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SUMMARY

The cement industry can meet the challenge of decarbonization by recycling otherwise-vented carbon dioxide (CO_2) into renewable methane (CH_4), a clean fuel that directly replaces fossil natural gas. Electrochaea's power-to-gas technology, called biomethanation, is an industrial-scale solution that takes hydrogen produced using renewable power and combines it with CO_2 to generate CH_4. This renewable methane can displace fossil natural gas use in the cement site's production process or be injected onto the gas grid to be sold into the market. Both alternatives offer carbon footprint reduction opportunities. The cement industry can drastically reduce greenhouse gas emissions and address the release of unavoidable CO_2 by recycling it as an input to Electrochaea's process. A biomethanation plant with an electrolyzer installed capacity of 100 MWe will enable yearly the recycling of approximately 80 000 tonnes of CO_2 and the production of 440 GWh as a displacement of fossil natural gas.

ZUSAMMENFASSUNG

Durch die Umwandlung von CO_2 in nachhaltiges Methan (CH_4) kann die Zementindustrie ihrem Ziel der Dekarbonisierung einen großen Schritt näher kommen. Das ansonsten in die Atmosphäre emittierte Kohlendioxid wird zu dem sauberen Brennstoff Methan umgewandelt, der fossiles Erdgas 1:1 ersetzt. Electrochaeas Power-to-Gas-Technologie, die Biomethanisierung, ist eine Lösung, die bereits industriell genutzt wird. Sie kombiniert durch erneuerbare Energien erzeugten Wasserstoff mit Kohlendioxid (CO_2). Das daraus entstehende nachhaltige Methan (CH_4) ersetzt fossiles Erdgas im Produktionsprozess von Zementwerken. Das Gas kann außerdem direkt in das Netz eingespeist und auf dem Gasmarkt verkauft werden. Beides führt bei den Betreibern zur Verkleinerung des CO_2-Fußabdrucks. Die Zementindustrie kann auf diesem Wege ihre Treibhausgasemissionen drastisch reduzieren und die Freisetzung von CO_2 verhindern, indem dieses Gas in den Biomethanisierungsprozess von Electrochaea umgeleitet wird. Eine Biomethanisierungsanlage mit einer installierten Elektrolyseleistung von 100 MWe kann jährlich etwa 80 000 t CO_2 recyceln und 440 GWh erneuerbares Methangas produzieren. Letztendlich ist diese Technologie in der Lage, fossiles Erdgas vollständig durch nachhaltiges Erdgas zu ersetzen.

Small microorganisms to decarbonize big industries: Archaea as an innovative solution for the cement industry

Kleine Mikroorganismen zur Dekarbonisierung großer Industrien: Archaea als innovative Lösung für die Zementindustrie

1 Introduction

The cement industry is faced with immense pressure to reduce greenhouse gas emissions in the global fight against climate change. With cement production emitting as much as 8 % of the world's carbon dioxide (CO_2), cement associations worldwide have recognized the role that the industry must play in the fight to halt climate change [1]. The European Cement Association has adopted goals of carbon neutrality by 2050, with an intermediate goal of a 30 % greenhouse gas emission reduction in cement production by 2030. Since 1990, the cement industry has reduced its CO_2 emissions by about 15 %. With no single route to decarbonization, the cement industry is considering a range of solutions: firstly the clinker substitution, renewable electricity, carbon-neutral transport, alternative fuels, thermal efficiency, concrete mix, in addition to Carbon Capture and Utilization (CCU) [2].

The cement industry can drastically reduce greenhouse gas emissions and address the release of unavoidable CO_2 by recycling of CO_2 as a process input to a new technology called power-to-gas. Specifically, Electrochaea has developed an industrial-scale carbon utilization solution that converts renewable electricity (the power) and CO_2 into grid-quality renewable methane (the gas). Electrochaea's power-to-gas technology, called biomethanation, takes hydrogen (H_2) produced using renewable power, and combines it with CO_2 to produce methane (CH_4), effectively storing the renewable electrical energy in the chemical bonds of the methane. The core of Electrochaea's system is a selectively evolved microorganism – a methanogenic archaea – that excels through unprecedented catalytic ability and industrial robustness. A biomethanation plant with a 100 MWe electrolyzer can enable annual recycling of approximately 80 000 t of CO_2, and the production of 440 GWh of renewable methane. This renewable methane can displace fossil natural gas use on-site, offering further carbon footprint reduction opportunities, or be sold into the market, as such valorizing CO_2 that would otherwise be released into the atmosphere. An example of a biomethanation plant is shown in ❱ Fig. 1.

Figure 2: Electron microscope photograph of the Electrochaea archaea strain, a variation of Methanothermobacter thermautotrophicus (Source: Prof. Andreas Klingl, 2017)

Figure 1: Electrochaea's 1 MWe industrial-scale pilot plant in Avedøre, Denmark, which was commissioned in 2016

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2 A brief biology lesson for cement executives: How can microorganisms reduce the carbon footprint?

Electrochaea's patent-protected technology uses a selectively evolved methanogenic archaea as a biocatalyst to produce methane from H_2 and CO_2 under anaerobic conditions by catalyzing the reaction $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$. Archaea are 3.5 billion year-old single-celled organisms (➧ Fig. 2). In the absence of either hydrogen and CO_2, the Archaea simply remain in "stand-by" mode – this can last for hours, days or months without affecting the microorganisms. Therefore, Electrochaea's biomethanation system has the ability to be turned on and off rapidly, and to be available in 'ready' mode at low cost. ➧ Table 1 shows the unique features of Electrochaea's biocatalyst, especially its remarkable productivity, converting >98 % of the available CO_2 into CH_4.

Table 1: Unique features of Electrochaea 's biocatalyst, a methanogenic archaea

Features	Comments
Productive	98.6 % of fixed carbon goes into methane
Effective	VVD of 850, H_2 mass-transfer limited (VVD = volumes of gas per volume of reactor per day)
Responsive	Quick return to methane production within seconds/ minutes
Selective	100 % methane, no intermediates
Robust	Tolerant to H_2S, CO, sulfate, ammonia, particulates
Simple	Moderate temperature range (60 to 65 °C) and pressure (1 to 10 bar)
Proprietary	Patented biocatalyst developed by L. Mets is licensed exclusively to Electrochaea by the University of Chicago

3 The Electrochaea story: The path from university laboratory to commercialization

The Electrochaea story started in the year 2006 with basic research and four years of proof-of-concept work in Professor Laurens Mets' laboratory (➧ Fig. 3) at the University of Chicago. De-risking of the process for commercialization began in 2011, using raw biogas to produce methane at a brewery digester in St. Louis, MO, and continued with field trials in Foulum, Denmark. In 2016, an industrial-scale plant (Fig. 1) was commissioned in Avedøre, Denmark at a wastewater treatment plant near Copenhagen; the so called BioCat plant was in intermittent operation for 3.5 years, with

Figure 3: Bioreactor in the laboratory at Electrochaea's global headquarters near Munich, Germany, where enhancements to the technology's performance continues

3500 h of total operating. Grid quality methane (> 97 % by volume methane) was produced by the self-sustaining biocatalyst and was injected onto the Danish gas grid. As part of the STORE&GO project funded by the European Union's Horizon 2020 Research and Innovation Programme [3], a second-generation plant with automated remote operation was commissioned in 2019 in Solothurn, Switzerland, and injected high-quality methane onto the gas grid within 96 h of startup. Electrochaea has successfully scaled from benchtop to industrial pilots (➧ Fig. 4), a 10000-times scale-up, and continues its technology de-risking and scale-up activities at its global headquarters outside Munich.

In 2020, Electrochaea received funding from the European Innovation Council`s Accelerator program [4], confirming that its market-ready biomethanation technology is a solution to mitigate climate change, supplying clean and affordable energy, and shifting to sustainable transportation, all goals of the European Green Deal. The European Innovation Council (EIC) program is helping to accelerate Electrochaea's scale-up efforts through the development of its 10 MW-scale (500 m^3/h (stp) of CO_2) commercial archetype design, a tenfold increase in methane production from its industrial-scale field trials in Denmark and Switzerland. As part of those efforts, a Process Design Package (PDP) was developed, providing a solid foundation for future clients, reducing risk, time, and investment for deployment of projects that require a 10 MWe plant or larger. Detail engineering activities have started towards the deployment of a commercial plant in Roslev, Denmark.

In June 2021, Baker Hughes announced its investment in Electrochaea, strengthening Electrochaea's position as a leading provider of renewable methane technology. This strategic investment will further accelerate the scale-up and commercialization of Electrochaea's technology. In 2022, Electrochaea is jump-starting its concept engineering phase for a 75 MWe design, equivalent to a biomethanation plant processing 3750 m^3/h (stp) of CO_2. This design will also have the option to combine multiple units to accommodate larger-scale projects, and to be combined with advanced carbon capture technologies for more challenging CO_2 waste streams.

4 Biomethanation: A large-scale solution to decarbonize the cement industry

Cement plants of the future will significantly reduce emissions by 2050: approximately 20 % will come from operational advances, such as energy-efficiency measures and clinker substitution, and an additional 10 % will come from alternative fuels [5]. Further decarbonization opportunities will be enabled by innovation advances such as scaling of Carbon Capture, Utilization, and Storage (CCUS) technologies, or new kiln technologies [6]. Biomethanation is a perfect example of such an innovative solution.

Biomethanation can be directly integrated into the cement production process to use CO_2 emissions for synthetic fuel production (➧ Fig. 5). CO_2 from the kiln is purified, compressed, and fed into the methanation reactor. At the same time, electrolysis, powered by renewable electricity, is used in the production of green hydrogen, which is also fed into the methanation reactor. When hydrogen and CO_2 are fed into the reactor at a 4:1 ratio (H_2:CO_2), the archaea housed within the reactor take up the gases and produce low-carbon intensity renewable methane. The renewable methane is a

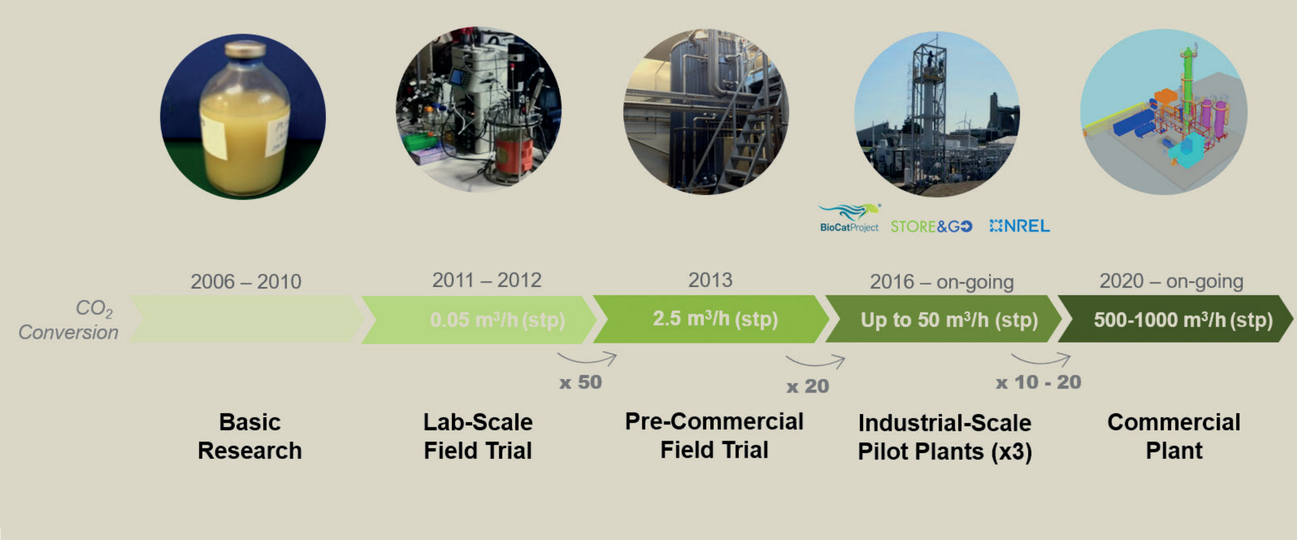

Figure 4: Electrochaea's scale-up activities began in 2011, with the first industrial pilot plant commissioned in 2016. Commercial archetype plant designs are currently being finalized

direct replacement for natural gas, and can be utilized on-site in existing processes, potentially reducing needs for extensive retrofitting or early retirement of cement plants to meet decarbonization goals [7]. Alternatively, the renewable gas can generate value by being sold in the market and directly injected in the existing natural gas grid or utilized as a green fuel for transportation or industrial applications.

5 Decarbonization: How can the cement industry contribute to greenhouse gas reduction?

As pressure to decarbonize the industry increases, the combination of new thinking, innovation and new business models will be critical in ensuring a profitable and greener future. An unprecedented level of collaboration, significant increase in investment in new technologies and operation under new ecosystems will be needed to achieve net-zero targets by 2050 [8]. The cement industry can further support and accelerate its green transition by promoting regulatory actions and incentives that facilitate the adoption of innovative technologies. Since power-to-methane can reduce greenhouse gas emissions, a regulatory landscape that recognizes the importance of the substitution of synthetic methane for fossil natural gas and the recycling of non-biogenic CO_2 is an important goal for the cement industry. Ultimately, the success of the energy transition will depend on leaders' abilities to achieve organization-wide mindset changes promoting the disruption of existing models. The cement industry can lead the way.

6 Final remarks

The cement industry is one of many essential industries where a large portion of its CO_2 is an unavoidable by-product of its production process. Biomethanation offers an innovative solution to utilize this unavoidable CO_2 and convert it to renewable gas to displace natural gas in all its end-uses, either on-site or beyond. The overall carbon footprint reduction can also be quantified against the rising CO_2 prices being observed around the world. Electrochaea's biocatalyst's high tolerance to contaminants offers multiple alternatives for cement plants to generate value from flue gases through carbon capture. Additionally, Electrochaea's technology maximizes the utilization of intermittent renewable energy sources, leverages the existing infrastructure and resources while optimizing required new investment, and recycles carbon to both mitigate atmospheric emissions and maximize new energy sources.

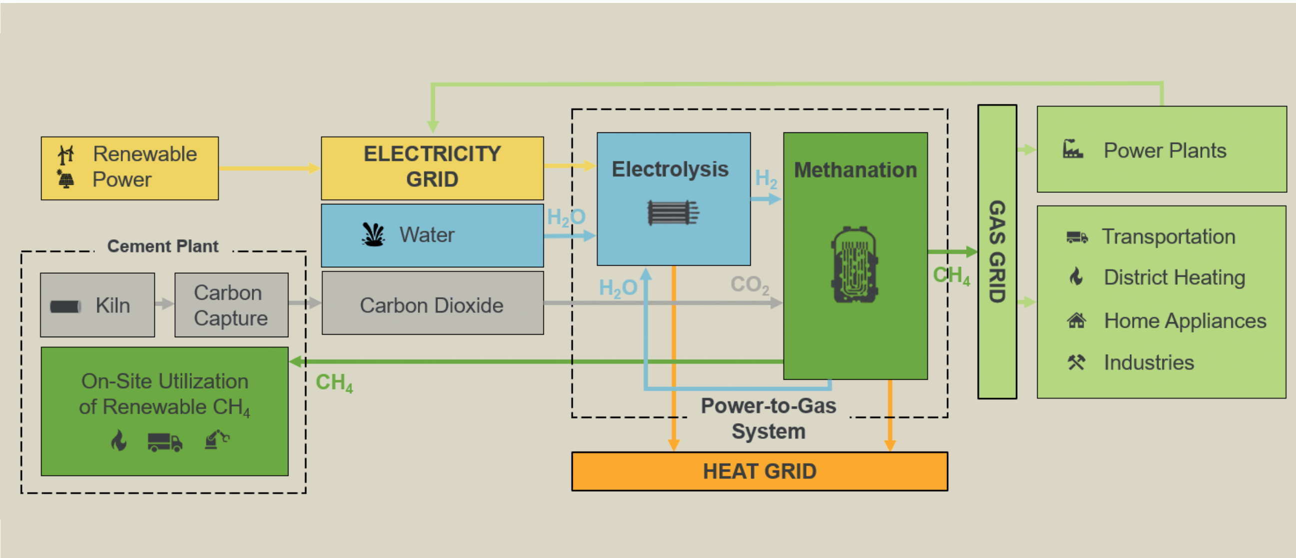

Figure 5: The integration of biomethanation in the cement production process

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