage and stimulate European investors under a common vision supported by leaders from both public and private sectors to:

- provide appropriate support at European, national and regional levels to ensure development of the various CO_2 conversion technologies up to pilot plant and first-of-a-kind industrial plant;
- ensure coherence and stability over time of the resource and energy policy framework, which will be essential to allow investment in related low-carbon technologies and ensure European leadership in clean processes.

The moment to take action in Europe and for Europe is now.

1. Final report of the High Level Group on Key Enabling Technologies - 24 June 2015
http://ec.europa.eu/growth/industry/key-enabling-technologies/european-strategy/high-level-group/index_en.htm



Sophie Wilmet

Sophie Wilmet joined the Research & Innovation department of the European Chemical Industry Council (Cefic), in 2007. Currently Innovation Manager in charge of enabling technologies, she is responsible for the activities related to CO_2 valorisation. She is a member of the Partnership Board of the PPP SPIRE and is also actively involved in the European Technology Platform for Sustainable Chemistry (SusChem). She graduated as a chemical engineer (ENSCMu) in France and holds a PhD in chemistry.

Dr Aïcha El Khamlichi

from the French Agency for Environment and Energy

TALKS TO SETIS

© iStock/Wavebreakmedia Ltd.

Why is CCU an important technology option for Europe?

A range of technical solutions is required to fight climate change. Among these, the capture and storage of CO_2 (CCS) emissions from fixed sources such as power plants or manufacturing industries could help to achieve emission reduction targets. In addition to CCS, CO_2 can be used as raw material for the synthesis of products with high added value or energy content, or materials. So, carbon capture and utilisation (CCU) technologies make it possible to transform CO_2 into value as new raw materials that could substitute oil in the long term. In Europe, there are many available sources of carbon dioxide: CO_2 capture at industrial emission sources (cement- or oil-based chemical processes, but also at any kind of combustion facility), or emissions coming from power plants, or recovery of CO_2 from the purification process of biogas (from biomass methanisation) or syngas (from biomass gasification). Another important point, CCU could have a positive impact on industrial activity. The deployment of CCU technologies will prevent the shutdown of industrial plants (e.g. through carbon leakage) in France and in Europe by emerging new sectors. In conclusion, CCU will allow us to create value and decrease CO_2 emissions by focusing on CO_2 applications with environmental benefits (using less fossil energy, emitting less CO_2…).

Many see CCU as an enabler to CCS, others as a pathway to new industrial opportunities. What is your opinion?

In my opinion, CCU is a pathway to new industrial opportunities. CO_2 can be used as a carbon source for the synthesis of products such as chemicals, fuels or materials. There are several differences between CCS and CCU. The main differences are the capture technologies and CO_2 volume involved. To use CO_2 as a raw material, we need to improve CO_2 capture technologies for small CO_2 emitters with two main constrains: the small space available for the capture equipment and the low cost. This is why there is the development of CO_2 applications with flue gases or a low level of CO_2 concentration - to decrease the cost of CCU. At the opposite end, CCS requires specific capture technologies for high purity of CO_2 for injection underground. Moreover, the volume of CO_2 is not the same for CCS and CCU. In most of the cases, CCU projects address a diversity of products for different markets, and they cover both niche and mass applications with volumes of CO_2 from thousands to tens or hundreds of thousands of tonnes. So the volume of CO_2 use will always be less than the volume of CO_2 stored where the amount, in most cases, is around 1 million tonnes of CO_2 per plant per year. One proposition is to develop a CCU project with CCS when it is possible. This synergy could make it possible to decrease costs if some of the CO_2 captured is used in CO_2 conversion to produce a high value product.

What are the most promising CCU pathways? What are the main technological barriers to their commercialization?

It is difficult to give an answer to this question. Seen from a climate change point of view, mineral carbonation is a priority target application because the CO_2 is immobilised for a long period just like CO_2 storage. But it is difficult to find profitability; the production price is higher than the market price.

CO_2-based fuels and chemicals are interesting pathways; these could enable the substitution of petroleum based products. But they provide short term CO_2 storage and they emit CO_2 when they are used. The CO_2 avoided is limited. But even for CO_2-based fuels and chemicals, it is difficult for CCU technologies to compete with conventional oil technologies. The economic barrier is the main hurdle for the deployment of CCU technologies. In a recent ADEME study, the main objective was to identify the most promising CCU pathways. Three processes were selected because they were promising: methanol synthesis by direct hydrogenation of CO_2, formic acid synthesis by electro-reduction of CO_2 and sodium carbonate synthesis by aqueous mineralisation. Finally, an environmental assessment showed that, although the CO_2 avoided was limited, each tonne of CO_2-based product produced makes it possible to not emit CO_2. Furthermore, a techno-economic assessment showed that only formic acid could be competitive with petroleum-based products. However, formic acid is a niche application so the market volume is low with a risk of saturation if CO_2 conversion to formic acid is developed. In conclusion, the study confirmed the potential of these three CO_2 chemical conversions.

The main technological barrier is the capture of CO_2. At the moment, it is extremely expensive. The deployment of CCU technologies implies a portfolio of breakthrough capture technologies. Also, another challenge is to work with the flue gas stream directly to transform CO_2 into products. The direct use of the CO_2 from flue gas, with minimal treatment, to be used locally where emitted, will make it possible to improve the energy efficiency of the process and limit utilisation costs.

How is research and innovation in CCU supported in France?

There are several programs to support CCU technologies from research to development and demonstration. Since 2010, several research and innovation programs have supported CCU projects with wide applications: chemical conversion to produce chemical products such as methanol, formic acid or calcium carbonate, or capture and purification of CO_2 for direct commercialisation, or methanisation in Power to Gas projects.

At the research programs level, CCU is included in the decarbonised energy program of ANR (French National Research Agency). For example, there was the Vitesse2 project on the production of methanol from CO_2 and hydrogen (produced by electrolysis of water and decarbonised electricity). Also, in the innovation programs of ADEME (French Agency of Environment and Management of Energy), CCU appears in several programmes dealing with different themes. For example, the utilisation of captured CO_2 for algae growth is included in the biomass technologies program. In 2015, two projects on the production of algae from flue gases were supported. For one project, the aim is to develop a system of algae production by directly injecting flue gases from the cement production process. Then the algae biomass will be transformed into a high-value product. For the other project, the aim is to try different flue gases from industrial processes. There are also several projects at demonstration scale on Power to Gas or chemical conversion of CO_2 supported by the French government through its Investments for the Future programme.

What have been the most significant achievements of CCU research to date?

CCU could be used to achieve several goals. One of them is to substitute chemical products based on petroleum. CCU technologies could also bring other benefits. In electricity systems for example, an increase in the supply of fluctuating renewable energy sources

© iStock/FeelPic

(wind and photovoltaics principally) implies more and more time periods during which production will exceed consumption. Research on technological solutions is in progress (curtailment, storage of electricity, etc.). One of these is Power to Gas: the conversion of electrical energy into chemical energy in the form of hydrogen gas (H_2) or methane (CH_4). This technology is a solution that gives value to these surpluses. The gas produced can be used in different ways, for example by manufacturers for their own process needs or it can be injected into gas distribution or transmission networks or stored locally for later conversion back into power. Power to Gas provides a new way to create added-value from power surpluses. The production of liquids from CO_2, electricity and hydrogen is currently being developed and it is known as Power to Liquids or Power to X. For example, CRI (Carbon Recycling International) produces methanol from carbon dioxide (from a geothermal power plant), hydrogen, and electricity.

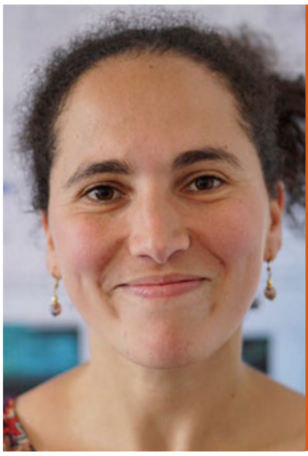
In France, also, several Power to Gas and Power to Liquid projects are under development. Currently, there is a call for projects, in Investment for the Future, on Power to Gas and Power to X at demonstrator scale.

How can policy and regulation support CCU?

CO_2-based products produced with captured CO_2 are much more expensive than traditional chemical synthesis routes so it is difficult to compete with conventional oil technologies. CCU technologies need support through a regulatory framework and a long-term policy (>20 years). There is the emissions trading system (ETS) market, but CCU is not part of this market, so this mechanism could be an obstacle to development for CCU technologies. For example, an industry with CO_2 emissions that wants to decrease GHG emissions by using a CO_2 conversion solution would not be eligible. So, it is necessary to effectively implement a mechanism for setting the price of CO_2 (carbon market, tax, etc.) and for which the CO_2 conversion solutions would be eligible. Since CO_2 is not stored permanently in most cases, the mechanism would require further study to take this into account. For CCU, it is necessary to calculate the CO_2 avoided rather than the CO_2 used in the process. A life cycle analysis could help to develop CO_2 technologies with environmental benefits. So the creation of a label certifying that the CO_2-based products are produced with better environmental benefits than the traditional routes would support the development of CCU.

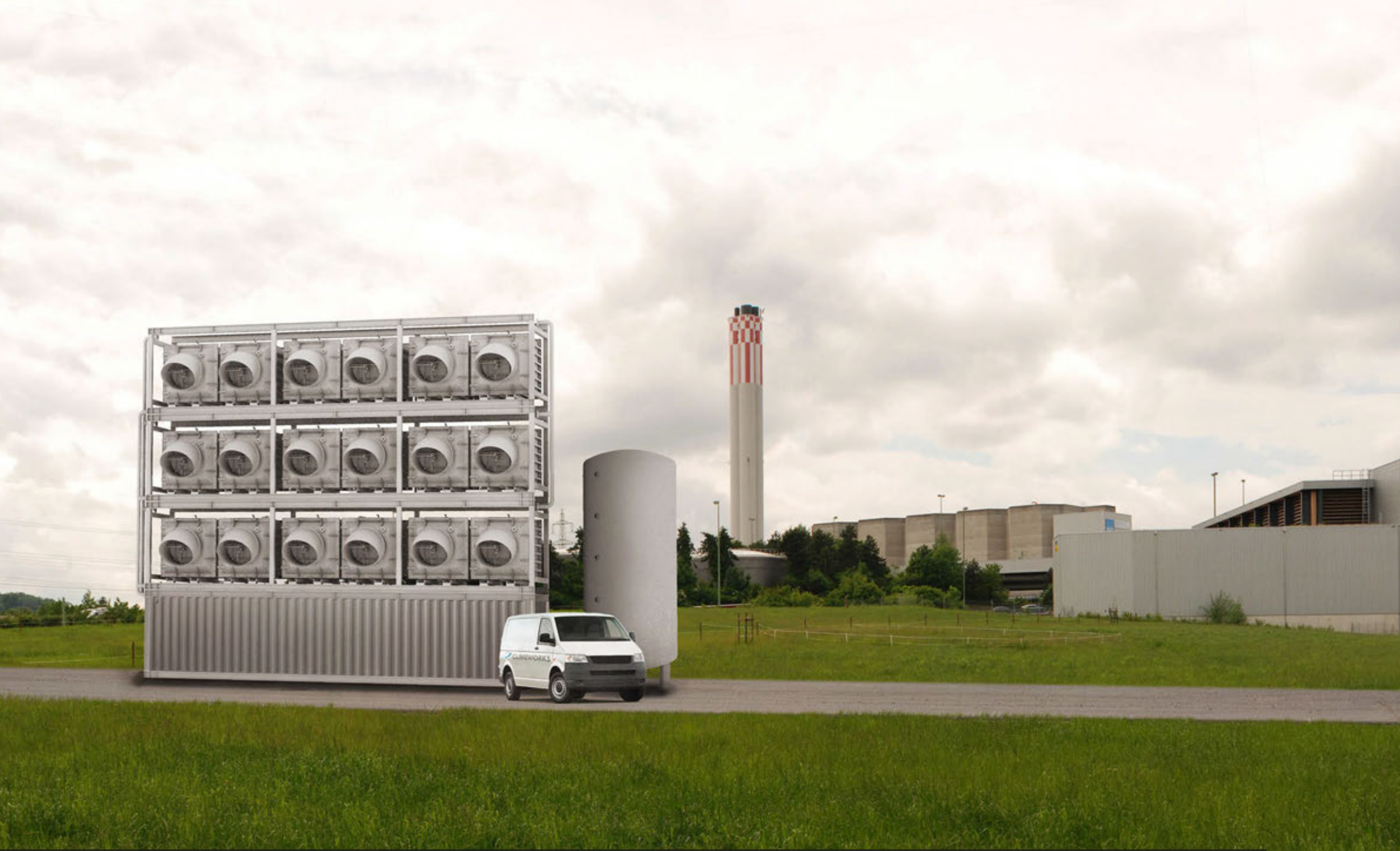
How does progress with the development of CCU in Europe compare with the rest of the world?

In Europe, several countries are working on CCU technologies, such as Germany, the UK, France, Italy... but they are not all at the same stage of development. Germany set up a dedicated program on Chemical Processes and Use of CO_2 included in its Technologies for Sustainability and Climate Protection Programme. This programme supported projects on chemical conversion (production of CO_2-based polymers). Also, a program on Sustainable Energy supported several Power to Gas projects. So Germany has made a lot of progress with the development of CCU. In spite of these advances, when compared with the rest of the world Europe is behind the United States, Japan and China. China and the United States are the first countries in terms of articles published on CO_2 utilisation technologies followed by Germany and Italy. In the ADEME study mentioned above, a review of international projects on CCU showed that the most advanced CCU technologies (at demonstrator scale or commercial units) were in the United States. This can be explained by the strong support from the US Department of Energy for CCU technologies. There are exceptions in Europe, when conditions are in place for the emergence of a particular CCU technology. For example, in Iceland CRI produces methanol from carbon dioxide (from a geothermal power plant), hydrogen, and electricity and it is profitable because the methanol is recognised as renewable.



Aïcha El Khamlichi

Aïcha El Khamlichi works for ADEME (the French Agency for Environment and Energy) as an engineer specialised in capture, use and storage of CO_2. In particular, she leads several studies on CO_2 conversion by chemical or biological transformation. Aïcha received a PhD in chemistry from the University of Rennes in 2010 after graduating from ENSCR Rennes as a chemical engineer in 2007.



CO_2 as a raw material for waxes and fuels

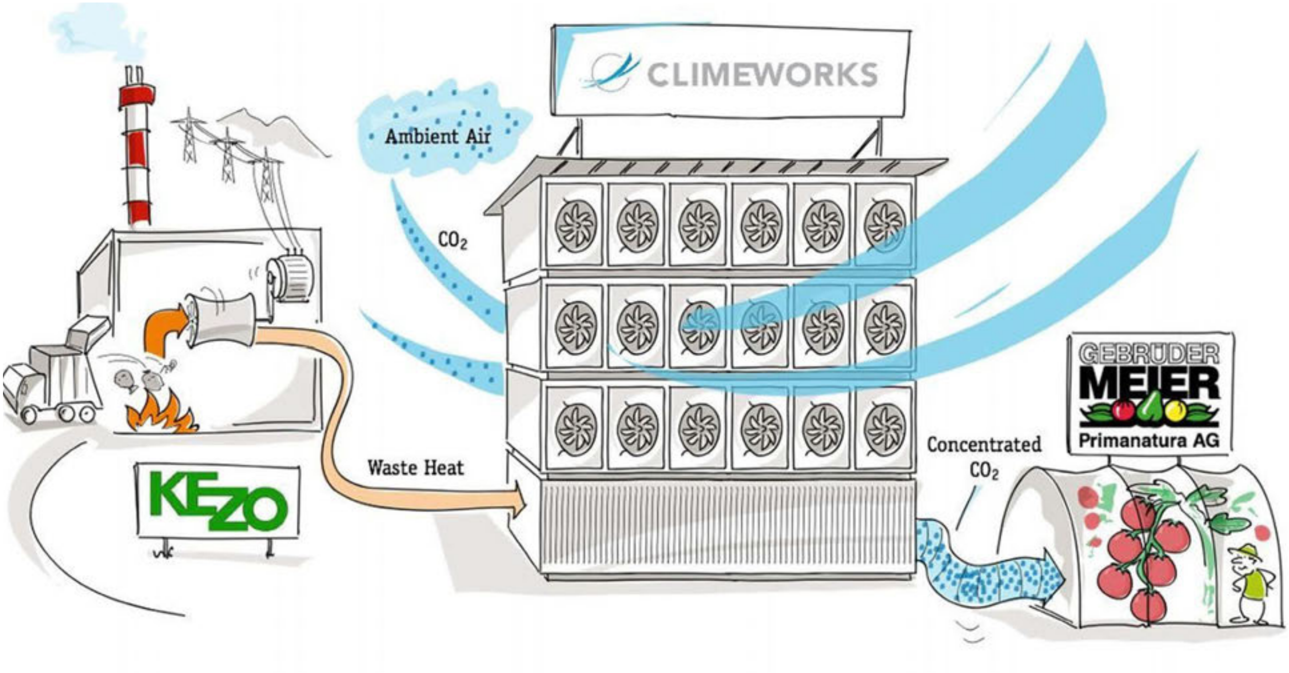
© sunfire

Intelligent processes now enable the capture and conversion of atmospheric CO_2 into environmentally friendly fuels. Cleantech firms Climeworks and sunfire have developed complementary technologies which facilitate both the effective filtering of CO_2 out of the air and highly efficient hydrogen production. When carbon monoxide and hydrogen are mixed at 900 degrees Celsius they react to form synthesis gas – the basis for all long-chain hydrocarbons.

The Direct Air Capture (DAC) technology developed by the Zurich-based firm Climeworks AG over the last five years filters CO_2 directly out of ambient air. It is based on a cycle of filtering and regeneration using a special solid filter material designed by Climeworks in cooperation with the EMAP research institute. The first step sees amines form a chemical bond with the CO_2 and deposit themselves on the surface of the filter.

Once the filter is saturated it is heated to a temperature of approx. 100 degrees Celsius and releases CO_2 with a high level of purity (99.9 per cent). The use of low-temperature heat is one of the key advantages of DAC technology and contributes to the profitability thereof. Whereas comparable techniques require the input of heat at a temperature of 800 degrees Celsius, the DAC technology developed by Climeworks sources around 90 of the energy required in the form of low-temperature heat.

Climeworks CO_2 collectors filter 135 kilograms of CO_2 per day and 50 tonnes of CO_2 per year out of ambient air and can be installed in series in order to increase overall capacity where required. By way of comparison a car emits 150 grams of CO_2 per kilometre and clocks up an average of approx. 15 000 kilometres per year. A single CO_2 collector therefore offsets the CO_2 emissions of 22 cars. The firm's first industrial-scale CO_2 filtering plant is set to be built in Switzerland in 2016 and will filter out an annual total of 900 tonnes of carbon dioxide which will be supplied to a nearby commercial greenhouse. The plant will consist of 18 CO_2 collectors housed in three 40-foot containers. Climeworks will apply the insights gained during the project to the refinement of its products with the aim of using CO_2 captured from ambient air for the production of synthetic fuels.



© sunfire

Complementary technology: High-temperature electrolysis from sunfire

This is where a partner such as sunfire comes in. The Dresden-based cleantech firm's fuel synthesis technology is based on high-temperature steam electrolysis and can be reversed for the purposes of electricity generation. This reversible solid oxide cell (RSOC) technology is the first step in a Power to X process which continues with the production of synthesis gas which is then converted into long-chain hydrocarbons. End products include synthetic fuels such as gasoline, diesel and kerosene as well as waxes for the chemicals industry.

High-temperature electrolysis is a highly beneficial part of this process for a number of reasons. On the one hand it works at high pressure (> 10 bar) and at high temperature (> 800 degrees Celsius). On the other it splits gaseous water (i.e. steam) rather than liquid water into its constituent parts (oxygen and hydrogen). This is achieved at 90 per cent efficiency (in terms of calorific value). In contrast with other established electrolysis techniques (e.g. PEM or alkaline electrolysis) steam can be produced using waste heat from subsequent steps (enthalpy of reaction).

Another special feature of high-temperature electrolysis is the fact that the process extracts oxygen molecules rather than hydrogen molecules. This is of key significance as it also allows the Power to X process to be used to reduce the CO_2 produced during steam electrolysis to carbon monoxide (CO) ready for synthesis (reverse water-gas shift reaction). The subsequent introduction of hydrogen yields a synthesis gas (CO and H_2) which provides a basis for all long-chain hydrocarbons.

The synthesis gas can be converted into gasoline, diesel, kerosene and other raw products for the chemicals industry (-CH2-). Synthesis releases heat which is in turn used to vaporize water for the purposes of steam electrolysis. This makes it possible to achieve a high level of efficiency of around 70 per cent. sunfire has already successfully produced long-chain hydrocarbons using an industrial demonstration rig at its headquarters in Dresden, and in April 2015 Federal Minister of Education and Research Dr Johanna Wanka filled up her car with the first litres of synthetic diesel produced. The CO_2 required can be captured directly from ambient air using the DAC technology developed by Climeworks, precipitated from biogas plants or extracted from other processes which give off waste gas.

The sunfire process is based on refined versions of both high-temperature steam electrolysis using solid oxide electrolysis cells (SOEC) and the water-gas shift reaction (the second step in the Power to Liquids process chain). What is more, sunfire is a true pioneer in the combination of these technologies with Fisher-Tropsch synthesis. This third step in the process is by far the most well-known element of synthetic fuel production, yet in many cases – for example in South Africa – Fischer-Tropsch synthesis is carried out using fossil fuels rather than CO_2, water and green energy.

Environmental balance sheet and CO_2 utilisation

The use of CO_2 for the production of green hydrogen, waxes for the chemicals industry or synthetic fuels is accompanied by substantial environmental benefits. Even when used in combustion engines, synthetic fuel is at the very least carbon neutral. What is more, the use of wind power reduces direct emissions (i.e. the emissions caused as a result of rig operation) to zero – the “raw material” is nothing more than wind. The sunfire process therefore represents a fully closed carbon cycle as found in nature. CO_2 is first extracted from ambient air using a Climeworks DAC unit. The sunfire rig then uses that CO_2 to produce synthetic diesel which can be used to fuel combustion engines. The accompanying CO_2 emissions equal the amount of CO_2 extracted from the atmosphere and used to produce the fuel itself.

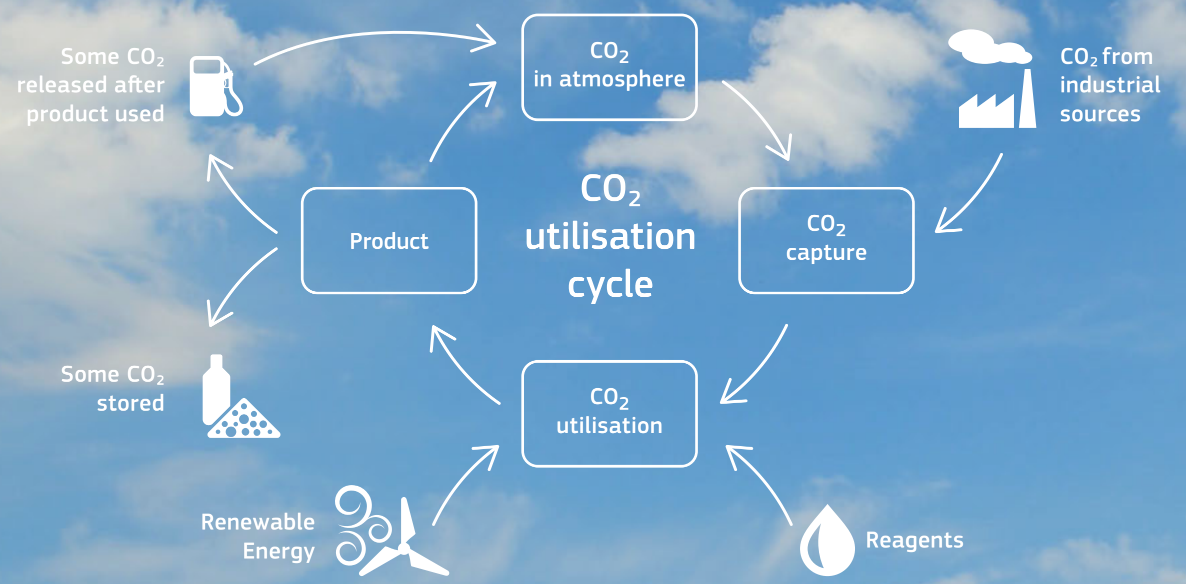
The main benefit is that the production of sunfire diesel requires exactly the same amount of CO_2 as is emitted from the vehicle exhaust after combustion. This means that fuel production and combustion form a closed CO_2 cycle. Total emissions (i.e. direct emissions from the combustion engine and indirect emissions attributable to rig production) have been determined with the aid of well-to-wheel analysis. The CO_2 released by the combustion of synthetic diesel in an engine was found to equal the exact amount of CO_2 extracted from ambient air for the purposes of fuel production. This essentially represents the closure of the carbon cycle and the achievement of CO_2-neutral mobility. If all related emissions are factored in – including the construction and operation of the sunfire rig – total emissions from a vehicle run on synthetic diesel stand at less than 30 g/km (well-to-wheel). If fuel production is taken into account this represents a 70 % reduction when compared with vehicles run on fossil fuels.

The next step in the commercialization of sunfire’s technology is the realization of various projects. To give an example the next few months are set to see Boeing become the first partner to use sunfire’s RSOCs in the USA, with the two firms cooperating on the further development of the technology. Even once all technical aspects have been finalized the commercialization of the overall process will nevertheless still be dependent on political factors.

Since mid-2015, electricity-based fuels from non-biogenic sources have been included in legislation for the first time. More specifically they are now taken into account in the EU’s Renewable Energy Directive and Fuel Quality Directive as well as the German Federal Immission [sic] Control Act. The aforementioned EU directives have nevertheless yet to be adopted into national law. In Germany, a move by the Upper House to ensure the rapid, comprehensive implementation of those directives would be welcome. Switzerland is already a step ahead in this regard, yet even there the majority of investors are waiting to see what form national laws will take. With this in mind the legislative context is set to continue to play a decisive role in the further progress of Power to Liquids technology as it moves towards commercialization.

Martin Jendrischik

Martin is a senior PR consultant and CEO of Cleantech Media. Additionally, he writes as chief editor for the online-magazine cleanthinking.de. As a qualified and experienced journalist he supports start-up companies from the cleantech sector with strategic public relations solutions. Martin has been living and working in Leipzig, Germany, since 2006.



Peter Styring

Director of the UK Centre for Carbon Dioxide Utilisation **TALKS TO SETIS**

© co2chem

Why is CCU an important technology option for Europe?

Carbon dioxide is an under-exploited resource that we really should use to produce value added materials - materials that can replace fossil oil as a petrochemical feedstock. We have emissions from power stations and industrial factories. We also have atmospheric CO_2 that we need to reduce the concentration of to avoid catastrophic climate change. We have to remove CO_2 from the environment so why not incorporate it into new molecules rather than relying on geological landfill. So, CCU can add to the European economy, providing economic growth while also having an environmental impact. We need to move away from considering CO_2 as a waste to looking at it rather as an important carbon feedstock or resource.

Many see CCU as an enabler to CCS, others as a pathway to new industrial opportunities. What is your opinion?

I see both sides of the issue. CCU will enable CCS by footing the bill. CCS is a waste disposal technology. CCU is a renewable commodity-based technology. I see the two technologies not as enemies but as siblings. There will always be rivalry but they must coexist. However, CCU has the capacity to use CO_2 emissions in stranded locations, where there is no opportunity for geological storage. That said, CCU should only be considered as an enabling technology if it results in at least a carbon neutral process and should ideally be carbon negative. In order to do this we need to look at the life cycle assessment across the whole process. Many have used CO_2 as a working fluid for enhanced oil recovery. However this should not be considered to be CCU as the cradle to grave LCA shows that more CO_2 is emitted over the process than is sequestered.

What are the most promising CCU pathways?

There are several. Power to X (PtoX) is gaining momentum as it helps in the creation of a circular economy. Diesel produced using this technology is cleaner than conventional fossil oil fuel. It uses captured CO_2 and so displaces fossil carbon. In terms of volume, kerosene has to be the major fuel target. Synthetic jet fuels, even if it is just a few percent of additive in conventional jet fuels, will have a considerable impact. Accelerated mineralisation is also a major target with a potentially large impact.

How is research and innovation in CCU supported in the UK?

This is an interesting point. The majority of funding still goes to CCS. However, the tide appears to be turning, albeit slowly. The Engineering and Physical Sciences Research Council (EPSRC) funded the CO2Chem Grand Challenge Network in 2010 and it is still going strong with over 1 000 members worldwide, the biggest global network. They have also funded the 4CU programme with £4.5 million (EUR 6.3 million) over four and a half years.

What have been the most significant achievements of CCU research to date?

There is huge interest in fundamental research which is of course essential to the development of the field. However, the real innovations have been where that fundamental research has been translated to commercial or near commercial activity. I would say there was not one significant achievement but three:

- Power to X (PtoX) where renewable electric power is converted to synthetic fuels, either liquids or gases. This is exemplified by the technology developed by companies like sunfire in Germany or CRI in Iceland.
- CO_2-containing polymers such as polyurethane polyols developed by Covestro (formerly Bayer Materials Science) and polycarbonates developed by Novomer in the US.
- Accelerated mineralisation, such as the conversion of waste residues into construction materials, such as the building blocks and aggregates developed by Carbon8 in the UK.

How can policy and regulation support CCU?

For policy to be effective, governments need to recognise the importance of CCU. Not just to the environment but to the economy. Governments need to see CO_2 as a commodity chemical feedstock and not a waste. Waste materials cost to have them remediated. They can never make a positive contribution to the national or global economy. By treating CO_2 as a commodity we generate products that have market value and so contribute profitability to the economy. On its own, this would be an excellent scenario. However, we will still need it to run alongside waste remediation technologies such as CCS, so CCU can be seen as a technology that will allow the economic bill to be offset. Policy and regulation need to be informed by expert scientific evidence. However, economics in the short term tend to dominate policy setting. If we look to a 2050 vision, that is 35 years in the future. In stable political regions this is typically seven changes in administration. Therefore, any long-term visions need to take a cross-party approach, which is difficult if not impossible at the best of times.

One thing that is essential is that there is a global carbon price. Much of current economic scenario setting has CO_2 cost as an unknown and unstable variable. Furthermore, if CCU is to operate successfully it must be on a level playing field with regards to subsidies. Vast subsidies are given to the oil and gas industries. The same is true for CCS projects, yet CCU does not attract subsidies. If CCU is to be competitive it needs to attract comparable subsidies, or each technology is forced to operate unsubsidised.

How does progress with the development of CCU in Europe compare with the rest of the world?

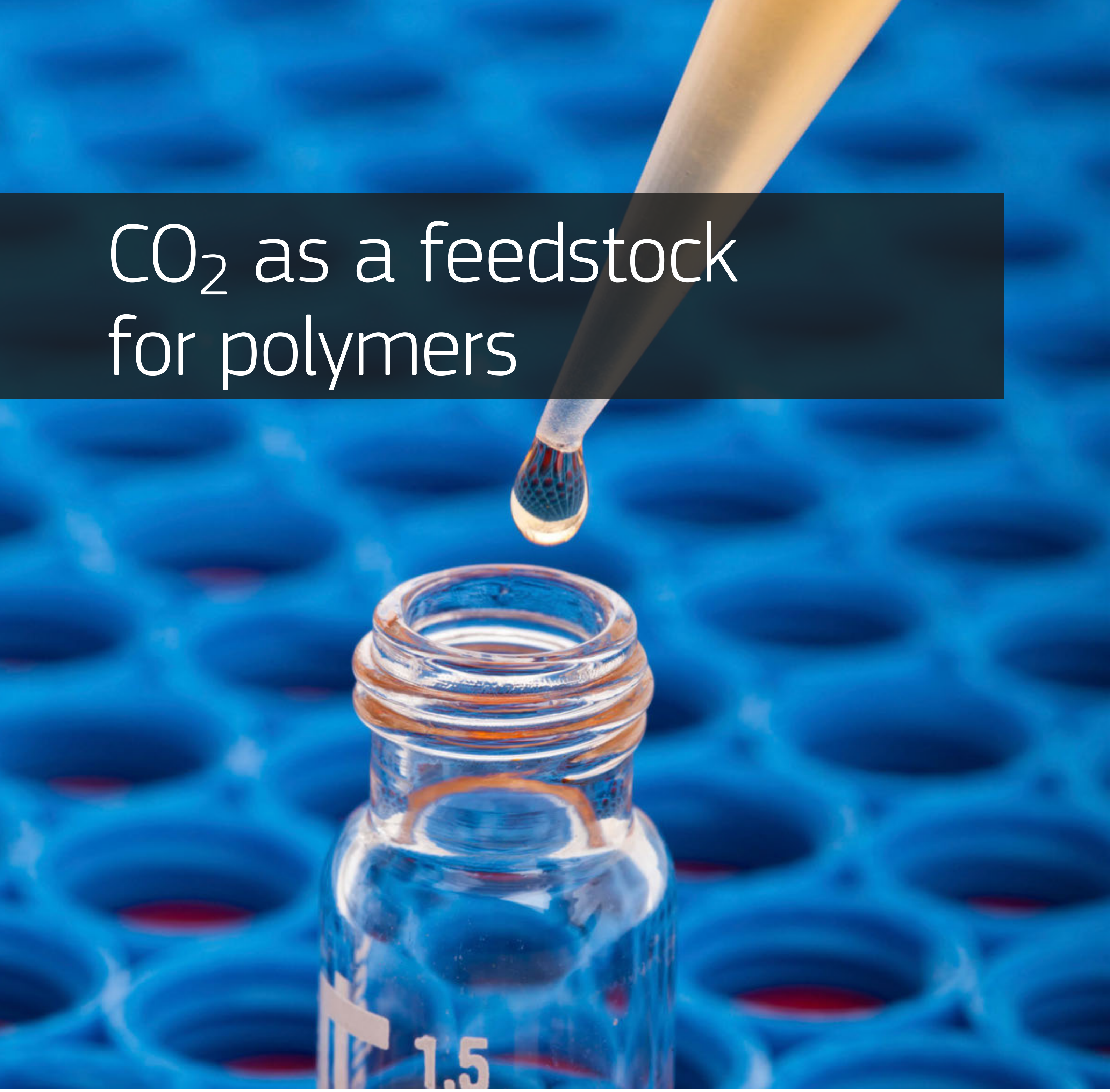
It is interesting to compare Europe as a whole or even individual member states against the rest of the world. The last International Conference on Carbon Dioxide Utilisation in Singapore (2015) had delegates from 32 different nations. The highest number was from China, then Singapore and South Korea. The UK was the fourth most represented nation with Germany seventh. However, if we combine all European Member States then the EU was by far the strongest representation. Germany is the most advanced Member State in terms of commercialisation, a result of a strong science and engineering base and an innovative funding strategy by the Federal Ministry of Education and Research (BMBF). The UK is also strong in this area although public funds are limited in comparison. While the US appears to be strong in CCU this has to be tempered by the fact that much of this is focuses on enhanced oil and gas recovery which adds new fossil carbon to the supply chain. CCU works best by removing fossil carbon from the system.

So the conclusion is that Europe is strong on the global stage, possibly the strongest. However, we need to build on this success to maintain a market lead. To achieve this we need engineers, scientists, economists and policy-makers working together to achieve European excellence and competitiveness. This places obligations at a European level but also, importantly, at Member State and regional level. Europe has a unique opportunity in CCU and we need to all work together as it will increase profitability while reducing fossil carbon from the environment while at the same time reducing greenhouse gas emissions and securing energy, chemicals and building materials supply throughout the years.

Professor Peter Styring

Peter Styring is Professor of Chemical Engineering & Chemistry at the University of Sheffield and Director of the UK Centre for Carbon Dioxide Utilisation. Peter is also Director of the CO_2Chem Network, one of the Engineering and Physical Sciences Research Council's (EPSRC) Grand Challenges in the Physical Sciences. He is co-author of the influential book "Carbon Capture and Utilisation in the Green Economy" and the Elsevier textbook "Carbon Dioxide Utilisation: closing the carbon cycle".

CO_2 as a feedstock for polymers



© iStock/nikesidoroff

Global CO_2 emissions are steadily rising rather than falling. Steps taken to date to curb emissions have clearly been inadequate. A contribution could be made by the chemical industry by using CO_2 as a new building block for high-value plastics. Doing so would both conserve fossil resources and help the climate.

Over 30 billion metric tonnes of CO_2 from buildings, cars, factories and other sources are released into the atmosphere worldwide year after year. Most experts, including the Intergovernmental Panel on Climate Change (IPCC), agree that this adds to the natural greenhouse effect. This results in long-term climate change, with increasing temperatures, melting ice and rising sea levels.

The top priority is therefore to avoid CO_2 emissions – primarily by expanding renewable energies, cutting energy consumption and improving energy efficiency. Energy utilities are also working on separating off the CO_2 generated by power plants and storing it permanently underground, a technology known as Carbon Capture and Storage (CCS).

A third option is also growing in importance – increased recycling of CO_2 as a raw material, which the experts call Carbon Capture and Usage (CCU) or Carbon Capture and Reuse (CCR). This is a focus of governmental funding programs.

CO_2 as a supplier of carbon

In times of fuel scarcity and the above mentioned funding programs, people are becoming more and more aware that CO_2 is much too valuable to just be released into the atmosphere and thus worsen the greenhouse effect. The gas contains something quite valuable: the element carbon, the foundation of all life and an important building block for the chemical industry.

Of course, we have been using CO_2 for a long time. As an industrial gas, CO_2 provides the carbonic acid in sparkling water, is used in fire extinguishers and also serves as a coolant. In addition, it has been traditionally used as a synthetic building block in chemical reactions to make products such as fertilisers and drugs.

Substitute for petroleum

But now there is another new and promising possibility: manufacturing plastics by using CO_2. Up to now plastics have been based primarily on petrochemical raw materials, meaning - essentially - petroleum. However, unlike CO_2, this important carbon source has only limited availability. Furthermore, processing petroleum into chemical precursors consumes a tremendous amount of energy, leading to further CO_2 emissions. The chemical industry has already made a lot of progress in implementing CO_2 as a new raw material.

Using CO_2 to manufacture plastics benefits the environment in two ways: firstly, CO_2 is directly incorporated into polymers and partially substitutes oil as a raw material. Secondly, the amount of emitted CO_2 during the manufacturing process is reduced by optimised, more environmentally-friendly processes compared to the established processes.

Naturally, this alone will not be enough to mitigate climate change. The demand for CO_2 for plastics and other chemical products is much too low. Some years ago, this was estimated at 180 million metric tonnes a year, which then would have been equivalent to no more than 0.6 percent of current global CO_2 emissions. However, a number of small steps together can add up to a great leap in progress.

Catalysis as the key

Why has CO_2 not been used before as a polymer building block? While there were certainly many ideas on how to create valuable materials out of the waste product CO_2, one problem remained: the low energetic level of CO_2. No matter what products one is aiming for, it always takes huge amounts of energy to enable a reaction with CO_2. Typically, this low reactivity of CO_2 can be overcome by high-energy reaction partners. When evaluating the overall energy balance and efficiency of the process, the energy used to generate these high-energy materials has to be taken into account. For these reasons, only very few reactions using CO_2 were suitably efficient to be used in practice for a long time. Therefore, the proper chemical utilisation of CO_2 became known as the “Dream Reaction”.

Moreover, the low energetic state of CO_2 often leads to a low energetic driving force of the reaction, low yields and low selectivity. One way to tackle these challenges is catalysis, a core technology for the successful and economically interesting use of CO_2 as a chemical feedstock, and still one of the most sophisticated and complex research areas of modern chemistry. Catalysis is used in the production of more than 85% of all chemical industry products. Although catalysis can lower the activation energy for CO_2 utilisation and improve product yields, the general energy challenge remains: since both CO_2 capture and utilisation usually require substantial energy inputs, the intuitive environmental benefits cannot be taken for granted. Thus, a detailed environmental assessment is required for processes utilising CO_2. For this purpose, life cycle assessment (LCA) provides a sound methodological framework. Specific guidelines for the application of LCA to CO_2 utilisation have recently been developed.

© iStock/diepre

Indirect CO_2 utilisation

While the environmental potential of direct utilisation of CO_2 for polyethercarbonate polyols has been demonstrated, CO_2 can also be utilised indirectly for many intermediates in the chemical supply chain of polyurethanes. For example, it can be converted to methanol and subsequently to formaldehyde and further on to its polymer, polyoxymethylene diol, which also constitutes a potential building block for polyols. Methanol based on CO_2 is the subject of many efforts in the industry, and it is already commercially available. The first material tests are showing encouraging results.

Outlook

In summary, even though the field of research is hardly new, the use of CO_2 as a raw material is still one of the most interesting and visionary technologies for the future. Since fossil resources are finite, using CO_2 as chemical feedstock is a promising approach to global carbon management. LCA investigations show that there is a clear ecological benefit for CO_2-based polymers as compared to conventional ones. This can even be improved by following the approach of the direct and indirect use of CO_2. First pioneer examples already show that the chemical utilisation of CO_2 for the production of polymers on an industrial scale is feasible. But establishing CO_2 as an alternative raw material in the chemical industry is still in its infancy. Future endeavours will demonstrate the potential of the gas and initiate a possible image change from an environmentally harmful greenhouse gas to a useful and sustainable new raw material.

Christoph Gürtler

Christoph Gürtler studied chemistry at the University of Bonn from 1987 to 1993 and obtained his PhD at the Technical University of Berlin in 1996. After a postdoc at the Massachusetts Institute of Technology (MIT) he joined Bayer AG, Central Research department. Dr. Gürtler is currently heading a competence center in the field of process and product development dedicated to new catalytic processes.

Annika Stute

After studying chemistry from 2004 to 2009, Annika Stute received her PhD at the University of Münster in 2013 with internships at the University of York and the University of Calgary. A postdoctoral research project at the University of Bristol followed before she joined Bayer MaterialScience in 2015 (since 9/2015 - Covestro). In her current position she focuses on strategic aspects regarding external cooperation and coordinating externally funded projects in the area of CO_2 utilisation.

ROAD – Rotterdam Capture and Storage Demonstration Project

© iStock/michal kodym

ROAD is the Rotterdam Opslag en Afvang Demonstratieproject (Rotterdam Capture and Storage Demonstration Project) and is one of the largest, integrated Carbon Capture and Storage (CCS) demonstration projects in the world. ROAD is being developed by Maasvlakte CCS Project C.V., a joint venture of E.ON Benelux and ENGIE Energie Nederland (known as GDF SUEZ Energie Nederland N.V. prior to April 2015). ROAD aims to capture CO_2 from the flue gases of Maasvlakte Power Plant 3 (MPP3) using post combustion capture technology. The captured CO_2 will be transported through a pipeline and injected into a depleted gas field under the North Sea.

Project Objectives

The main objective of ROAD is to demonstrate the technical and economic feasibility of a large-scale, integrated CCS chain deployed on power generation. To date, post-combustion CCS has been applied to a 110 MWe facility in Canada in the power industry. Further large-scale demonstration projects are needed to show that CCS is an efficient and effective CO_2 abatement technology.

With the knowledge, experience and innovations gained by projects like ROAD, CCS could be deployed on a larger and broader scale: not only on power plants, but also within energy intensive industries. CCS is one of the transition technologies expected to make a substantial contribution to achieving climate objectives. It should play a pivotal role in all credible scenarios towards a decarbonised energy supply.

The ROAD project is co-financed by the European Commission (EC) within the framework of the European Energy Programme for Recovery (EEPR) and the Government of the Netherlands. The grants amount to EUR 180 million from the EC and EUR 150 million from the government of the Netherlands. In addition, the Global CCS Institute is a knowledge sharing partner of ROAD and has given financial support of AUD$ 6.2 million (EUR 4.1 million) to the project.

Integrated CCS Chain

ROAD applies post combustion technology to capture the CO_2 from the flue gases of a new 1 069 MWe coal-fired power plant (Maasvlakte Power Plant 3, “MPP3”) in the port and industrial area of Rotterdam. The capture unit has a capacity of 250 MWe equivalent. During the demonstration phase of the project, approximately 1.1 megatons of CO_2 per year will be captured from MPP3. The capture installation is planned to be operational in 2019 – three years after the Financial Investment Decision, which has now been rescheduled to Q1/Q2 of 2016.

© iStock/digitalimagination

From the capture unit the CO_2 will be compressed and transported through a pipeline: 5 kilometres over land and about 20 kilometres across the seabed to the P18-A platform in the North Sea. The pipeline has a transport capacity of around 5 million tonnes per year. It is designed for a maximum pressure of 140 bar and a maximum temperature of 80 °C.

ROAD plans to store the captured CO_2 in depleted gas reservoirs under the North Sea. These gas reservoirs are located in block P18 of the Dutch continental shelf, approximately 20 kilometres off the coast. The depleted gas reservoirs (P18-2; P18-4; P18-6) are at a depth of around 3 500 meters under the seabed of the North Sea. In the first phase CO_2 will be injected into depleted gas reservoir P18-4. The estimated storage capacity of reservoir P18-4 is approximately 8 million tonnes.

CCS Demonstration and Knowledge Sharing

ROAD is a CCS demonstration project intended to facilitate the generation and dissemination of new technical, legal, economic, organisational and societal knowledge and experience. ROAD will share this knowledge and experience through the European CCS Demonstration Project Network with governments, companies and knowledge institutions. Furthermore, ROAD has drafted a series of reports for the Global CCS Institute and delivered a large number of presentations and articles for various conferences and publications. In this way, ROAD can make a significant contribution to the commercial introduction of CCS and ultimately to the worldwide reduction of CO_2 emissions.

Project Status Quo

Since the first half of 2012, the ROAD project has been slowed down because of the financial gap caused by structural low carbon prices (EU ETS). Although the project had already made substantial progress and reached several essential milestones (e.g. engineering, permitting, contracting) no Financial Investment Decision (FID) was taken due to a lack of sufficient funding.

Consequently, ROAD decided to review its position, after consulting the EC and in close co-ordination with other key stakeholders. The objective of this review was to find alternative funding sources, improve the project economics and to explore a phased project approach.

This review has resulted in a number of alternative project scenarios. Currently, ROAD is focusing on a scenario that includes an alternative storage location and CO_2 utilisation, and is assessing its feasibility. It is expected that ROAD will finalise these feasibility studies within the coming months.

Dr Andy Read

In Andy's current role, he is one of four directors responsible for the ROAD Project – a 250 MW CCS demonstration in Rotterdam.

For the last five years, Andy has focused on CCS project development, leading projects at Killingholme and Kingsnorth in the UK, and now as Capture Director for the E.ON / GDF SUEZ joint venture at Maasvlakte, Netherlands (ROAD Project). He has previously worked on several new build projects, most notably the early development of the 1 275 MW Grain CHP plant.

Commercial capture and mineralisation of carbon in manufactured aggregates

© iStock/Stefan Laws

The beneficial re-use of discarded materials is an essential part of a circular economy. The recycling of process waste–based products directly into the materials supply chain results in considerable sustainability gains and drives innovation. The process presented here involves the use of both solid and gaseous waste in combination to produce aggregate for use in concrete.

The application of accelerated carbonation technology has enabled Carbon8 to stabilise and solidify industrial residues into hardened manufactured aggregates that are a direct substitute for natural stone (Gunning et al., 2009). In the UK, thermal residues are commercially aggregated by carbonation, and incorporated into concrete construction blocks. The technology has however, wider possibilities (Gunning et al., 2011a, b), as a variety of wastes can be carbonate-cemented into products suitable for a number of engineering applications.

The route to commercialising this innovative use of waste CO_2 involved clearly demonstrating the transition from hazardous waste feedstock to safe usable product. This was both difficult and complex and involved rigorous independent validation before 'end-of-waste' designation by the Environment Agency was possible.

In early 2012, Carbon8 commissioned a bespoke zero-emissions commercial plant in Suffolk, East Anglia, which now produces 60 000 tonnes of manufactured carbonated lightweight aggregate/year (Figure 1). A second plant (100 000 tonnes/year) is nearing completion in Avonmouth (Figure 2), and 3 more UK plants of a similar size or larger, are expected to be operational by 2018.

Figure 1: The Suffolk carbonated aggregates plant

Figure 2: The C8 Avonmouth plant under construction, Summer 2015

Figure 3: Stock-piled carbonated manufactured aggregate at Carbon8's Suffolk plant

Waste is brought to site by powder tanker and is pneumatically conveyed and stored in silos before being delivered into the multi-stage carbonation process. Rainwater is harvested for use in the plant and stored CO_2 (captured and delivered from a local point source) is fed directly into the process in such a way that none is lost to atmosphere. Furthermore, renewable energy is used to power the plant. The Carbon8 process results in a carbon negative manufactured aggregate, as it contains more imbibed carbon than is generated by its production (see Figure 3).

Consequently, the concrete construction blocks incorporating the aggregate can also be carbon negative. Independent block maker Lignacite produces such blocks, under the name 'Carbon Buster' (Figure 4).

In addition to diverting wastes from landfill, the amount of carbon dioxide that can be locked up as carbonate salts i.e. limestone rather than emitted to the atmosphere, is potentially significant. As production increases, Carbon8 will be mineralising tens of thousands of tonnes of CO_2 in its manufactured aggregates in the UK (Figure 5). Worldwide, the potential of common waste streams (Gunning et al., 2010), including: pulverised fuel ash, steel slag and kiln dusts to imbibe CO_2, could amount to hundreds of millions of tonnes.

Legislative and Commercial Challenges

The European waste legislation and its implementation presented numerous challenges to the development and commercialisation of the carbonation process in the UK. At each stage of scaling-up, the support of the regulator was required, and accredited laboratory testing and validation of the aggregates and blocks to European Standards was necessary.

In accordance with waste legislation, it was necessary to demonstrate that (a) the aggregate did not pose an environmental risk, (b) had a clear end use and (c) was a suitable replacement for natural aggregate. The submission was fully supported by third party accredited testing of the physical and chemical properties of the aggregate product and the resulting concrete blocks (to BS EN 771), so a clear end use for the material and confirmation that there were no detrimental effects were demonstrated. Thus, by working closely with the Environment Agency, 'End of Waste' for the aggregate was achieved and a commercial plant was permitted and was operational in 2012.

Figure 4: 'Carbon Buster' blocks containing C8A.

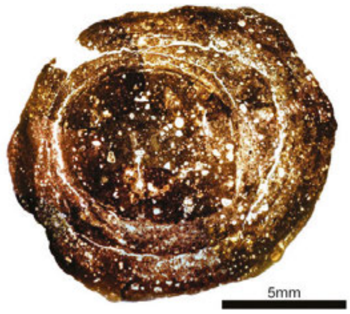


Figure 5: A micrograph showing an example of carbonated manufactured aggregate displaying concentric layers of carbonate forming the hardened product (transmitted polarised light)

Despite satisfying the considerable demands to achieve 'End of Waste' in the UK, this still presents a challenge elsewhere in Europe, as the Waste Framework Directive (2 000) is interpreted very differently in different Member States, e.g. France and Norway. The lack of a route to achieve product status is a significant barrier to the commercial development of innovative technologies and undermines the potential of this technology to contribute to Europe's objective for the development of a Circular Economy.

Quality assurance of carbonated products

The carbonation process operated by Carbon8 utilises a strict quality system in compliance with ISO14001, OHSAS18001 and ISO9001. Daily checks on the physical and chemical properties of the incoming waste and outgoing aggregate product are carried out to ensure that the latter meets the agreed specification set out in the 'End of Waste' documentation.

The future

The Carbon8 process in Suffolk relies upon CO_2 that is captured from the production of bio-ethanol. The CO_2 is delivered by tanker from a short distance away, but it remains an expensive product due to its purity and this currently limits what wastes can be processed economically.

As CO_2 use gains a value, it is likely that Carbon8 will sequestrate more of this gas in its products whilst also increasing the number of wastes it can treat. This shift will also facilitate the direct capture of CO_2 from point sources, as has been shown is technically possible during trials at a landfill site and cement plant. Apart from making the aggregated product more carbon negative by increasing the amount of CO_2 that is mineralised, the option to capture more significant amounts of CO_2 from small and medium-sized emitters (that fall outside the scope for CCS) then becomes a possibility.

As the greater possibilities for carbonated products and their application become more obvious, and the economics of using waste CO_2 as a feedstock improve, a new industry based upon carbonation engineering is a realistic outcome. However, for new mineralised products and processes to become available to the market a level regulatory 'playing field' is also required. Only then will Europe's current lead in this area be fully consolidated.

References

Gunning, P.J., Hills, C.D., Carey, P.J. (2009). Production of lightweight aggregate from industrial waste and carbon dioxide. Waste Management, 29, 2722–2728

Gunning, P.J., Hills, C.D. and Carey, P.J. (2010). Accelerated carbonation treatment of industrial wastes. Waste Management, 30, 1081–1090.

Gunning, P.J., Antemir, A., Hills, C.D., Carey, P.J. (2011a). Secondary aggregate from waste treated with carbon dioxide. Proceedings of the Institution of Civil Engineers: Construction Materials, 164, 231-239.

Gunning, P.J., Hills, C.D., Carey, P.J., Antemir, A. (2011b). Novel approaches to the valorisation of ashes using aggregation by carbonation. In: Proceedings of the 2nd International Slag Valorisation Symposium, Leuven, Belgium.

Waste Framework Directive http://ec.europa.eu/environment/waste/framework/list.htm. Accessed 25.09.2015.

Professor Colin Hills

Professor Hills has an extensive research and publishing record on the encapsulation of waste and soil, including innovative treatments of waste via mineralisation by accelerated carbonation. He has contributed to The Carbon Sequestration Leadership Forum's Carbon Dioxide Capture, Utilisation and Sequestration Technical Working Group Report and is currently a Lead Author on the UNEP Report GEO6 (Climate Change and Chemicals and Waste) and is an expert advisor to the FP7 project Smart CO_2 Transformation (SCOT), which is developing the European roadmap for CO_2 utilisation.

Moving CO_2 from source to storage

© iStock/ssuaphoto

Carbon capture and storage (CCS) in geological formations is a promising tool for reducing carbon dioxide (CO_2) emissions to the atmosphere. As the name suggests, there are two core processes involved here - the capture of carbon dioxide at its source, and its subsequent storage in such a way as to prevent its entry into the atmosphere. However, there is a vital link connecting these two elements - transportation. If CCS is to become a viable option for low-carbon power generation, its deployment will require the construction of dedicated CO_2 transport infrastructure in Europe (JRC 2014)[2]. While considerable research effort has been focused on capture and storage, relatively little has been directed towards filling the knowledge gaps in CO_2 handling and transportation in a safe and economically efficient manner from generation point to storage site.

CO_2 pipelines have been in operation in the US, Europe and North Africa since the 1980s – transporting pure CO_2 for enhanced hydrocarbon recovery. However, due to the effects of the various impurities contained in flue gases, it cannot be assumed that knowledge and experience regarding the transportation of pure CO_2 can be transferred to the design challenges presented by the transportation of anthropogenic CO_2 mixtures (Spinelli, 2011)[3]. Consequently, dedicated research into the transport of CO_2 from flue gases is required. In addition to research into the infrastructure needs for the safe transportation of CO_2, there are also financial, legal, environmental and societal acceptance hurdles that need to be evaluated and overcome to ensure that an optimal solution for the transportation of CO_2 is achieved.

It was to address these and other challenges that the CO_2Europipe project - 'Towards a transport infrastructure for large-scale CCS in Europe' - was set up in 2009. The aim of the project, which was completed in 2011, was to define the optimal path towards a large-scale CO_2 transport infrastructure for Europe. To achieve this, it aimed to describe the infrastructure required for large-scale transport of CO_2, while taking into consideration the options for re-use of existing natural gas infrastructure that is expected to be slowly phased out in the coming decades. The project also aimed to provide advice on how to remove any organisational and other hurdles to the realisation of large-scale CO_2 infrastructure, and develop a business case for a series of realistic scenarios to study both initial CCS projects and their coalescence into larger-scale CCS infrastructure. Finally, the project aimed to demonstrate the need for international cooperation on CCS and summarise all findings in terms of actions to be taken by the EU and national governments to facilitate and optimise the development of large-scale CCS infrastructure.

To begin with, the project conducted an evaluation of existing infrastructure and standards, regulations and modes of practice to ascertain to what extent CO_2 transport can benefit from them. It was concluded that, in principle, existing pipelines could be used to transport CO_2, but that most of these pipelines would be given over to the transportation of natural gas for years to come and would not be available for CO_2 transport. Furthermore, when they do become available, in most cases they will have a pressure rating too low to accommodate dense phase CO_2 transport, which means that

2. https://ec.europa.eu/jrc/en/publication/articles-journals/international-transport-captured-co2-who-can-gain-and-how-much
3. http://www.pipeline-conference.com/sites/default/files/papers/Spinelli.pdf

they are not an economically viable solution for high-pressure CO_2 transport when compared with newly built pipelines.

The CO_2EuroPipe project also examined whether the current worldwide gas tanker fleet is capable of transporting CO_2 on a large scale, in liquefied, solid or gaseous form. It concluded that of the existing fleet of 1 300 gas carriers, only 34 could be used for CO_2 transport. These vessels are technically capable of transporting CO_2, although they would have to be converted for this use. As with pipelines, however, the project found that, from a commercial point of view, CO_2 transport by newly built dedicated CO_2 carriers is probably the best option.

The CO_2Europipe project found that there is a current bias towards offshore storage which, if it continues, will be reflected in a bias towards transport infrastructure to support this option. This will have an impact the cost of CCS, as allowing onshore storage would result in significantly lower overall costs due to shorter transport distances. These findings were confirmed in a separate study that looked at two scenarios - with and without onshore aquifer storage (Kjärstad et al, 2013)[4]. This study showed that transport costs increase significantly when storage in aquifers is restricted to offshore reservoirs, with the result that total investment for the pan-European system more than doubles - from EUR 31 billion with onshore aquifers to EUR 71 billion without.

The EU's emissions trading system (ETS) is the mechanism by which the EU may create the financial basis for CCS projects. However, the price of CO_2 is not expected to increase sufficiently rapidly to render CCS commercially feasible. Consequently, the CO_2Europipe researchers recommended that additional mechanisms be put in place to support the development of CCS projects after the first wave of demonstration projects. They also recommended that the EU provide financial guarantees to further increase the attractiveness of CO_2 transport projects for investors.

A report published by the European Commission's Joint Research Centre[5] found that the development of a trans-European transport network will require advanced planning to ensure optimal design, taking into consideration the anticipated volumes of CO_2 that will have to be transported in the medium and long term and the location of CO_2 sources and sinks. This network will require coordination between national authorities. The CO_2Europipe project also concluded that, given the international character of CCS, strong co-operation would be required between Member States, along with clear signals at a pan-European level to encourage CCS development. A robust policy roadmap, or equivalent, is fundamentally important for

4. http://www.sciencedirect.com/science/article/pii/S1876610213004232
5. http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/15100/1/ldna24565enn.pdf

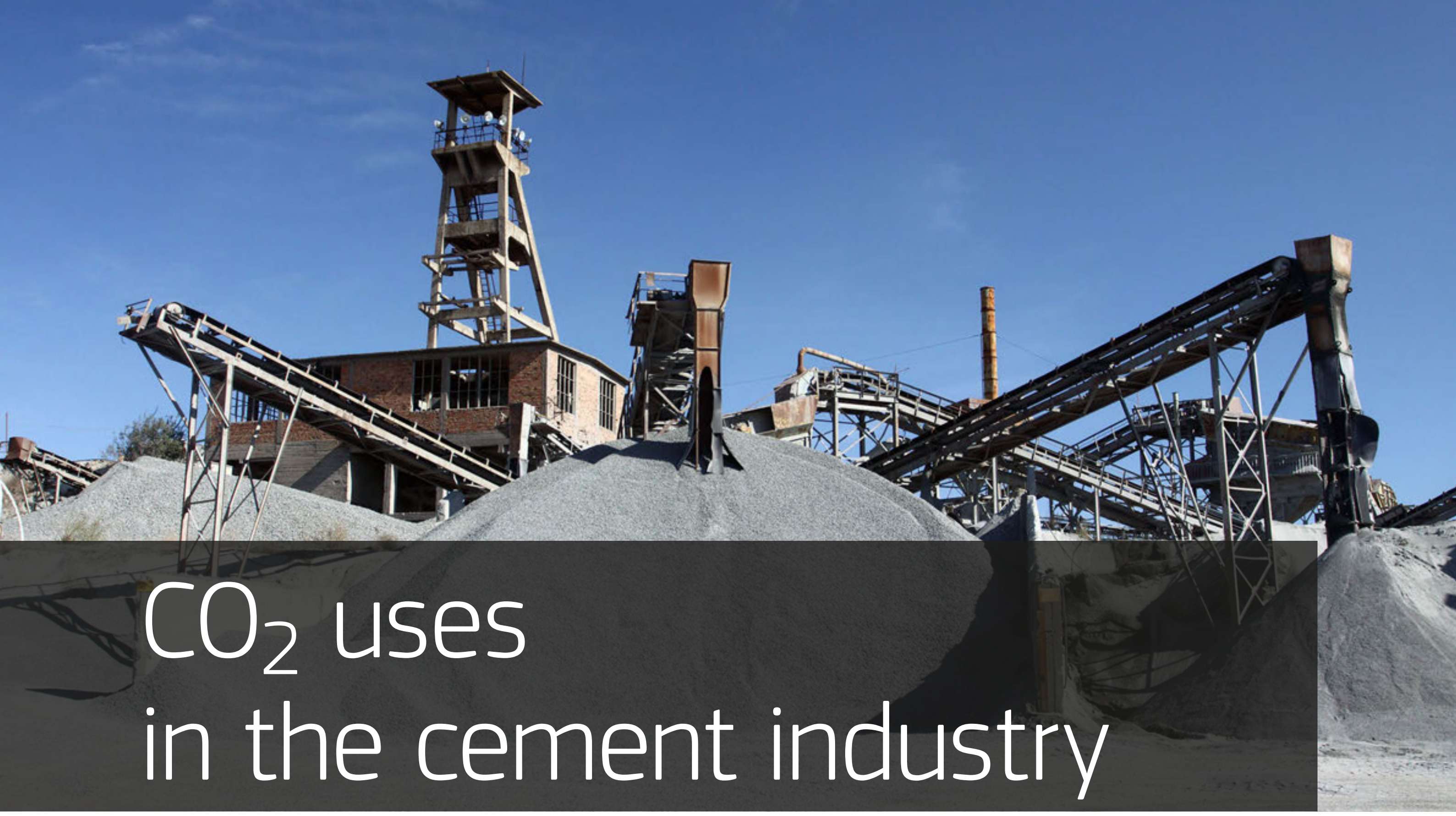
© iStock/bomboman

private industry and the public sector alike to efficiently manage the financial and associated risks, and continued leadership at European level in providing this guiding framework will significantly reduce the uncertainties currently facing potential CCS developments.

The CO_2Europipe recommended that one of the ways in which the EU and Member States can support the development of CCS is through the development and maintenance of Master Plans. These will provide information regarding the timing and size of expected volumes of captured CO_2 together with the planned locations for storage. This will help alignment within the industry, focus efforts and improve the efficiency of network development. At the EU level, a CCS Master Plan is recommended as part of the energy infrastructures plan. At the Member State level, the Master Plans should include cross-border issues and set the timeline for the development of capture efforts and infrastructure construction while also providing relevant information on storage. The researchers stress that these Master Plans will provide the EU and Member States with clarity of vision on the development of CCS and help disseminate information so that industry may reduce the perceived risk associated with developing CCS projects. While planning is undoubtedly important, in real terms not much progress has been made on the implementation of CO_2 transport projects in Europe. For CO_2 transport projects to make the jump from the planning stage to practical implementation it will be necessary to adopt a more proactive approach to incentivising carbon capture and storage technologies and providing the necessary financial guarantees to attract investors.

For more information:
http://www.co2europipe.eu/

CO_2 uses in the cement industry



© iStock/Alexander Kosev

Worldwide anthropogenic emissions of CO_2 are estimated at 37 Gt in 2013. The cement industry accounts for 2 to 2.5 Gt CO_2/year i.e. between 5.5% - 6.5% of total emissions. Our industry represents an important share of greenhouse gas emissions worldwide and the consumption of cement and concrete is going to increase in the coming years due to both economic development and growth in the global population. It is therefore very important that our industry develops new products and new technologies in order to mitigate its CO_2 emissions. LafargeHolcim has been leading or participating in several projects on this subject over the last nine years, in an attempt to find ways to reduce its CO_2 footprint.

The Cement Industry

Portland clinker is produced through a combustion process: first calcium carbonate from the quarry is calcined to lime; then this lime is combined with clay to produce clinker. This process requires thermal energy, e.g. 2.9 GJ/t clinker with the best available technology (BAT). The CO_2 emission related to both calcination and combustion is ~ 830 kg CO_2/t clinker produced.

Unlike combustion industries, only 1/3 of the CO_2 emitted by the cement industry comes from combustion, while 2/3 come from the limestone calcination. Limestone calcination (i.e. CO_2 removal) is highly endothermic and occurs at 850°C in the precalciner of the cement plant while clinkerisation is slightly exothermal.

Producing 1 metric tonne of clinker emits 830 kg CO_2, of which 540 kg come from the limestone calcination and 290 kg from the combustion itself. Once produced, the clinker is augmented by several "cementitious" materials so that the production of 1 metric tonne of Portland cement in our company finally emits around 600 kg of CO_2.

The usual performance levers applied in our cement plants are well managed. In particular, these are saving programs that deal with both kWh of electricity and thermal energies. In addition, our product mix has also evolved towards more complex products using cementitious product additions as clinker extenders. Today, 1.35 tonnes of cement is produced from 1 tonne of clinker compared to 1.1 tonnes only 30 years ago. All these levers have led to considerable progress over the last 30 years: a reduction of about 30% in CO_2 emissions in 1990-2014.

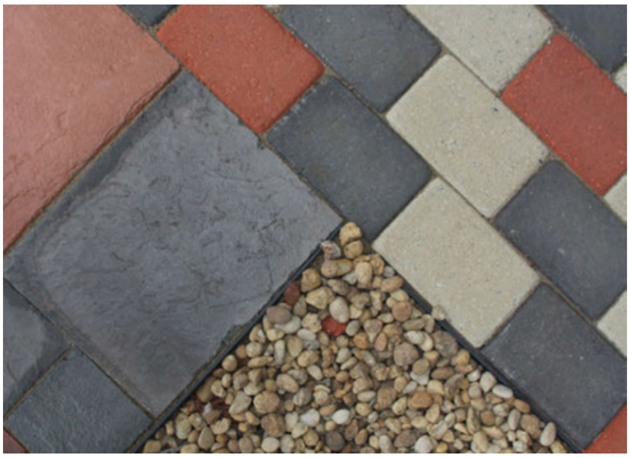
Nevertheless, although the performance levers are still very efficient, we have developed a new approach in designing low-CO_2 products able to substitute Portland cement. AETHER Cement™, a new binder allowing a 30% reduction in CO_2 emissions (www.AETHER-Cement.eu) and SOLIDIA Cement,™ may make it possible to reduce CO_2 emissions by up to 70% as compared to ordinary Portland cement.

SOLIDIA Cement™ and Concrete

This new product is a complete breakthrough for Portland cement and concrete. Although its mineralogical and chemical composition differs from Portland (less limestone), it sets and hardens through a carbonation process and not through hydration. This means that the CO_2 emissions related to the burning process of this new product are reduced by 30%, and it captures additional CO_2 during the curing process i.e. ~ 250 kg CO_2/t binder. Altogether, the emissions per tonne of binder will be reduced by at least a factor of 2, i.e. to under ~ 400 kg CO_2 instead of 840 kgCO_2/t for Portland clinker (for some applications a CO_2 reduction of up to 70% is possible).

This cement develops as much strength in 24 hours as Portland cement in 28 days and can already address several market segments such as precast (pavements, blocks, railroad crosses, road sleepers…) and some structural and concrete ready mix applications. LafargeHolcim is currently developing this new product with the North American start up SOLIDIA®, the inventor of the product.

It is too early today to make a precise forecast on the overall CO_2 reductions linked to SOLIDIA® which is related to its market development. However, we can say that this product combines direct CO_2 reduction during the production process with CO_2 recapture during material setting and it inscribes fully into the circular economy and industrial ecology concepts. In addition, it combines mineral carbonation (dealing with CO_2 uses) and production of a useful product for the construction business.



© Solidia Concrete™ pavers and stones

The industrial feasibility of this product was demonstrated through two production campaigns: 5000 tonnes of SOLIDIA® clinker at a North American plant in April 2014 and 3000 tonnes in Hungary in June 2015.

We expect this lever can contribute to significantly reducing the cement industry's CO_2 emissions. However, although emitted in a huge quantity worldwide, the CO_2 market is quite small today and we could paradoxically encounter supply shortages for mass mineral carbonation applications.

The capture of CO_2 from diluted flue gas is still expensive when compared to the cement market price and the current supply shows over quality for emerging applications in construction materials. Indeed, the liquid CO_2 price is today ≥ 100 EUR/t, whereas the cement market price in Europe and North America ranges from 50 to 100 EUR/t. It may additionally be subject to high shipping costs. Therefore, local access to cheap CO_2 supply will determine the future of CO_2 utilisation to produce new low-CO_2 binders and, to a certain extent, the future of most of the other carbon dioxide technologies also.

In summary, we think that this type of product is a good example of a CO_2 application adapted to our industry. We do produce and sell mineral products and we know how to market them, and are able to develop them for numerous application segments. The CO_2 capture through mineral carbonation is therefore tailor made for our core business.

Conclusion

Altogether, the global impact of our industry is reduced through incremental levers linked to performance management of our industrial sites, but also through breakthroughs in developing innovative products, i.e. new cements and concretes. The development of a holistic approach with new solutions embedded into the construction industry is equally important.

Michel Gimenez

Michel Gimenez is a Chemical Engineer with a Doctorate in Physical Chemistry. His career has covered both the chemical and cement industries, and has been split roughly equally between operations and R&D/industrial transfer. At LafargeHolcim, his main focus is CO_2 mitigation, sustainability and industrial innovation. He is currently involved in numerous projects and partnerships, primarily in the areas of CO_2 capture and use and sustainable development as well as in technological & product innovation.

The challenges of the CCU industry

© iStock/BarbraFord

Currently, 130 million tonnes per year of CO_2 are used in industrial processes, including enhanced oil recovery (EOR) - 60 million tonnes; urea / fertiliser production - 36 million tonnes; and in other applications such as the food and beverage industry. This quantity could be multiplied by a factor of five in 2030 as new uses emerge.

The main CCU technologies are:

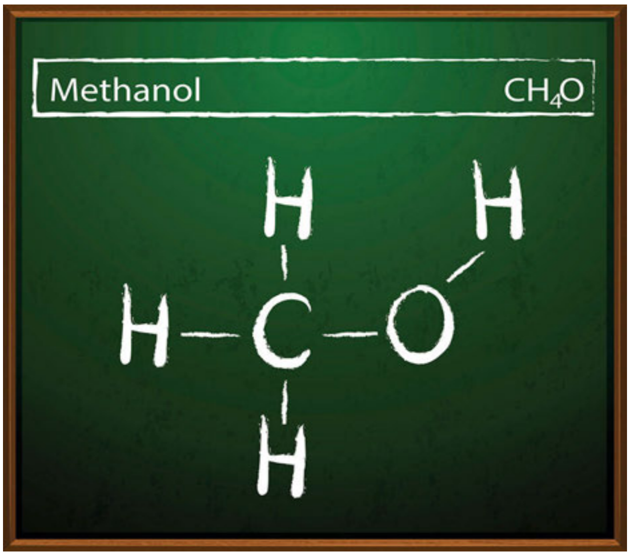
- Direct use, allowed by cheap access to CO_2: more than 60 million tonnes of CO_2 are extracted from natural domes for economic reasons. Here a cheap capture technology could make it possible to re-use CO_2 from flue gas emissions.
- Specialty chemicals made from CO_2: mainly niche applications (e.g. polycarbonate), with a low impact on CO_2 levels. It's generally easier and cheaper to make these products from fossil CO_2.
- Mineralisation with initial developments in alkaline waste carbonation. Large-scale development requires natural ores (wollastonite, olivine...) which are limited by a slow conversion rate.
- Power to Liquid: this is already industrial and could be the largest pathway for CCU in fuels, due to the replacement of fossil carbon by recycled carbon (circular economy approach).

Focusing on Power to Liquid, this involves the conversion of CO_2 into methanol (MeOH) using H_2 produced by electrolysis. Here the challenge is to identify an adequate industrial ecosystem and the appropriate economic conditions to allow a financially acceptable scheme for this conversion. A complete simulation of a 125MW Power to Liquid process, producing 100 kT of MeOH from 150 kT/y of CO_2, leads to a cost for MeOH of 600-700 EUR/T for an electricity price of 45 EUR/MWh. The cost of electricity is the major variable here, since a 10 EUR/MWh increase in the cost of electricity leads to a 100 EUR/T increase in the cost of MeOH.

Although the cost of the Power to Liquid MeOH is higher than for fossil MeOH, it is in the same order of magnitude as biofuels if we compare the cost of their energy content (20-30 EUR/GJ). The development of Power to Liquid can be accelerated by:

- Its use in transportation fuel by direct blending, transformation into methyl tert-butyl ether (MTBE), transesterification for the biodiesel process or transformation into gasoline via the methanol to gasoline (MTG) process.
- A regulatory scheme that will allow it to be competitive with biofuels (EU transport directive).
- Development of new fuels (e.g. dimethyl ether (DME)) requiring adaptations for the transport industry.

Power to Liquid could find its place within the context of energy transition, by offering flexible capacities to store energy excesses arising from an increase in renewables. The electricity is transformed into MeOH and fuels that can be transported and stored. By allowing better financial management of baseload assets, the transformation into fuel of the excess energy that cannot be absorbed by the grid makes it possible to keep an acceptable production capacity.



© iStock/blueringmedia

Conclusion

The CCU industry already exists mainly in current applications of CO_2 and can be boosted by cheap CO_2 capture technologies. Power to Liquid could be the largest pathway for CCU, contributing to energy transition. It should be considered in a circular economy context: each tonne of CO_2 recycled to make transportation fuel can avoid one tonne of fossil CO_2 to make the same fuels. It could be competitive versus biofuels if we can resolve the challenges of its incorporation and compatibility with fuels (from drop in to new fuels). The long-term horizon for CCU is the transformation of CO_2 using energy from the sun, and micro-algae could probably be the earliest pathway.

Robert Gresser

Robert Gresser is Director of the Sustainable Energy Innovation Platform of Solvay Corporate Research & Innovation, where he is in charge of all corporate programs related to energy. He is a Chemical Engineer with a PhD in Physical Chemistry and joined Rhône-Poulenc (now Solvay) in 1981 as a research engineer. Since 1995, he has focused on marketing and innovation, reinforcing the alignment of innovation, marketing and strategy and piloting innovation programmes.

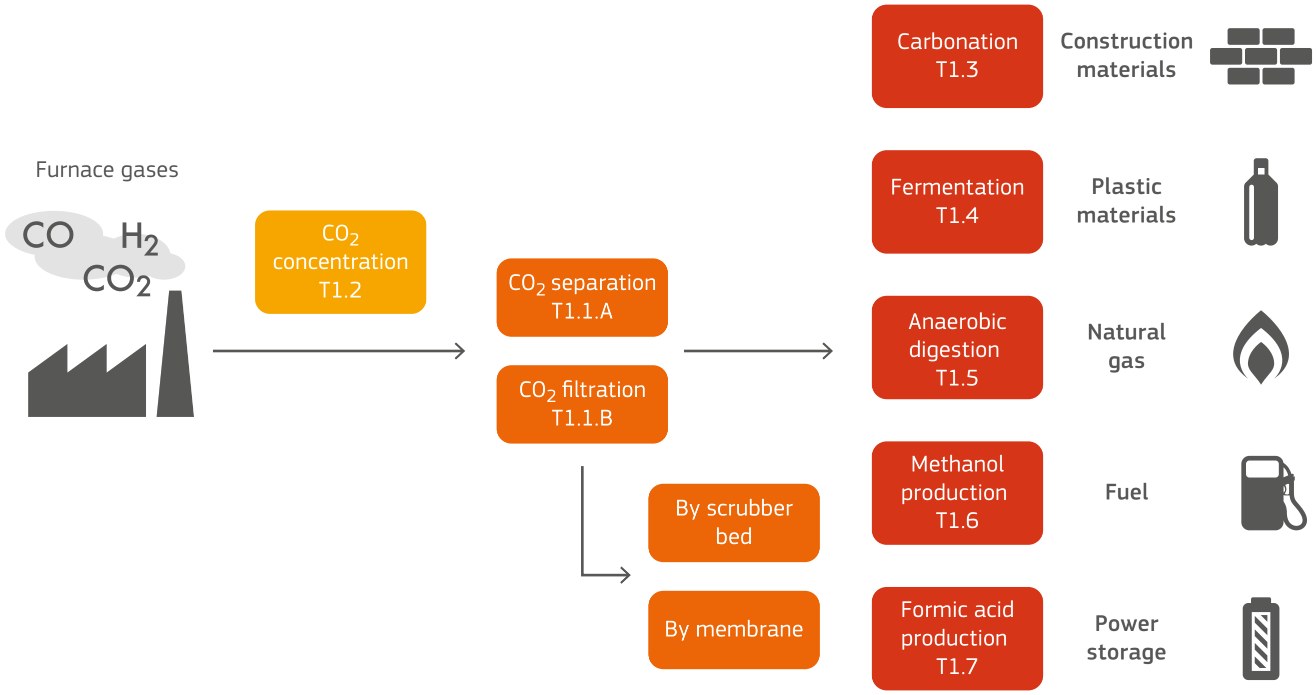
The zero-emission steel plant of the future

© iStock/moodboard

Introduction

The European steel industry has made tremendous past efforts to reduce its carbon footprint. The CO_2 emissions in conventional steelmaking have been reduced from 3.5 t/tonne of steel down to as low as 1.7 t/tonne. The same effort has been made in electrical steelmaking, leading to huge reductions in energy consumption of up to 50%. Depending on the origin of the electricity, electric arc furnaces emit as little as 1 tonne of CO_2 per tonne of steel. Nevertheless, iron and steel making, with a global production of 1.6 billion tonnes in 2014, remains the biggest industrial emitter of greenhouse gases (GHGs). Unlike the power industry, carbon is not a combustible for iron making, but a reagent for iron ore reduction. In a blast furnace, two atoms of C are required for two molecules of CO to react with one molecule of Fe_xO_y.

Whereas blast furnaces in Europe are now reaching the limits of their technological capabilities in terms of CO_2 reduction, competitors in new economies have retained high emission rates due to obsolete steelmaking facilities, a lack of technological skills and scrap shortages. While the global average of CO_2 emissions per tonne of steel is 2.6 t/t, large steel volumes are produced with emissions of up to 4 t/t. The low emitters are the electric arc furnaces, the natural gas-based iron reduction units and the European steel mills with levels of less than 2 t/t on average. The high emitters of CO_2 are the mills from Eastern Europe, the former Soviet Union and Asia, still at 3.5-4 t/t, the level where Europe used to be in the 1950s.



In France, the steel industry is collaborating with universities and institutions in the VALORCO-programme to reuse CO_2 for the production of valuable fuels and chemicals.

The story

The European steel industry faces a two-fold challenge. Not only is energy scarce and very expensive compared to the continents that have their own resources; a second competitive handicap is the carbon tax, enforced by environmental regulations. This carbon tax applies to all steel mills, since the benchmark level, for which free allowances are provided, cannot be obtained by conventional steel producers. The gap from the best to the bench is about 30%.

Compared to other industries, the steel industry has a much lower margin per tonne of CO_2 emitted and will thus be the first to have to stop activities if an overly high carbon tax is imposed. Efforts to re-use CO or CO_2 of fossil origin are not at all rewarded by current legislation. Attempts to produce hydrogen, the only alternative reactant for carbon (for example through high-temperature electrolysis from steel waste heat) are also disadvantaged, because the ETS does not differentiate between industries. So CO_2 taxes are the same for everyone, even when a green alternative exists, and green electrolysis H_2, which generates no CO_2 emissions, stands no chance against steam methane reforming (SMR)-H_2, although the latter emits 10 tonnes of CO_2 per tonne of H_2.

Japanese steelmakers are studying the use of H_2 as a reagent as part of the COURSE 50-project, research which is entirely funded by the Japanese government. But the lack of hydrogen from coke making, and the need for coke as a support for the iron ore in the blast furnace have reduced ambitions to a 30% reduction in CO_2 at the most.

The Zero Emission Plant concept being elaborated by steel producers therefore targets some socially acceptable and possibly economically viable principles. The goal of the project is to separate the CO from the CO_2 in order to use both constituents as feedstock for new industries, thus creating value and employment.

The pure CO and CO_2 gases can be combined with the H_2 from coke oven gas, electrolysis or supplied by a neighbouring industry, because in most industrial zones several thousands of tonnes of hydrogen are still burnt as fatal gases. The fuels and chemicals targeted by these new technologies can replace products derived from fossil fuels or biomass (without indirect land use) such as naphtha, methane, ethanol, methanol, acetone, formic acid, caproic acid and many others. Biochemical fermentation, catalytic reaction or electro-chemical transformation can be used as conversion methods.

These developments are ongoing, in parallel with the search for cheap hydrogen, which will be the limiting factor. High-temperature electrolysis is particularly interesting in this regard as it reduces electricity consumption by almost 14%. The heat can be derived from waste energy produced through steel making. CO_2-electrolysis, which makes use of the surplus of renewable electricity, is a technology that has been tested in a solar tower. In steel mills, the heat required for the electrolysis cells could come from the waste heat of steel making.

A more mature technology is the dry reforming of CO_2 with natural gas or coke oven gas. The ULCOS steelmakers' consortium in Europe previously conducted tests with a 2 MW-plasma torch. This hot syngas can be injected into the furnaces to reduce the iron ore. A direct reduced iron (DRI)-unit using a trial plasma arc, up to 20 MW, is likely to be the next step in the development of this technology.

© iStock/icarmen13

But CO_2 can also be used without H_2, and can simply be stored in steel slags and minerals that absorb CO_2. Carbonation trials with olivine, serpentine, wollastonite and steel slags have shown a net CO_2-sequestration potential of 15 – 35 weight %. PCC (precipitated calcium carbonate) is the possible end-product of this carbonation, together with other materials which can be used for the construction industry for example. The simple sale of CO_2 to greenhouses is an obvious end-use.

The ambition is to come as close as possible to the predicted volume of reusable anthropogenic CO_2 between 10 and 20%, with the aim of finding a use for at least 25 – 30% of the CO_2 produced from steelmaking. This would also bridge the gap between the best performing EU-mills and the benchmark set out by the European Union.

Conclusion

Given the value created by CO_2 conversion technologies, every industry should be able to afford to capture all of the CO_2 it produces. The revenue generated from the sale of chemicals and fuels produced from part of this CO_2 could cover the cost of making the remainder publically available, for example through a public pipeline, which will in turn attract new industries and create new employment. This would also enable the sufficient and uninterrupted supply of CO_2 that could be liquefied for Enhanced Oil Recovery or storage in a landfill by the state authorities. Consequently, CO_2 conversion should not incur any additional costs for the industry and there will be no financial handicap with regard to competitors that continue to vent their CO_2.

Contributors to this article:

Karl Buttiens, Environment Manager, AM Corporate

Robert-Jan Jeekel, AM Finance & Services Belgium

Arne Langner, Environment Manager

Eric De Coninck, AM CTO ETD New Technologies

Frank Schulz, AM VP, Head of Environmental Affairs

Mary Varkados, Environment Manager

How carbon capture can play a role in urea production

© iStock/Egilshay

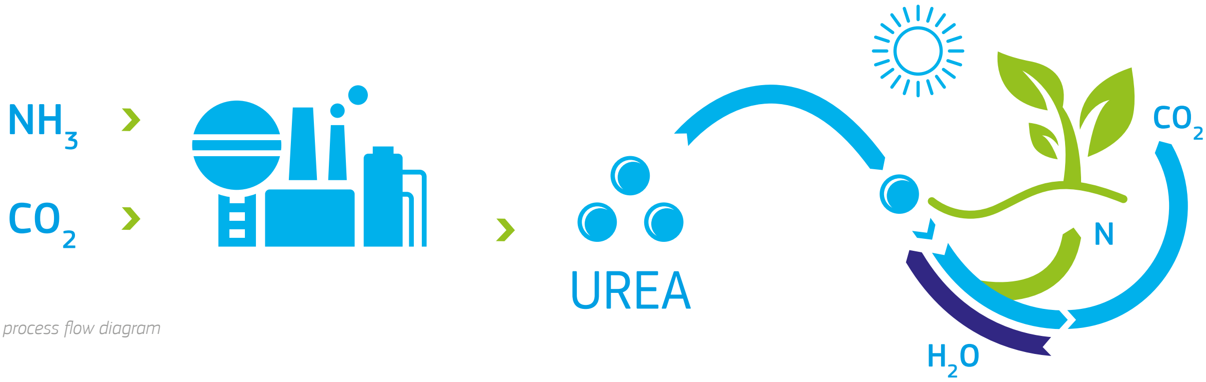
Over the next 35 years the world population is likely to grow to over 9 billion people according to the UN[6]. This will put immense strain on the earth's natural resources which are already feeling the impact of climate change. To put this in context: the average human consumes about 2 500 calories per day. Multiply this by 365 days and by 9 billion people and you end up with more than 8 quadrillion calories (which is equal to approximately 19 billion kg of rice) that will be needed per year to feed the world's population. The Food and Agriculture Organisation of the United Nations (FAO) claims that the world would have to increase its food production by 70% - that is taking into account that 70% percent of the population will earn a higher income, which will lead to a higher consumption[7].

This becomes even more problematic when looking at available arable land. In 2 000 the World Bank estimated the agricultural land area to be around 5 billion hectares, however only 1.5 billion hectares were identified as arable land[8]. Even though the earth has the potential to expand its arable land, the FAO measured that the majority of potential land is not equally spread but clustered in a few countries in Latin America and sub-Saharan Africa. On top of that, the FAO's research revealed that a great deal of this land is only suitable for growing certain crops and some other parts of this land are either forested or protected by local governments[9]. This means that arable land isn't expanding at the required pace. This calls for the expansion of arable land and/or improving crop yields on existing farmland. The latter is preferred, because this solution produces lower emissions of greenhouse gases and doesn't involve the disruption of existing ecosystems[10]. Yield improvement is not just a practical way to increase food production in developed countries, but also in developing countries. According to the FAO 70% of increased cereal production can be allocated to yield improvement techniques and only 15% to the expansion of arable land[11].

The National Center for Biotechnology suggests it is thanks to new farming technologies and synthetic fertilizers that farmers have been able to increase crop yields since the 1960's[12]. The United Nations (UN) estimated that 40-60% of the world's food production is due to the use of commercial fertiliser and it has been claimed that over 2.4 billion people would have starved to death if it were not for fertilisers[13]. As the world population increases so does the need for fertiliser.

Fertilisers provide the essential nutrients that crops need to grow and resist diseases. The primary nutrients needed are Nitrogen (N), Phosphors (P) and Potassium (K). Since its discovery in 1 773, urea has been the most important nitrogen-based fertilizer in the world[14]. Urea is a white crystalline organic compound that contains approximately 46% nitrogen. The production of urea involves the reaction between

6. http://esa.un.org/unpd/wpp/Publications/Files/Key_Findings_WPP_2015.pdf
7. http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf
8. http://www.tradingeconomics.com/world/arable-land-percent-of-land-area-wb-data.html
9. http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf
10. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2613695/
11. http://www.fao.org/docrep/004/y3557e/y3557e08.htm
12. https://www.ipni.net/ppiweb/bcrops.nsf/$webindex/0022BBC19C02604A852575C50062FBB7/$file/BC09-2p12.pdf
13. Wolfe, David W. (2001). Tales from the underground: a natural history of subterranean life. Cambridge, Mass: Perseus Pub.
14. http://www.gov.pe.ca/photos/original/af_fact_ufcp.pdf



Urea process flow diagram

synthetic ammonia and CO_2, yet the production of urea itself hardly emits CO_2 making it more eco-friendly. The ammonia-CO_2 reaction forms ammonium carbamate which is dehydrated to produce urea. A prilled or granulated solid is usually the final product. The urea prills or granules are sowed on agricultural land where it reacts with water to release nitrogen. Nitrogen is released at the optimum rate by the decomposing ammonia enabling plants to grow strong. The CO_2 is released into the atmosphere where some of it is absorbed by plants to be used for photosynthesis.

Most of the CO_2 used to produce urea comes from the CO_2 generated during the production of ammonia. The ammonia and urea plants are usually located in close proximity to supply the feedstock for urea production. However, seeing that ammonia production uses natural gas as feedstock, part of the natural gas feedstock can be replaced with CO_2 sourced elsewhere.

A substantial part of the CO_2 generated in the ammonia process is vented via flue gases to the atmosphere. Carbon Capture and Utilisation (CCU) technology is capable of recovering this CO_2 by means of well proven CO_2 recovery systems based on amine solution. For example, flue gases contain about 0.5 kg-CO_2/kg-ammonia, which can contribute up to 10% of the required CO_2 needed for the production of urea and replace natural gas feedstock.

Advanced CCU technology and innovation will become more-and-more interesting in the world of fertiliser production, taking into account that to produce approximately 1 tonne of urea, 0.7 tonnes of CO_2 is required, and over 169 million tonnes of urea was produced in 2015. This implies that around 12 million tonnes of CO_2, currently produced from natural gas, can potentially be substituted, thereby decreasing the global carbon footprint of urea production. The actual impact may be even more substantial as the global urea market is growing by more than 3% annually. With an average of 1 million tonnes of urea produced per urea plant, this means that around six new urea plants will need to be built each year.

Stamicarbon has been developing and licensing technology for the urea industry since 1947, and has been responsible for innovations such as pool condensation technology and the corrosion-resistant Safurex® material. More than 250 urea plants licensed around the world, or over 50% of installed capacity, have used Stamicarbon technology to add nutrients to crops, replenish arable land and increase crop yields.

Joey Dobrée

After graduation Joey Dobrée started working as a process engineer for Stamicarbon in 2007, the Licensing and IP Group Center of Maire Tecnimont (MT). At the moment Mr. Dobrée is Licensing Manager - responsible for the acquisition, management and development of Stamicarbon's technologies worldwide, with a focus on the nitrogen fertiliser chain. Mr. Dobrée has a Bachelor Degree in Chemical Engineering from the Hanze University and a Master Degree in Industrial Engineering and Management from the University of Groningen, the Netherlands.

Carbon capture and utilisation - synthesis of fuels, chemicals and materials

© Fotolia

Carbon dioxide utilisation for the production of fuels, chemicals and materials has emerged as a possible complementary alternative to CO_2 storage and as a promising source of competitive advantage for European industry. In order to contribute to the on-going debate regarding the potential of CO_2 utilisation as a CO_2 mitigation tool and the competitiveness of carbon utilisation processes, the Joint Research Centre (JRC) - the European Commission's in-house science service - has focused on the study of five products: methanol, formic acid, urea, aggregate for concrete, and polyethercarbonate polyol for polyurethanes.

The following results correspond to the findings of the JRC's on-going study, the methodology of which is based on process system engineering. The results show that all the simulated processes are >95% efficient in terms of CO_2 conversion and entail fewer CO_2 emissions compared to their equivalent conventional processes, mainly because the carbon that would otherwise be provided by fossil fuels is provided by CO_2. The positive impact on CO_2 mitigation increases significantly when the hydrogen needed to react with CO_2 is produced using renewable electricity. In this case, hydrogen is considered to be produced in an alkaline electrolyser. The comparison of a carbon utilisation plant vs. a conventional process is made at plant level (see Figure 1).

Methanol is emerging as a viable alternative to fossil fuels in the transport sector, including the maritime sector. Its current global market is around 61 Mt/yr. The process modelled considers a catalytic reactor that combines H_2 and CO_2, and the downstream product separation steps (in flash vessels and in a distillation column). The considered plant scale is 450 kt/yr of methanol. It was found that in order to have a process that has a net consumption of CO_2 (i.e. indirect and direct emissions of CO_2 smaller than the CO_2 used as a raw material), the electrolyser has to be powered by renewables (zero emission sources).

Operating costs are higher than benefits (with electricity consumption as the main contributor), thus the NPV is negative at the current assumed market prices. The price of methanol, oxygen, CO_2 and electricity and the investment cost of the plant, have been varied one by one to analyse their influence on the NPV. It turns out that the most influential variable is the electricity price, followed by the product price. An electricity price of EUR 9/MWh (current reference price is EUR 95/MWh) or a methanol price of EUR 1,400/t (current market price is EUR 350/t) would make the investment profitable. The price of CO_2 as income for the methanol plant at which the NPV is equal to zero is EUR 670/t (the reference market price is EUR 38/t).

We have analysed the market penetration of methanol based on its annual growth in demand, the coverage of imports, its possible use in the shipping sector, its use in fuel cells and residential cooking (as stationary applications) and its use in passenger and light commercial vehicles, according to the guidelines of the Fuel Quality Directive. In 2030, around 40 Mt/yr of CO_2 may be required to meet European demand for methanol, under assumed penetration percentages and specific pathways.

Formic acid has a current global market of 0.65 Mt/yr. It is a candidate to be used as a hydrogen carrier, and so is a product that could notably increase its demand. The process modelled is composed of a catalytic reactor that combines H_2 and CO_2, and the downstream

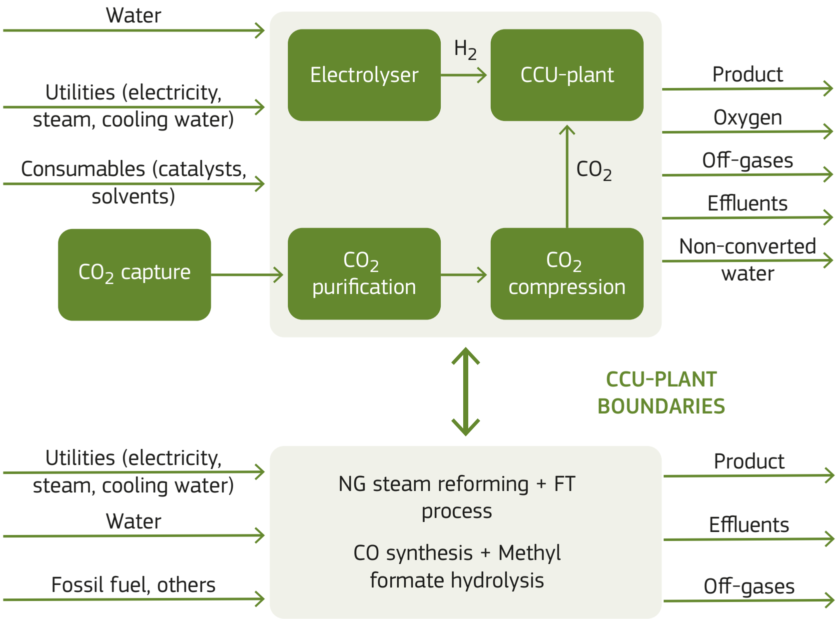


Figure 1: Boundaries of the JRC analysis

product separation steps (liquid-liquid separation and two distillation columns). The considered plant scale is 11.4 kt/yr of formic acid. As in the case of methanol, the electrolyser has to be powered by renewables to have a net consumption of CO_2.

Operating costs are higher than benefits; variable costs of consumables (catalysts, followed by solvents), electricity and steam, are the main contributors. In order to have a positive NPV, we have studied the sensitivity of the NPV to variations in the prices of formic acid, oxygen, CO_2, electricity, steam, and to the variation of the investment cost. The most important variables are consumables (particularly, specialised catalysts), formic acid and electricity prices. Prices of formic acid higher than EUR 1 600/t (current market price is EUR 650/t) would allow positive NPVs. Analogously to the methanol case, we have estimated formic acid penetration pathways. The fuel cells market as a stationary application and its use as a hydrogen carrier in the transportation sector (in fuel cell vehicles and combined with compressed natural gas) are taken into account. Its total request for CO_2 in Europe would be for 7 Mt/yr in 2030, under assumed penetration percentages and specific pathways.

Urea is the main nitrogen-based fertiliser. Moreover, its use in stationary and mobile nitrous oxide (NOx) reduction applications combined with diesel is increasing. Its current global market is around 160 Mt/yr. It is conventionally produced by the combination of CO_2 with ammonia. The CO_2 used in this process comes from the separation of H_2 and CO_2 during the ammonia synthesis process. We have studied two situations:

- Due to the stoichiometric unbalance of conventional plants that use natural gas to produce H_2 and CO, which is converted into CO_2 and separated to be used in the urea process, there is a certain amount of ammonia that is not combined with the CO_2 to produce urea. The use of this "extra" ammonia is what is known as urea yield boosting. This can increase production per plant by 5%. In our assumed plant scale (283 kt/yr), this results in a use of 0.01 Mt/yr of captured CO_2 per plant. The overall EU potential for CO_2 uptake could be in the range of 0.32 Mt/yr of CO_2.
- In order to consider all the CO_2 used for the urea process coming from a CO_2 capture plant, ammonia has to be synthesised by combining H_2 and nitrogen, with the H_2 coming from electrolysis. The process, similar to the methanol and formic acid case studies, needs renewables to power the electrolyser. Operating costs are higher than benefits, with electricity as the main cost element. The sensitivity of the NPV to variations in the prices of urea, oxygen, CO_2, electricity, and to the variation of the investment cost, demonstrates that the main influencing variables are electricity, investment cost and the price of urea. An NPV equal to zero is obtained when the urea price is EUR 1 400/t (the reference market price is EUR 245/t) or CO_2 income equals to EUR 1 550/t. The European urea market growth up to 2030 would imply a CO_2 demand of 7 Mt/yr.

Calcium carbonate and polyols syntheses do not require hydrogen to be combined with CO_2. In the particular case of aggregates, fly ash and/or other alkali residues are used as feedstock. The prime market for aggregates is the building sector. Concrete is the most widely used construction material: it is estimated that the average consumption is 1 t/yr per person. The global output of fly ash is around 800 Mt/yr, approximately half of which is disposed of as a waste product. The global market for polyols is about 6.7 Mt/yr. The simulated plants are of 100 kt/yr of aggregates and 120 kt/yr of polyol. Preliminary results show that both processes have positive

NPVs. Optimisation of process conditions could help decrease the pay-back periods and attract stakeholders into CO_2 utilisation as a new business proposition. Market penetration, taking into account growth of the polyols market in Europe, could imply a demand of 0.12 Mt/yr of CO_2. The results for the ammonia-urea process and for calcium carbonate and polyols syntheses are under review and the calculation of the CO_2 demand for aggregates is still ongoing.

Overall, according to the selected processes in this work, and according to the assumed hypotheses, the CO_2 utilisation potential by 2030 could reach 55 Mt/yr of CO_2, assuming a number of optimistic penetration pathways for the methanol and hydrogen economies that are not yet broadly developed. As a matter of comparison, the Boundary Dam Carbon Capture and Storage Project (Canada) has a capture capacity of 1 Mt/yr of CO_2. For processes that consume H_2 as a raw material, it is crucial to power electrolysis by renewable sources. As it has been depicted in this article, different favourable conditions may help the various technologies to reach or to enhance their profitability, and a combination of them is desirable. What is common to all is: lower electricity and steam prices (also, better plant integration) and higher prices per tonne of CO_2 and/or for products synthesised from CO_2 are needed.

R&D is also crucial to decrease operating costs, especially in the use of catalysts. Carbon utilisation processes provide a net contribution to CO_2 emissions reduction. However, the context and the "supply chain" are not yet in place. The context, i.e. legislation and regulations, should take into account products made from carbon dioxide (as the recent Renewable Energy Directive/Fuel Quality Directive is paving the way to fuels synthesised from CO_2). At present, however, CO_2 fuels and products are not fully defined in regulation. As regards the supply chain, carbon dioxide to be used in different utilisation processes varies in terms of its purity (thus, the availability cost). For instance, methanol synthesis should use a pure stream, while mineralisation can even be used as a capture method.

This is also a criterion for CO_2 utilisation movers, when selecting their source of CO_2. Due to the costs incurred in CO_2 capture plants in power plants or heavy industry processes, the CO_2 utilisation investor may be attracted by other purer and/or cheaper CO_2 sources (for instance, those derived from biomass processes or from CO_2 capture from the atmosphere). Therefore, measures to motivate the use of CO_2 coming from power plants and heavy industries need to be put in place if the aim is to support a combination of CCS and carbon utilisation processes. Moreover, such CO_2 utilisation processes that consume H_2 as a raw material will benefit from specific renewable/energy storage advancements.

For further information please visit:
https://setis.ec.europa.eu/publications/jrc-setis-reports

Mar Pérez-Fortes

Dr Pérez-Fortes received her Master of Science in Industrial Engineering from the Universitat Politècnica de Catalunya (UPC) in 2005. She then started her PhD at UPC, in the Centre for Process and Environment Engineering (CEPIMA) group. In 2011 she was awarded her PhD in Process System Engineering. After a Post-Doctoral period in the University of California - University of Connecticut, she joined the Joint Research Centre (JRC, in Petten) in September 2013 and since then she has been working on the techno-economic evaluation of different options of CO_2 utilisation.

Evangelos Tzimas

Evangelos leads the 'Carbon Capture, Utilisation and Storage (CCUS)' Project of the Energy Technology Policy Outlook Unit in the Institute for Energy and Transport of the European Commission's Joint Research Centre.

The aim of his work is to provide scientific and technical support for the conception, development and assessment of energy and climate policies of the Union through techno-economic assessments and targeted analysis of low-carbon energy technologies, addressing their potential, benefits and barriers to their large scale deployment. The current focus of his work is the implementation of the European Strategic Energy Technology Plan (SET-Plan).

CO_2 conversion - pathways to alternative storage and carbon derivatives

© iStock/KatarzynaBialasiewicz

The main causal factor of climate change is the release of carbon dioxide (CO_2) and other greenhouse gasses into the atmosphere. As natural processes will be insufficient to absorb future anthropogenic CO_2 emissions, it is generally agreed that carbon capture, use and storage technologies are the optimal way to tackle this problem, by capturing CO_2 and converting it for reuse or storage, thereby preventing its release into the atmosphere.

To date, carbon capture followed by transportation to a storage site with subsequent structural storage, where CO_2 is injected under pressure into a geological formation and kept in place by an impermeable layer of cap rock, has been the most common option for the mitigation of CO_2 emissions. However, alternatives exist to the storage of CO_2 gas. Mineral carbonation (MC) is a process whereby CO_2 is chemically reacted with metal oxide bearing-minerals to form stable carbonates, offering an attractive solution for the permanent and safe storage of CO_2. This reaction can take place either below (in situ) or above ground (ex situ). In situ mineral carbonation involves the injection of CO_2 into underground reservoirs to promote the reaction between CO_2 and alkaline-minerals to form carbonates. Ex situ mineral carbonation relates to above-ground processes, which require rock mining and material comminution as pre-requisites for MC[15].

The CO2SolStock project, funded under the EU's Seventh Framework Programme (FP7), investigated a biomimetic approach to CO_2 carbonation and aimed to investigate microbial carbonation as an alternative way to store carbon. The project aimed to map the various microbiological pathways of capturing CO_2 through carbonation and establish a methodology and a testing toolkit, to enable future research teams to investigate and evaluate scientifically similar pathways. Finally, the project aimed to validate its technological strategy with at least two novel recipes that were potentially competitive and ready for a proof of concept test.

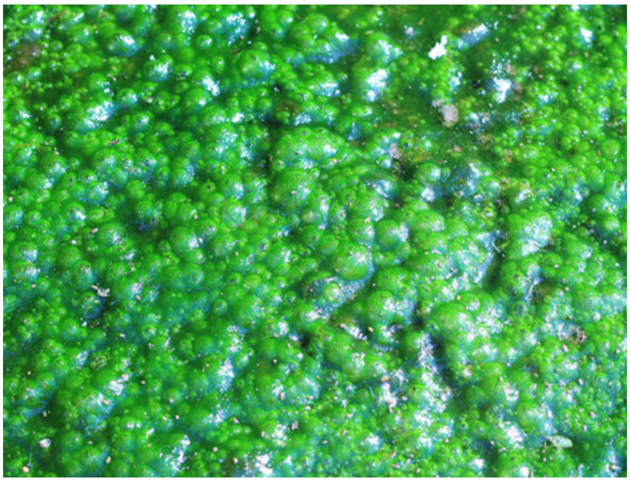
The project investigated four main CO_2 storage pathways. In the first of these, subterranean pathways using bacteria in deep saline aquifers were shown to be potentially complex and energy intensive for low results in terms of carbon storage. However, this option might still prove to be of interest for sealing saline aquifers used to store supercritical CO_2 in some carbon capture and storage (CCS) schemes. Another approach sought to combine two sources of industrial by-products: desalination brines as a calcium source and domestic wastewater as a carbon source. For this pathway, the potential for precipitation of calcium carbonate in terms of bacterial strains was demonstrated in the lab, but the correct recipe has yet to be worked out and needs further experimentation. Dual wastewater anaerobic treatment and silicate rocks weathering was the third pathway, in a first stage, a bacterial acid attack on silicate minerals frees the necessary calcium, while in a second stage, other bacteria produce the alkalinity needed to precipitate limestone and generate high-quality biogas. Finally, in an oxalate-carbonate pathway, an ecosystem management approach was developed based on the discovery of a triple symbiosis between some special trees, fungi and bacteria, leading to the precipitation of limestone in acidic soils around and below the tree roots.

15. http://pubs.rsc.org/en/content/articlepdf/2014/cs/c4cs00035h

The project found that bio-carbonation pathways represent a real paradigm shift, as they deal with CO_2 that could be beyond the reach of classical CCS. Bio-carbonation pathways also mimic the natural-geological CO_2 storage mechanism and fix CO_2 as a stable solid, which can be either stored or could potentially be used as a building material. Hence storage sites do not necessarily need to be big or subterranean with a sealing cap rock. Bio-pathways also have the significant advantage that they can address past emissions by fixing atmospheric CO_2 through photosynthesis, unlike CSS.

While CO2SolStock dealt primarily with in situ carbonation, ex situ processes were the focus of the CO2NOR[16] project, funded under Horizon 2020. The two-year project, launched in September 2015, will investigate an innovative and sustainable method for mineral carbonation to ensure the safe storage of CO_2. This method includes the creation of novel nanomaterials via a ball milling process, based on low-cost ultramafic and mafic rocks from the Troodos ophiolite (Cyprus). Ophiolitic rocks are considered to be one of the most promising lithotypes for CO_2 storage due to their high reactivity.

A systematic study of the applicability of these rocks for CCS will be carried for the first time as part of this project. It is anticipated that ball milling will accelerate the kinetics of rock-fluid reactions during the carbonation procedure. Hence, carbonate minerals, which are stable over geological timescales, will provide a safe long term CCS solution. Additives will also be tested in the nanomaterials in an attempt to increase their CO_2-storage capacity. The proposal also involves applied research into the use of the end-product carbonates in the building industry.



© iStock/13015954

Mineral carbonation is not the only option available. It is also possible to capture CO_2 released by large-scale industrial sources and feed it immediately into a conversion unit that will convert it into a marketable carbon derivative[17]. As many of the feedstocks for the most widely used commodity chemicals are currently derived from non-sustainable carbon sources such as petroleum, the replacement of these sources with recycled CO_2 becomes an even more attractive proposition. Furthermore, the technologies exist to reuse the CO_2 captured in this way as a carbon source for the manufacture of commodity chemicals, particularly liquid and gaseous synthetic fuels.

The ESBCO2 project, which was funded under FP7 and ran from 2012 to 2015, looked at the production of biofuels through microbial electrosynthesis (MES). MES is a process that exploits the ability of microbes to make electrical contacts with electrodes and other cells and the production of biofuels through MES is of great interest. Specifically, the project aimed to examine mechanisms by which microorganisms conserve energy when directly accepting electrons for MES from electrodes, and to further explore carbon and electron flow during CO_2 reduction to biofuels at a cathode. The project will contribute to the development of a cost effective alternative to current fuel production, using greenhouse gas CO_2 as a feedstock. It will use new concepts based on electron (e-) transfer/exchange, conductive biofilms and other novel materials to deliver an environmentally sustainable solution for biofuel production.

The European Union's Bioeconomy Strategy supports the development of production systems with reduced greenhouse gas emissions, including increased carbon sequestration in agricultural soils, sea beds and the appropriate enhancement of forest resources[18]. The research conducted in the above projects and other projects funded under Horizon 2020 will feed into this support. The fragmentation of know-how and activities across Europe is one barrier to the fast development and uptake of CO_2 conversion technologies. With respect to bio-conversion, this is something that is being addressed by the European Commission's Bio-observatory, which is managed by the Joint Research Centre. The task ahead is enormous. For the technologies outlined above to influence CO_2 levels on a scale that would impact on climate they will need to span the chasm from R&D to large-scale market uptake, requiring billions of euros in investment. That said, given that the stakes are so high, it is clear that carbon dioxide conversion technologies will have a key role to play, along with emission reduction and storage solutions, in future strategies to restore balance to the global carbon cycle.

16. Project full title: "Carbon dioxide storage in nanomaterials based on ophiolitic rocks and utilization of the end-product carbonates in the building industry".
17. http://co2forum.cpe.fr/wp-content/uploads/2015/05/4.1.1.-Closing-the-carbon-cycle-v-4.5.pdf
18. http://ec.europa.eu/research/bioeconomy/pdf/201202_innovating_sustainable_growth_en.pdf

Commission activities to enable CO_2 transformation and utilisation

© iStock/Evgeny Gromov

On the basis of the Council conclusions from March 2014[19], and the continued pressure to lower CO_2 emissions and find alternatives to fossil fuels, the Commission together with Cefic (The European Chemical Industry Council) took the initiative to organise a scoping workshop "Transforming CO_2 into value for a rejuvenated European economy"[20], which took place on 26 March 2015. The event, hosted by the Directorate for Key Enabling Technologies of DG RTD, aimed at opening a discussion on CO_2 conversion and utilisation, gathering a critical mass of stakeholders at all levels, from decision makers (representatives of ministries and programme owners) to industry delegates and European Commission representatives. The event gave a broad overview of the status of CO_2 conversion technologies in Europe, including programmes and projects currently running. This gave the chance to gain a common understanding of the state-of-the-art and the potential for demonstration of CO_2 transformation and utilisation technologies at industrial scale.

The technological discussion revolved along three main axes:

- CO_2 as a new renewable feedstock for production of chemicals, polymers and inorganic materials;
- CO_2 conversion for energy storage and fuels;
- Direct photoconversion of CO_2.

The workshop provided a discussion forum for setting an agenda of shared priorities on the topic at European level, leading potentially to the development of a Europe-wide initiative. It was also an important step to understand whether there is a political will from the relevant actors to set up a shared initiative, the feasibility of such a major endeavour and the instruments that might be suitable and available to launch such a programme. The workshop featured presentations from programme owners from 7 European countries (BE, DE, ES, FR, NL, NO and PL) followed by an overview of the currently deployed technologies and 18 individual presentations by industrial representatives about currently ongoing projects. The programmes and projects presented addressed a wide range of technologies covering many industrial sectors (e.g. chemical, steel, cement, automotive, energy), thereby illustrating the importance of the topic in the different European countries and for European industry. Industry presented several technology options, which made it possible to appreciate the level of maturity (TRLs) of the concepts (broadly between TRL 2 and 9 depending on the technologies) as well as business models that could provide economically viable ways to exploit such technologies. Industry stressed that such technologies provide a convenient and innovative way to replace intermediates and products which are currently produced from fossil sources, providing potentially more sustainable analogues, thus making them a desirable alternative. It was emphasised that, considering the whole life cycle, the improved sustainability of the analogues obtained from CO_2 strongly depends on the hydrogen production process utilised. Hydrogen production technologies are tightly linked to CO_2 conversion technologies, and a major improvement in the

19. http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/141749.pdf
20. http://bookshop.europa.eu/en/transforming-co2-into-value-for-a-rejuvenated-european-economy-pbKI0215532/

environmental footprint of products and intermediates obtained from CO_2 can only be obtained if clean technologies are utilised for hydrogen production (e.g. electrolysis of water).

From the presentations and discussions, the following general issues arose:

- The business case for CO_2 utilisation as an alternative to fossil carbon is not yet there (low oil prices, competing against established processes, currently no impetus from regulatory framework). However, companies have positioned ongoing CO_2 conversion activities as part of their sustainable business models (increasing the sustainable impact of their products). Some activities are still at research or innovation phase, while other activities are already at first industrial production or close to commercialisation.
- The need for an urgent integrated action (considering global competition) was stressed by many companies. It was considered important to advance now with pilot and demonstration projects in order to be prepared when oil prices go up in order to advance faster than the competing regions.
- The high potential for new chemical pathways and routes and the high commercialisation potential for large-volume applications were highlighted by different companies.
- Several companies stressed the importance of the regulatory context: in particular the Emission Trading System and the Renewable Energy Directive/Fuel Quality Directive would have significant impact on the reuse of CO_2 as a feedstock for chemicals or fuels in Europe.

Many of the national programme owners stated clearly during their presentations an interest, for the respective countries, in discussing and potentially participating in a large Europe-wide initiative to support the development of CO_2 conversion technologies. The commitment from industry was also clear, considering the statements and the significant projects that are currently running.

In an extension of the Council conclusions from March 2014, the opportunity to use the new state aid instrument on Important Projects of Common European Interest (IPCEI), as a potential vehicle to work on projects with a European dimension which are of strategic importance for the EU economy, was suggested by the Commission. Such a project could combine funds from the Member States and the regions, while leveraging industrial investments for a large-scale common European demonstration programme. The IPCEI Communication of June 2014 (2014/C 188/02)[21] comprises special state aid rules providing major novelties compared to other state aid regimes, notably for the following reasons:

- They are open to all domains of economic activity and can be relevant for all EU policies (e.g. research, energy, KETs);
- They provide a greater variety of support measures (e.g. repayable advances, loans, guarantees or grants);
- They enable the possibility for a coverage up to 100% of the funding gap on the basis of an extended list of eligible costs;
- They provide that state aid may be granted for first industrial deployment (i.e. beyond R&D) of a new product with high research and innovation content and/or a fundamentally innovative production process.

Speakers from the European Commission (EC) highlighted that CO_2 conversion and utilisation holds the promise to create new business opportunities for European industries, while addressing some of the major societal challenges in the EU, and is thus fully in line with the priorities of the European Commission, as shown by EC activities relating to for example the Energy Union or the Circular Economy. The EC speakers emphasised that a large-scale European project in the area of CO_2 conversion would require close cooperation between private and public actors and strong commitments from both sides. They also stressed the Commission's support for an EU-wide strategy on transforming CO_2 into value and its commitment to facilitate the process to shape a large-scale project.

© iStock/maxkabakov

21. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.C_.2014.188.01.0004.01.ENG&toc=OJ:C:2014:188:FULL

The main outcomes of the discussions were the following:

- The workshop showed the potential to transform CO_2 from a problem to a resource.
- CO_2 valorisation could provide significant opportunities for the European industry, in terms of opening new markets and creating jobs and growth.
- The participation in the workshop of a wide variety of stakeholders, from Member States' representatives to industry delegates, engaging in constructive discussions was positive and testifies to the commitment of the different actors, showing real potential for building an ambitious initiative on CO_2 conversion technologies.
- The instrument of "Important Projects of Common European Instruments (IPCEI)" could be suitable for a large-scale project in the area of CO_2 conversion and utilisation, bringing together public and private actors, combining their resources in line with EU state aid rules.

The Commission services reminded the workshop participants that, while they can count on coordination support from the EC, it is up to industry and the interested Member States to engage in the preparation of such a major initiative on "CO_2 conversion technologies" to make a big difference for them and for Europe.

The workshop clearly represented the starting point for further discussions in view of setting up new activities. Additional meetings have taken place among stakeholders to find synergies and strengthen common European activities in regard to showing the potential for industrial demonstrations of the technologies and it is anticipated that a roadmap that outlines the different European activities together with a timeline will be developed within the first half of 2016.

In addition to the above, the Commission has launched several relevant calls (among others) within Horizon 2020[22] to help the research community in developing the above-mentioned technologies to a stage that would allow industrial demonstration and thereby show whether CO_2 utilisation is a viable approach for sustainable production of fuels, chemicals and intermediates:

SPIRE 5 (2016): Potential use of CO_2/CO and non-conventional fossil natural resources in Europe as feedstock for the process industry;
SPIRE 8 (2017): CO_2 utilisation to produce added value chemicals;
SPIRE 10 (2017): New electrochemical solutions for industrial processing, which contribute to a reduction of CO_2 emissions;
BIOTEC 05 (2017): Microbial platforms for CO_2-reuse processes in the low-carbon economy;
LCE 25 (2016): Utilisation of captured CO_2 as feedstock for the process industry;
NMBP 19 (2017): Cost-effective materials for "power-to-chemica" technologies;
NMBP 20 (2017): High-performance materials for optimizing carbon dioxide capture.

All in all, stakeholders feel that CO_2 transformation and utilisation is an economic and technological opportunity that the EU should not miss.

22. http://ec.europa.eu/research/participants/portal/desktop/en/home.html

This article was contributed by the European Commission's Directorate General for Research and Innovation: http://ec.europa.eu/research/

SETIS

Information For Decision-making

http://setis.ec.europa.eu