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Analyzing current carbon capture, utilization and storage (CCUS) research and pilot projects in the European cement sector

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Ali Abdelshafy, OIES-KAPSARC Research Fellow & RWTH Aachen University (Operations Management)
Grit Walther, Professor, RWTH Aachen University (Operations Management)

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1. Introduction

Reaching carbon neutrality necessitates radical changes in terms of energy sources and industrial technologies. While some sectors such as transportation and heating will be able to mitigate their emissions via renewable energies in the form of electricity or green hydrogen, the industrial sector faces a major challenge where emissions cannot be avoided using carbon-free energy sources only. Some industries such as cement and lime emit significant amounts of process emissions, which will continue to be generated regardless of the type of energy source employed. These process emissions are classified as "hard-to-abate" and will need to be permanently sequestered via carbon capture, utilization and storage (CCUS) technologies. The CCUS value chain is characterized by a multitude of technological options, most of which are already in use. Nonetheless, current CCUS industrial applications remain limited and deploying them on a large scale will be influenced by various techno-economic aspects as well as their respective policies.

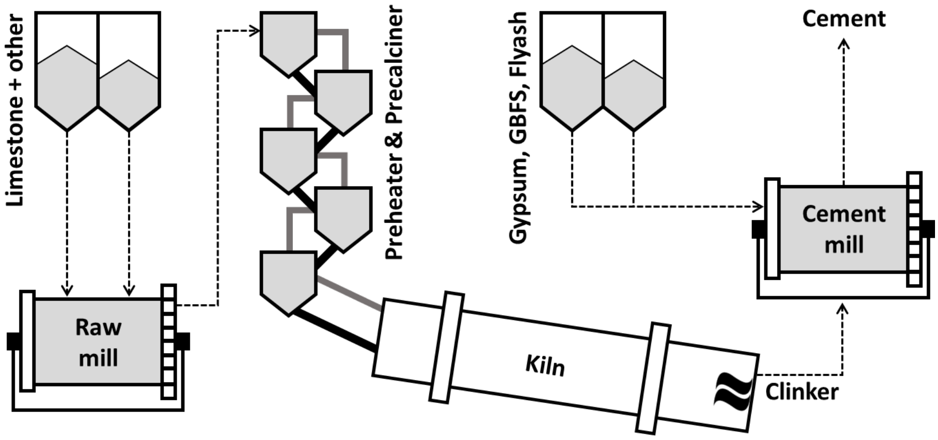
Novel technologies such as CCUS normally experience successive innovation modes before they reach high technological maturity and commercial adoption. In this regard, several mechanisms and strategies can be used to promote CCUS technologies and upgrade them from their current demonstration phase to market development and commercial diffusion. Such tools can be classified in various ways (e.g. market-pull vs. technology-push; market-based vs. voluntary, etc.). Research and pilot projects are an effective technology-push tool to decrease the relevant uncertainties, risks and costs and increase the technology readiness level. In recent years, different CCUS demonstration projects have been implemented and financed differently. This study investigates the role of these projects in the future deployment of CCUS technologies, with focus on the cement sector specifically. As this paper focuses on CCUS technologies which have not yet reached high maturity levels, CO_2 transportation and geological storage have been omitted. The discussions center around CO_2 capture technologies and further sheds light on the potential for CO_2 utilization for permanent sequestration such as carbonation and mineralization.

Overall, this study aims to evaluate the status quo of decarbonization of the cement sector via CCUS and to discuss the required future activities and measures to enhance the technology's integration into the sector. As such, the paper first provides an overview of existing decarbonization technologies in cement production (Section 2). Section 3 then describes a theoretical background on technology innovation modes, the role of pilot and research projects in developing a technology learning curve, and relevant policies. Subsequently, Section 4 presents different CCUS projects in the European cement sector from a techno-economic perspective, and highlights the similarities and differences in terms of funding and supporting mechanisms. Section 5 concludes with lessons for deriving future strategies and underlines challenges and opportunities of developing similar projects in other regions.

2. Decarbonization technologies in the cement sector

Cement production is responsible for six percent of global greenhouse gas (GHG) emissions, rendering the sector the second largest industrial emitter after steel (Bataille, 2019). Cement's carbon footprint averages 0.59 tonne of CO_2 per tonne of cement (IEA, 2021; OWD, 2020), which varies due to different production technologies, fuel mixes, efficiency measures and cement types in each region. While the cement production process is simpler than other emission-intensive industries, its decarbonization can be more challenging. As shown in Figure 1, the production process begins with limestone, which is mixed and grinded with other input materials to prepare the raw material. Input materials are then transferred to the kiln, where temperatures can reach 1450^{o} C, in order to produce clinker. In modern cement plants, the input materials pass through a preheater and precalciner before reaching the kiln. These represent additional modules that can be added to increase energy efficiency and consequently decrease heat consumption. The main reaction in the kiln is called calcination, which is the transformation process of calcium carbonates ($CaCO_3$) to calcium oxides (CaO). This process is responsible for the major part (roughly two thirds) of production emissions ($CaCO_3$ + Heat → CaO + CO_2) (≈ 525 kg CO_2/ton clinker) (Schorcht et al., 2013; ETSAP, 2010). The rest of the direct emissions (approximately one third) can be attributed to the fuel consumption (≈ 3.7 GJ/ton clinker) (IEA, 2022). Finally, cement is produced by grinding and mixing the clinker with other materials such as gypsum and granulated blast furnace slag. The cement production is also responsible for additional indirect emissions due to electricity consumption (≈ 110 kWh/ton cement) (VDZ, 2018).

Figure 1: The cement production process.



Source: based on Kogut et al. (2021)

As process emissions are intrinsically associated with the calcination process, mitigating them can be only achieved via CCUS. CCUS refers to the technique of capturing the CO_2, transporting it and eventually using or storing it. The carbon capture process is an indispensable phase in the CCUS industrial system due to the low CO_2 concentration in the flue gas. It is relatively more expensive than the following steps (i.e. transportation and utilization or storage) and is also associated with various techno-economic challenges, as discussed in a previous OIES Energy Insight paper (Abdelshafy et al., 2022). Some carbon capture techniques have been recognized as suitable technological options for the cement industry, including amine scrubbing, oxyfuel combustion, calcium looping and direct separation. As such, CCUS research and pilot projects in the cement industry have focused on using these technologies.[1]

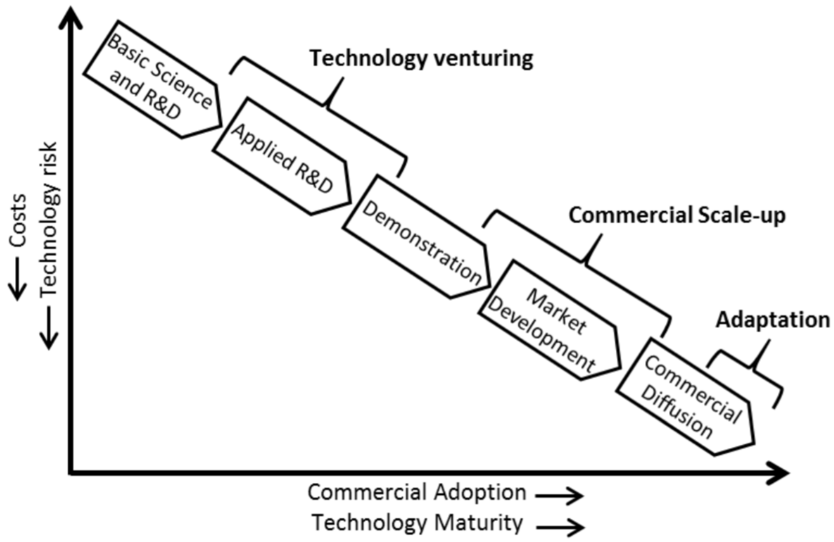
Carbon capture technologies vary significantly in terms of concepts (Abdelshafy et al., 2022), efficiencies, energy requirements (Jensen, 2015; Palma, 2020; Gardarsdottir et al., 2019), technology readiness level (TRL) (Kearns et al., 2021), and capital and operational costs (CAPEX and OPEX) (Anantharaman et al., 2018). For example, amine scrubbing has a high TRL, is already used in some CCS projects, and can utilize the waste heat available in the cement plant (Bellona, 2020). However, the technology is very expensive. Some technologies are expected to be cheaper, but there are challenges with their upscaling (e.g. LEILAC) or they have not been proven at an industrial scale yet. Other technologies (e.g. oxyfuel) are reliable and could be cost efficient. Nonetheless, the final CO_2 purity may not be suitable and an additional module (compression and purification unit) may be needed. To that extent, pros and cons of each technology must be considered and a comprehensive analysis is required. Moreover, as most technologies to be discussed are still under development, there is an evident discrepancy in the literature regarding various techno-economic aspects, even for the same technology. It should be also highlighted that not all available information can be fully reliable as each technology developer or provider normally praises its own technology. Hence, any information, numbers or values regarding superiority should not be adopted without caution.

[1] A brief technical background on each technology is provided in the annex of this paper.

3. The role of research and pilot projects in technology development

Any technology normally passes through various stages and innovation modes before it becomes commercially available in the market (IRENA, 2013). As shown in Figure 2, a technology's lifecycle can be classified into five phases: (1) basic science and research & development, (2) applied research and development, (3) demonstration, (4) market development, and (5) commercial diffusion. These phases can be also grouped into three 'innovation modes': technology venturing, commercial scale-up, and adaptation (where low costs and risk & high maturity are reached). Technology venturing refers to the activities and efforts that are carried out to move the technology from the research and development phases to demonstration. At this phase, the technology is normally associated with low maturity levels, while associated risks and costs are high. Thereafter, the commercial scale-up phase prepares the technology for commercial diffusion. Here, technology risks are lower but economic uncertainties are high. Finally, adaptation is the phase when the technology enters a new market. Numerically, the technological maturity is indicated by the TRL scale which is a widely-used KPI and ranges between 1 and 9 (GAO, 2023).

Figure 2: Innovation modes of clean technologies

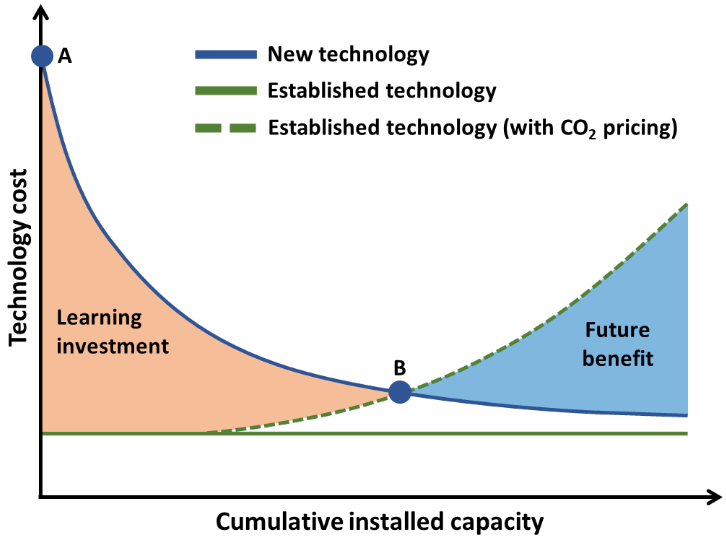


Source: adapted from IRENA (2013).

The reason behind these developments is that "good designs are not always enough", where technologies are only proven and improved by actual operations (i.e. learning by doing) (Ferioli et al., 2009). The first version of any technology or plant, "First-of-a-kind" (FOAK), is usually more expensive and risky than the following ones, "Nth-of-a-kind" (NOAK), in terms of both CAPEX and OPEX (Rubin, 2019; Rubin et al., 2021). In terms of CAPEX, new technologies require more construction time, design margins, redundancy and spare items. Furthermore, new technologies are associated with peculiar designs, nonstandard items, materials and contracts (i.e. there are no economies of scale). Special measures and analyses are also needed to ensure the safety of the design and operations. Correspondingly, acquiring the required permits is more challenging. Such elements have a significant effect on CAPEX. For example, process contingency costs represent more than 40% of the capital costs of a new technology, whereas this figure can be less than 10% for a mature technology (Theis, 2019). Similar figures are also relevant for the different CCUS technologies discussed in this paper (Gardarsdottir et al., 2019). Similarly, the operational costs of FOAK are higher for various reasons. For instance, new technologies can require new materials or chemicals, which may not be available on a commercial scale. The performance of these inputs may also not be guaranteed. Assumptions regarding fixed operational costs (e.g. maintenance, labor, etc.) may also higher and more conservative for new technologies.

This subsequently highlights the importance of the "learning curve". A technology learning curve shows the relationship between technology cost and its cumulative installed capacity. Specifically, the learning rate can be defined as "the relative cost reduction (in %) after each doubling of cumulative production" (Ferioli et al., 2009). Existing technologies with high levels of maturity took a long time to experience such innovation modes and develop their own learning curves. These developments took place within conventional market conditions and without an urgent need to reach certain milestones at specific times. This is in contrast to the development of decarbonization technologies: with an aim to reach carbon neutrality within the next three decades or so, relevant technologies need to reach a meaningful level of maturity and achieve low costs as quickly as possible. However, this represents a major challenge from an economic perspective. The real costs of negative externalities due to the environmental impacts (GHG emissions) are not already reflected in the carbon prices or taxes (Ferioli et al., 2009). Moreover, such costs cannot be introduced promptly due to social and economic reasons (e.g. carbon leakage). Therefore, on the one hand, the technology needs to be demonstrated and used to develop a learning curve, otherwise costs will not decrease. On the other hand, the industrial sector cannot adopt breakthrough clean technologies such as CCUS (especially at current high costs) as they will not be able to retrieve costs back via higher prices. As such, government intervention is required to address such a market failure. Figure 3 depicts the stages of this development.

Figure 3: Technology development, learning investment and future benefit



Source: based on Wiesenthal et al. (2012); Neuhoff (2005); Grubb (2004).

The blue curve represents the learning curve of the new technology (e.g. cement production + with CCUS). In the beginning, the technology is at its highest cost (point A), for instance when a FOAK plant is deployed. The green curve illustrates the cost of the established technology (e.g. cement production without CCUS), which is significantly lower than the new technology. The incremental increase of the environmental costs in the form of higher CO_2 prices will result in the dotted green curve. As depicted, two areas can be identified on the curve: the learning investment and the future benefit. As the cumulative installed capacity of the new technology increases, the technology cost decreases. A cost difference between the new and established technologies remains until both the blue and green curves intersect. Herein, the area between both curves before the intersection point is called the learning investment, which refers to the additional expenditures needed for learning by doing (Grubb, 2004; Wiesenthal et al., 2012), while future benefits are represented by the area following the breakeven point (point B). Expectedly, higher CO_2 prices which occur earlier in this process would result in lower investments and higher benefits (Neuhoff, 2005).

Following on this, the subsequent question is "who should bear the learning investment?". Compared with other industries, such as information technology, required decarbonization investments can be too high, and therefore are too risky. Here, governmental intervention is indispensable for providing an enabling environment for investment (Hansen et al., 2017). Based on the specific objectives and the TRL of decarbonization technologies, there are various options and forms for such interventions (Grubb, 2004). Generally, different policies can be classified into two major categories: technology-push vs market-pull[2] (Table 1) (Groba and Breitschopf, 2013).

Technology-push policies focus on supply by means of decreasing the cost of developing the technology, which is necessary at early stages of innovation (Nuñez-Jimenez et al., 2022; Brem and Voigt, 2009). For example, public funding can be an effective approach for decreasing technology costs and investment risks. On the contrary, market-pull policies aim at increasing demand, which also results in further technology developments. Hence, market-pull options are more suitable after the technology has reached a higher level of maturity. Other examples include imposing specific standards and carbon pricing such as introducing a carbon tax, amongst others. As the paper focuses on technology-push policies, and more specifically on the R&D and demonstration projects, the following section presents the major milestones that have so far been reached in decarbonizing the cement sector in Europe. This subsequently demonstrates the upcoming steps and areas of focus for CCUS technology deployment in the sector.

Table 1: Policies and mechanisms used for promoting clean technologies

Market-pull policies				
Market-based	**Technology-specific**			**Non-technology-specific**
		Price-driven	**Quantity-driven**	EU ETS Carbon Tax
	Investment incentives	Investment subsidies	Tendering systems	
	Generation incentives	Feed-in tariffs		
Command and control	Technology and preformace standards			
Voluntary	Investment promotion			Voluntary agreement
	Generation promotion			

Technology-push policies
Publicly funded R&D projects
Tax credits to invest in R&D
Education & training

Source: based on Groba and Breitschopf (2013).

4. CCUS pilot project in the European cement sector

There are several research and pilot projects that focus on CCUS in Europe. Here we discuss the projects that focus on the cement sector and also show the wide range of investigated technologies, partnerships, funding schemes and budgets. Compared with nationally-funded projects, European projects usually have larger scales due to the size of their funding schemes. Also, consortiums normally include several stakeholders and different countries, which ensures know-how dissemination. The EU framework programme for research and innovation is one of the most renowned EU funding schemes. Its most recent two program versions are (1) Horizon 2020, which ran between 2014 and 2020 with a budget of approximately 80 billion EUR, and (2) Horizon Europe, which started in 2021 and will last till 2027 (budget 95 billion EUR) (EC, 2021). The program's objectives are translated in detailed structure and a series of funding mechanisms and sub-programs. These programs have three main pillars or priorities – excellent science, industrial leadership, and societal challenges, each of which is further divided into subcategories (EC, 2018, 2014). While elaborating on the targets and mechanisms of these programs remains out of this paper's scope, it is noteworthy that they provide significant consideration

[2] Market-pull policies can be also grouped into technology-specific and non-technology-specific, or market-based, command & control, and voluntary.

to themes of climate, industrial transformation and decarbonization. As such, various CCUS projects have been funded by the program (as presented later). The program also allows for public-public partnerships, i.e. co-funding via EU and other governments (e.g. ERA-NET Co-fund) (ERA Learn, 2022). As an example, ACT[3], an ERA-NET co-fund, is an important international initiative that aims at promoting CCUS technologies (Cordis, 2022b; ACT, 2022a) which has so far funded more than 30 CCUS projects (ACT, 2022b).

Another crucial EU funding scheme is the Innovation Fund, which is exclusively dedicated for promoting low-carbon and green technologies (European Commission, 2022a). It is one of the largest global funding schemes that focus on carbon neutrality, and mainly targets four fields: energy-intensive industries, production and use of renewable energies, energy storage, and carbon capture and utilization/storage (Kitscha, 2022). The Innovation Fund is financed by revenues from the EU-ETS with an estimated budget of 38 billion EUR until 2030. The fund supports two types of projects: large-scale (i.e. CAPEX > 7.5million EUR) and small-scale (CAPEX < 7.5million EUR). As will be discussed later, the capital expenditures of the supported large-scale projects in the first two calls are significantly higher than 7.5million EUR. In the first call, 7 large-scale projects were granted 1.1 billion EUR (Marcu et al., 2022). This amount was enhanced by 60% in the second call (1.8 billion EUR) to support 17 large-scale projects (Trendafilova, 2022; European Commission, 2022g). In these two calls, several CCUS projects have been accepted which focus on a wide range of aspects and operations along the CCUS supply chain (GCCSI, 2022).

In contrast, the scale of CCUS projects supported by national funding schemes are mostly smaller than European ones; however, there are examples of generous national and regional funds such as the Longship project in Norway (discussed later). From a broader perspective, there are numerous national programs that support research activities on decarbonization, which also include CCUS. For instance, various CCUS projects in Ketzin pilot site (close to Berlin) were supported by the German federal ministry of education and research (BMBF) and the Germany federal ministry of Economics and Energy[4] (Ketzin, 2022). Some regions and federal states also support similar projects and research activities. For example, the SCI4climate.NRW project focuses on decarbonizing heavy industries in the German federal state of North Rhine Westphalia (NRW) and was financed by the state's ministry of economic affairs, innovation, digitalization and energy (SCI4climate.NRW, 2022). There are also some national research programs or calls that focus exclusively on CCUS research. For example, CLIMIT is a dedicated national program for CCS research in Norway (CLIMIT, 2022). It should be also noted that, although the majority of CCS projects are funded publicly, the private sector still burdens expenses, either within the publicly-funded projects or through research activities that are entirely financed by the companies. Both paradigms are also presented and discussed in the following examples.

4.1 Longship project

The **Longship CCS project** aims at capturing CO_2 from two industrial sites in Norway and store it permanently in an offshore reservoir (around 3 km below seabed) (Lepic, 2021). The project is the first CCS project to cover the whole CCUS value chain (Gassnova, 2020; Bellona, 2020). In total, 800,000 tCO_2 can be captured from Norcem's cement plant in Brevik and the waste incineration plant of Hafslund Oslo Celsio[5] in Oslo (400,000 tCO_2 each) (Figure 4). According to the announced plans, the project should be commissioned in 2024 (Gassnova, 2020). The cement plant of Norcem in Brevik is going to adopt a post-combustion capture technology (amine scrubbing), which will be provided by Aker Carbon Capture. The project is considered as the coronation of several preparations in the last two decades. For example, various desk analyses and small-scale tests have been carried out in the cement plant in Brevik since 2005 in order to investigate the technology and assess its techno-economic feasibility (Bjerge and Brevik, 2014; Brevik, 2022). On the national level, Norwegian advancements in the field of CCS have also been very distinct and effective. For example, the Technology Centre Mongstad (TCM)

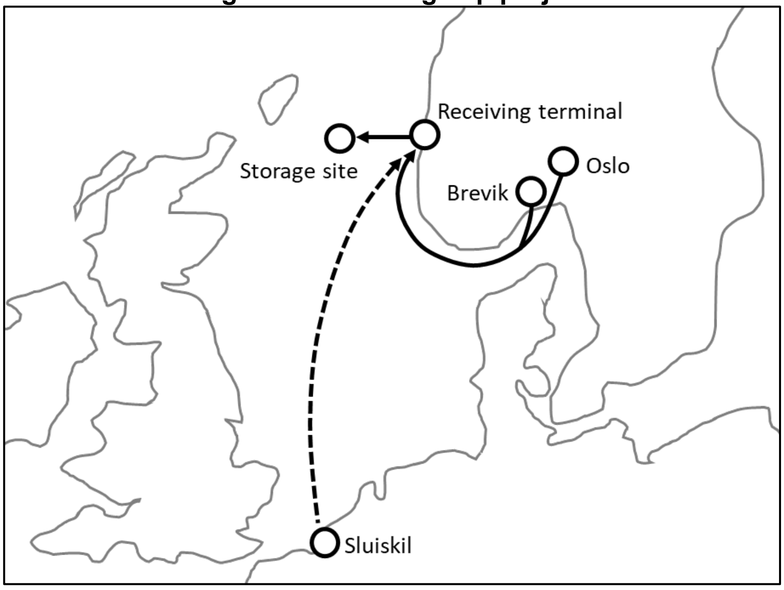
[3] ACT stands for Accelerating CCS Technologies

[4] Now: the Germany federal ministry of Economics and climate protection (BMWK)

[5] Formerly Fortum Oslo Varme

was established in 2012, representing the largest carbon-capture testing center to date (ClimateChance, 2021). Government support covers roughly two thirds[6] of the Longship project costs in the first phase (Knudsen et al., 2022). Such significant amount of public financial support (18 billion NOK ≈ 1.8 billion USD) is unprecedented for a climate project in Norway, likely also in comparison to many other countries (NMPE, 2021; Lepic, 2021). Moreover, the state also acts as an intermediary[7] between CO_2 emitters and the Northern Lights project, and takes the burdens on significant risks (e.g. CO_2 leakage) (NMPE, 2020).

Figure 4: The Longship project.



Source: BrevikCCS (2022).

4.2 Horizon 2020 projects

There are various Horizon 2020 projects that focused on CCUS in the cement industry. First, there is **CEMCAP** (CO_2 capture from cement production), a project which aimed at identifying and analyzing carbon capture technologies suitable for the cement industry and provide the required techno-economic analysis needed for the large-scale projects. In this project, five technologies were selected to be investigated in detail, mainly via desk analysis (amine scrubbing, chilled ammonia, oxyfuel, membrane-assisted CO_2 liquefaction and calcium looping). Knowledge dissemination has been very important in this project. The analyses were both copious and informative, with several scientific studies published based on the project's outcomes, including: (Lena et al. 2019; Ditaranto and Bakken 2019; Alonso et al. 2017; Voldsund et al. 2019; Gardarsdottir et al. 2019). The extensive simulation and desk assessments of the mentioned technologies can be considered a comprehensive reference.[8] The project's budget was 10million EUR, of which roughly 90% was covered by the EU and 700k EUR was a contribution from the Swiss Government (Cordis, 2022c; CEMCAP, 2022b). The project included 15 partners[9] and lasted 42 months (2015-2018).

Second, **LEILAC** (Low Emissions Intensity Lime and Cement), which is the only pilot-scale project that demonstrates the direct-separation capture technology discussed earlier. The first phase (LEILAC 1)

[6] There is a discrepancy about the exact governmental support

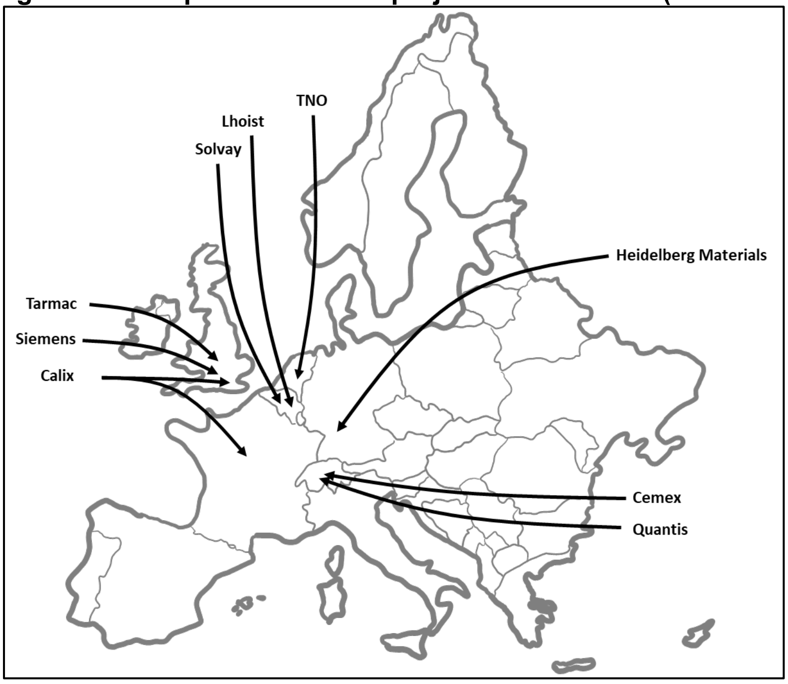
[7] There is actually no direct contract between the emitters and Northern Lights project

[8] A full list of the project's reports and publications can be found on the project's website (CEMCAP, 2022a).

[9] Italcementi Group (now Heidelberg Materials), NORCEM, Heidelberg Materials (formerly HeidelbergCement), GE, GE power, IKN, Thyssenkrupp, SINTEF, ECRA, TNO, ETH Zürich, Unoversity of Stuttgart, Politenco di Milano, CSIC and VDZ

has been a Horizon 2020 project with 11 partners[10] and a duration of approximately 5 years (2016-2021) (Figure 5). Within this phase, the technology developed by Calix was tested in Lixhe (Belgium) with a capture capacity of 25,000 tCO_2 per year (Beumelburg, 2021). The project budget was roughly 21million EUR, of which more than 50% was funded by the EU (Cordis, 2022f). The success of the first pilot project led to the initiation of the second phase (LEILAC 2), which is also funded as a Horizon 2020 project. LEILAC 2 aims at scaling up the capture capacity four times to reach 100,000 tons of CO_2 per year, which corresponds to one fifth of the cement plant that hosts the project (Heidelberg Materials' plant in Hanover). Moreover, the project aims to assess storage options and the possibility of using more types of energy inputs (i.e. electrification, alternative and renewable fuels) (Coppenholle and van der Meer, 2021). The overall budget is estimated to be more than 1.5 times the amount of the first project (approximately 35million EUR), of which the EU will contribute 16million EUR (Cordis, 2022g). Similar to the first phase, the project encompasses several industrial and academic partners[11] and is supported by 6 entities[12] (LEILAC, 2022).

Figure 5: Example of a Horizon project's consortium (LEILAC 1).



Source: Cordis (2022f).

Third, **ACCSESS** project (providing access to cost-efficient, replicable, safe and flexible CCUS), which was launched in 2021 and will last for four years. The project activities focus on CCUS in different industries from an interdisciplinary perspective, which is why the consortium include a wide range of stakeholders[13]. The total cost is approximately 18.5million EUR, of which 15million EUR are provided by the EU (Cordis, 2022a). The project activities are classified into three areas: (1) conventional cement kiln & new capture technology, (2) conventional capture technique & new cement kiln, and (3) concrete carbonation (ACCSESS, 2022d). The novel carbon capture technology is a combination of two new concepts: enzymatic solvent and rotary packed bed (RPB) absorber. Due to the low regeneration

[10] Heidelberg Materials, CEMEX, Lhoist, PSE, Quantis, Tarmac, The Carbon Trust, TNO, Calix, Solvay, and Imperial College London

[11] Heidelberg Materials, CEMEX, BGR, The Centre for Research and Technology Hellas, CIMPOR-Indústria de Cimentos, ENGIE Laborelec, Calix, The Geological Survey of Belgium, IKN GmbH, Lhoist, Politecnico di Milano and the Port of Rotterdam

[12] GCCA, GCCSI, CEMBUREAU, ECRA, University of Clausthal and EuLA

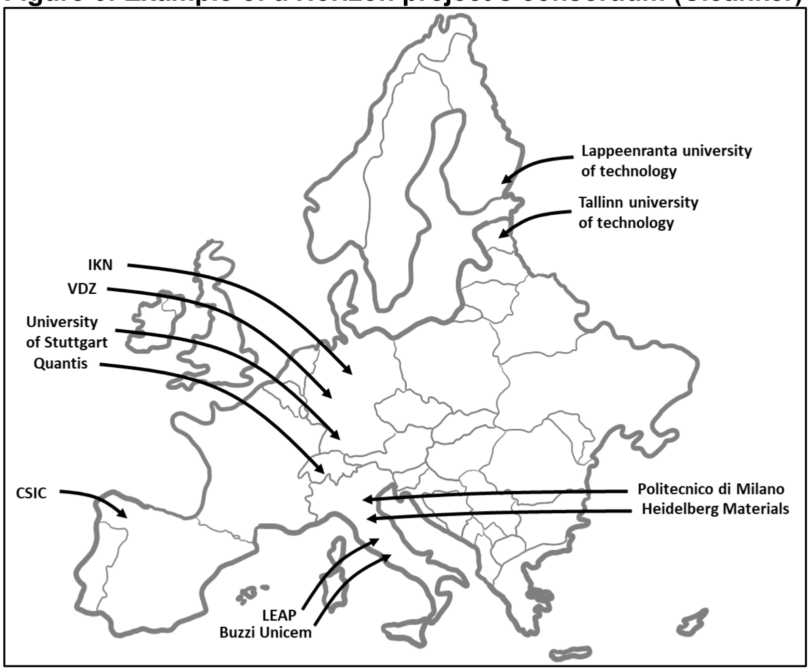
[13] SINTEF, Stora Enso, Heidelberg Materials, Hafslund Oslo Celsio, SEIPEM, Prospin, Neustark, Linde, KHD Humboldt Wedag, Equinor, Total Energies, Technology Centre Mongstad, VBSA, ETH Zürich, VDZ, Fraunhofer IAO, Chalmers University of Technology, Heriot-Watt University

temperatures of the enzymatic solvent (up to 80°C) and the compact size of the RPB absorber, energy and costs savings can be achieved (ACCSESS, 2022b).

The project offers an exemplary model of the synergies between several industrial partners and effective distribution of roles. This is clearly manifested in the project's roadmap to upgrade the TRL of the new capture technology to reach TRL 7 (ACCSESS, 2022a). The lab-scale RPB technology is to be tested by Prospin in Poland and the Saipem solvent will be tested in the waste-to-energy plant of Hafslund Oslo Celsio in Oslo, Norway. Afterwards, both technologies are to be commissioned in Technology Centre Mongstad (Norway). Finally, two pilot-scale test campaigns are planned to be carried out for six months in the pulp and paper mill of Stora Enso in Skutskär (Sweden) and the cement plant of Heidelberg Materials in Górażdże (Poland) (ACCSESS, 2022c).

Fourth, the **Cleanker** project (clean clinker production by looping process), which aims at demonstrating a calcium-looping capture technology at TRL 7. The project investigates an integrated configuration of the technology which is provided by IKN and tested in the Vernasca cement plant of Buzzi Unicem (Italy). The technology also uses an oxyfuel combustion during the calcination process in order to obtain a pure CO_2 stream (Fantini, 2019). Moreover, the project aims at testing different types of raw meals and demonstrating carbon sequestration via mineralization (Fernandez et al., 2019; Yörük et al., 2020; Magli, 2021). Besides the technical assessments, the project also investigates the economic and environmental aspects (Sessa and Kounina, 2019; Fantini, 2018) and considers the subsequent phases after CO_2 capture (i.e. transportation and storage) (Shogenova et al., 2021; Shogenova et al.). The consortium comprises 13 stakeholders[14] that represent 5 EU countries[15] and various profiles (academia, industrial associations and companies) (Figure 6). The project started in 2017 and is planned to be accomplished in the first quarter of 2023. The total budget is 9.2million EUR, of which approximately 9million EUR is an EU contribution and the rest is provided by the Chinese Government (Cordis, 2022e). A full list of the project's reports and publications can be found on the EU CORDIS platform (Cordis, 2022d).

Figure 6: Example of a Horizon project's consortium (Cleanker)



Source: Cordis (2020).

[14] Leap, CSIC, VDZ, Politecnico di Milano, Tallinn University of Technology, Lappeenranta University of Technology, University of Stuttgart, Tsinghua University, Quantis, IKN, Buzzi Unicem, Heidelberg Materials and Amici della Terra

[15] Including two stakeholders from Switzerland and China

Other projects have been financed via the ACT co-fund, such as **AC²OCem** project (Accelerating Carbon Capture using Oxyfuel technology in Cement production) (AC²OCem ,2022c). As the Oxyfuel technology has been also investigated in other previous and ongoing projects, the analyses do not start from scratch but rather address the knowledge gaps and build on existing know-how. The project activities, which include analytical and experimental assessments, should support increasing the TRL of the 1^{st} generation oxyfuel to reach 8 (currently 6) and the TRL of the 2^{nd} generation to reach 6 (currently 2). For the 1^{st} generation technology, the analyses focus on designing and optimizing the retrofitting of existing cement plants. Here, the project considers two actual case studies: Lägerdorf cement plant of LafargeHolcim in Germany and Slite cement plant of Heidelberg Materials in Sweden (Kroumian et al., 2021). The pilot-scale experiments of the 2^{nd} generation have also been carried out at the institute of combustion and power plant technology (IFK) – University of Stuttgart (Volosund et al., 2021). Particularly, this project investigates using 100% alternative fuels, which can lead to negative emissions if bio-based energy sources are used (AC²OCem, 2022c). Also, similar to other projects, minimizing the energy consumption as well as CAPEX and OPEX is one of the main project's objectives (Maier, 2019). The respective consortium comprises 11 stakeholders[16] from five countries (Germany, France, Greece, Norway and Switzerland) (AC²OCem, 2022b). The project started at the end of 2019 with a duration of 3.5 years and a budget of roughly 4.3million EUR. Approximately 3million EUR have been provided by the ACT program and the rest secured via private financing and financial support from the governments of the participating countries (AC²OCem, 2022a; VDZ, 2022).

Another ACT project is **ANICA,** which focuses on an advanced indirectly heated carbonate looping process (Ströhle et al., 2021). The technology is based on heating the calciner indirectly by means of heat pipes (Greco-Coppi et al., 2021a; Konstantina et al., 2021). Similar to AC²OCem, the project also includes both analytical assessments and experimental analyses, which aim at reducing the capture costs and improving the technology to reach TRL 6 (ANICA, 2022d). Besides modelling and process simulation, the concept has been tested in a pilot plant with a capacity of 300 kW_{th} at TU Darmstadt (ANICA, 2022a; Ströhle, 2020). Additionally, the project provides a design of 20 MW_{th} demonstration plant, which is needed to increase the TRL (ANICA, 2022b). The project also focuses on using alternative and biogenic fuels, which can lead to negative emissions and cast savings (Greco-Coppi et al., 2021b). The possibility of integrating the direct separation concept (LEILAC) is also investigated (ANICA, 2022c). Moreover, the analyses include techno-economic and environmental assessments of different scenarios and conditions (Rolfe et al., 2022). The consortium of ANICA consists of twelve stakeholders[17] from three countries (Germany, Greece and the UK), and its duration and budget are analogous to AC²OCem (ACT, 2019).

4.3 Upcoming & recently-launched large-scale projects (Private & Innovation Fund)

Recently, some pilot- and industrial-scale CCUS projects have been announced in the cement sector, which demonstrate the momentum and techno-economic advancements that the preceding research projects have achieved. Although there is still no detailed information or reports on these new projects, available announcements and descriptions already provide some insights on how they are going to develop in the coming decades. For instance, the **Catch4climate** is a joint venture that was recently established in order to demonstrate the pure-oxyfuel technology at a pilot scale (Catch4climate, 2022). The capacity of the test kiln is approximately 165,000 t/y, which is under construction in the Mergelstetten cement plant of Schwenk (Henrich, 2021). The required investments are more than 100million EUR, which are going to be covered by four European cement producers (i.e. Heidelberg Materials, Dyckerhoff, Schwenk, Vicat) (Thormann, 2021). The pure-oxyfuel technology (polysius) is provided by Thyssenkrupp Industrial Solutions (ThyssenKrupp, 2022). According to the announced plans, the project will operate within the next two years (Kaschke, 2021).

[16] University of Stuttgart, SINTEF, NTNU, VDZ, CERTH, Thyssenkrupp, Heidelberg Materials, LafargeHolcim, Titan, Air Liquide and Total.

[17] TU Darmstadt, University of Erlangen–Nuremberg, VDZ, Dyckerhoff, Lhoist, SUEZ Recycling, ESTRA, Ulster university, Calix, CERTH and CaO Hellas.

There are also five relevant large-scale projects that have been selected for the Innovation Fund. First, the **GO4ECOPLANET** project in the cement plant of LafargeHolcim in Kujawy (Poland). The total project costs are approximately 4.7billion EUR, of which 260million EUR are capital costs and 265million EUR are provided by the EU (European Commission, 2022e). The project should sequester more than 10Mt CO_2 in the first decade of operations, using the CryoCap FG technology developed by Air Liquide which is a combination of both adsorption (Pressure Swing Adsorption/PSA) and cryogenic carbon capture techniques (Rodrigues et al., 2021; Global Cement, 2022). The captured CO_2 will be transported to Danzig via railway and then shipped to the North Sea for geological storage.

The second project is **Carbon2Business (C2B)**, which will be implemented in Lägerdorf cement plant of LafargeHolcim (Germany). In total, the project will cost roughly 6billion EUR, of which 410million EUR are capital costs and 110million EUR are the EU contribution (European Commission, 2022c). Based on the official announcement, the second-generation oxyfuel technology will be used and approximately 13Mt CO_2 will be sequestered in the first ten years of operations. The project location should also allow future synergies within the potential industrial cluster of Westküste 100 (e.g. CCU) (Holcim Deutschland, 2022; Westküste, 2022). Third, there is the **CalCC** project in the lime plant of Lhoist in Réty (France). The project will also adopt the cryogenic technology (Cryocap) of Air Liquide and is planned to sequester 5.8Mt of CO_2 (European Commission, 2022d). The captured CO_2 is planned to be transported by a pipeline to Dunkirk and then via shipping to the North Sea for geological storage. The total project costs are expected to be more than 3billion EUR, of which 200million EUR are capital costs and 125million EUR will be provided by the EU.

Fourth, the **ANRAV project** in Devnya cement plant of Heidelberg Materials (Bulgaria) is expected to sequester 7.8Mt CO_2 in the first decade of operations. In terms of technology, not a lot of technical information is currently published on the project. According to the EU innovation fund platform, the project will demonstrate a hybrid capture technology concept (i.e. Oxyfuel and Amine) and will be supported by 190million EUR from the EU (European Commission, 2022b). The company also announced that the captured CO_2 will be transported via a pipeline to be geologically stored in the Black Sea (Beumelburg, 2022). Finally, the **K6 program** in the cement plant of EQIOM (CRH) in Lumbres (Hauts de France) France will use two technologies (i.e. oxyfuel and cryogenic carbon capture) and eliminate 8.1Mt of CO_2 in the first decade of operations (European Commission, 2022f). The project partner Air Liquide is going to supply the oxygen and provide its cryogenic technology (Cryocap) (AirLiquide 2022). The project's location (Northern France) will also facilitate transporting the captured CO_2 to the North Sea to be geologically stored. Moreover, it will also allow synergies with the potential CO_2 hub in Dunkirk. The total costs of both the K6 program and the ANRAV project are not announced, but will likely be in the range of costs of other Innovation Fund projects (i.e. billions). The K6 program is going to receive approximately 150million EUR as an EU contribution.

4.4 Carbonation and mineralization projects (National Fund)

Although the majority of projects focus on carbon capture, there are some European and national projects that have been dedicated to CO_2 sequestration via carbonation and mineralization. An example is **CO2MIN** which is a BMBF project that investigated the potential of mineralization from an interdisciplinary perspective for three years (2017-2020) (BMBF, 2017). The project had three stakeholders (Heidelberg Materials, IASS Potsdam and RWTH Aachen University) and a budget of approximately 2.9million EUR. The project generated a wide-range of analyses such as optimizing the mineralization process design (Bremen et al., 2022), techno-economic modelling and cost analyses (Strunge et al., 2022b; Strunge, 2021), environmental assessment (Ostovari et al., 2021), policy analysis (Olfe-Kräutlein et al., 2021), and studying the perception of the relevant stakeholders, and providing a multi-criteria decision analysis (Strunge et al., 2022a). The **C²inCO2** is a more recent BMBF project that focuses on carbonating recycled concrete and subsequently using it (Schmitt, 2020). The project started in 2020 and will last till 2023, with a budget of 3.2million EUR (BMBF, 2020). As the project aims at investigating all relevant upstream and downstream operations, the consortium is composed of seven stakeholders[18] that represent the whole value chain (Fraunhofer, 2021; CO2WIN, 2020). According to the announced plans, the analyses shall include (1) improving the recycling process in order to yield a concrete waste stream with a higher quality, (2) investigating the carbonation process and using the carbonated outcomes in the cement production, and (3) conducting a life cycle assessment.

FastCarb is another project that has also focused on carbonating recycled concrete (Torrenti et al., 2022). The project had 23 stakeholders[19] and was supported by the French Government (FastCarb, 2021b). The analyses were carried out in both lab and industrial scales to address various knowledge gaps. The lab experiments aimed at demonstrating the concept and assessing the impacts of the relevant factors on the carbonation performance (e.g. water content, physical properties, CO_2 concentration, kinetics, etc.) (Sereng et al., 2020; Sereng et al., 2021). Industrial-scale trials were also conducted in two cements plants (Créchy & Val d'Azergues) via retrofitting and using existing equipment (Izoret et al., 2023). Additionally, life cycle assessment and cost analysis were also conducted in order to study the environmental impact the economic feasibility (FastCarb, 2021a). Another project is **RECODE** (Horizon, 2020), which focused on a different carbonation technique (RECODE, 2022b). The analyses focused on the potentials of using the flue gas of the cement plant to produce calcium carbonates nanoparticles and other chemical products (RECODE, 2020). The project ran for 5 years (2017-2022) with a consortium[20] of 13 stakeholders (6 EU countries) and a budget of approximately 8million EUR, which was fully covered by the EU (Cordis, 2022h).[21]

5. Discussion and conclusions

The paper investigated several projects that cover various types of technologies and also different funding schemes and paradigms (e.g. EU, national and industrial). These projects do not only provide important scientific outcomes, but their wide variety also offers a unique opportunity to empirically study their development and impact on technology deployment. Although it is not easy to determine the usefulness of each project individually or track the exact trajectory of their technology's development, their respective TRL increase in the past years demonstrates the overall value and effectiveness of these projects. Analyzing the large number of projects that have been financed and carried out in the last decade is of importance to derive and improve R&D strategies, not only in Europe but also in other regions. It is important to note that such projects and funding programs should not be isolated from other policies and tools (e.g. Carbon Border Adjustment Mechanism and Carbon Contracts for Difference) or other relevant lending and investment programs (e.g. InvestEU, NextGenerationEU) (Janda and Sajdikova, 2022). Each of these aims at addressing a specific challenge or market failure, but they jointly provide the required enabling environment for relevant technologies to be developed and deployed at scale.

Admittedly, such number, scale and types of projects may not be found in other regions outside the EU, even in other developed and industrialized economies. Investigating *why* that is the case remains beyond the scope of this paper, but there are some obvious factors behind this phenomenon. First, there is a high public awareness and an interest from EU citizens (taxpayers) in environmental themes, which places pressure on policymakers. This has recently clearly manifested in a multitude of EU and national environmental policies (e.g. the green deal and the European climate law). Second, companies dare to invest in developing and testing these technologies as there is a good level of mutual trust

[18] Fraunhofer IBP, Heidelberg Materials, Thyssenkrupp, Loesche GmbH, Sika, Bauhaus University Weimar, RWTH Aachen University

[19] Université Gustave Eiffel, CSTB, Cerema, CERIB, ATILH, CEMEX, Ciments Calcia, CLAMENS, EQIOM, LAFARGE France, SNBPE, UNPG, VICAT, Saint-Gobain, FFB, Nicolas Jacquemet EIRL, Ecole des Ponts ParisTech, ESTP, GeM, Icube, LASIE, EPAMARNE

[20] Fonadazione Istituto Italiano di Tecnologia (IIT), Avantium, Certh, European Research Institute of Catalysis, DVGW, KIT, Politecnico di Torino, RUG, Hysytech, Iolitec Ionic Liquids Technologies, Uab Modernios e-Technologijos, MTM and Titan cement

[21] A full list of outcomes (reports and publications) can be found on the project's website (RECODE 2022a).

between the policymakers and the industrial system. Even more, there is perhaps a strong notion that the announced targets have to be, or will be, achieved, where today's investments will yield future savings and benefits. Third, time/urgency is one of the main challenges associated with the energy transition. If carbon neutrality were to be met in the coming three decades, any potential useful technology, implemented in any of the major emitting sectors, should not be disregarded.

Fourth, low-carbon technologies offer new business models and opportunities. For example, the Norwegian CCS activities (e.g. Longship) should not only be seen from an environmental lens. The potential economic benefits which can be accrued, including creating job opportunities and becoming a prospective carbon hub, can be an additional motive to promote the CCS supply chain and relevant research activities and technologies (Knudsen et al., 2022). Another significant aspect which is explicitly relayed by the Norwegian Government is the importance of the project and the whole CCS supply chain in the production of blue hydrogen (NMPE, 2021). Such notion or conception should be also clear for other countries which have significant reserves of hydrocarbons (e.g. Saudi Arabia/gulf region). On the one hand, CCS can transform fossil energy resources to clean energy carriers (i.e. blue hydrogen), at least as an intermediate solution in the short- and mid-term. On the other hand, depleted oil and gas fields are also ideal candidates (and also cheaper than other alternatives) for storing hard-to-abate CO_2 (e.g. from the cement industry), not only from national producers but also cross-border ones

Along the CCS supply chain, carbon capture is considered as the main bottleneck towards the technology's deployment, due to its high costs and techno-economic uncertainties. This is why a large number of CCS projects have been focusing on developing capture technologies in order to make them cheaper and more reliable. In the same context, the majority of these projects have been publicly funded and supported as an effective technology-push policy. It should be highlighted that governmental support should not only be limited to the financial aspects. As some of these projects and technologies are being established for the first time, the flexibility and understanding of the relevant governmental bodies are also mandatory (e.g. for permitting) (Climate Group, 2021). Policymakers and strategists should be also aware of the temporal dimension of these undertakings as a long time will be needed until such sophisticated technologies reach a high TRL. For example, projects under the EU Innovation Fund are going to be operational by the end of this decade.

It is clear that main industrial partners in the aforementioned projects are large and multinational companies. These operators can benefit from economies of scale by allocating the financial and know-how resources that will support many plants. Here, lessons and know-how can be transferred to other plants and subsidiaries of the same company. In comparison, smaller companies may not afford that. It is thus unclear whether smaller companies which are involved in the cement business in some European countries, such as in Germany, would be capable of surviving without support for such expensive research activities and required investments. The industrial sector cannot, and should not, bear the costs of increasing the TRL of all these technologies from 1 to 9. Each project type and funding scheme can be considered as a filtration phase for the next one. The number and types of technologies decreases once the technologies move from the lab-scale to the pilot- and industrial scale. This is also evident in the number of projects (and their budgets) within the different funding schemes presented earlier. Each project is normally based on previous activities and a former project (with a smaller budget). For example, the EU contribution per project in its Innovation Fund is around ten times the contribution per project in the Horizon 2020 projects. However, the number of projects is significantly lower due to the need to demonstrate the technology on a larger scale. Overall, this paper highlighted how a technology, CCUS in this case, needs to pass through various development and innovation phases before it is demonstrated and approved – depending on its various degrees of costs and risks – and should represent a starting point for further research on CCUS developments in the cement sector in other regions of the world.

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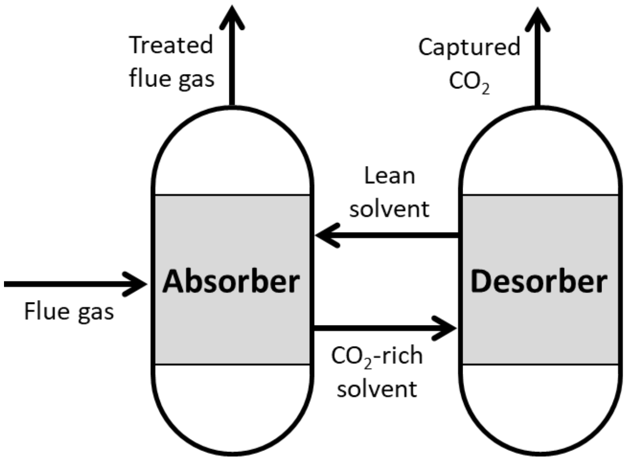
Annex

A brief technical background on carbon capture and CCU technologies

Amine scrubbing & Chilled ammonia

The amine scrubbing and chilled ammonia technologies capture CO_2 by chemical absorption, which is based on the different solubility between the CO_2 and the other flue gas components. Herein, the CO_2 reacts with the solvent (e.g. monoethanolamine) and the rest of flue gas leaves the absorber. Afterwards, the CO_2-rich solvent is sent to the desorber for heat regeneration, and the pure CO_2 stream can then be acquired (Figure 1A). The amine scrubbing technology has a high maturity level as it has been already in use for decades. The technology has been used for CO_2 capture from hydrogen and natural gas since the 1930s (Rochelle 2009). The notion of using it for capturing the CO_2 from the flue gas has evolved in the 1970s, basically for commercial applications, i.e. Enhance Oil Recovery (EOR) (Fang and Zhu 2016). Some CO_2-EOR projects in North America are currently supplied by CO_2 captured by Amine scrubbing from an industrial flue gas (Panja et al. 2022). However, the technology is costly and associated with drawbacks such as costs, high energy consumption, corrosion and degradation (Park et al. 2015). Variations of concept and technology are being investigated in order to achieve cost reductions and avoid the technical problems.

Figure 1A. Amine scrubbing carbon capture process

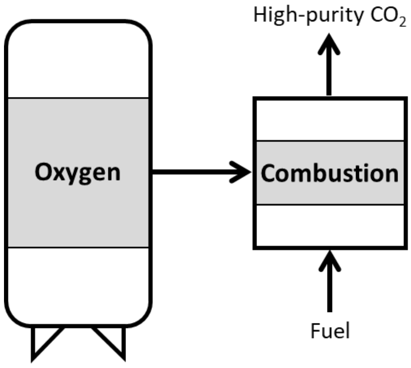


Source: based on Abu-Zahra et al. (2016); Fang and Zhu (2016)

Oxyfuel combustion

The combustion process is normally performed using air, which results in low concentrations of CO_2 in the flue gas. Contrariwise, the oxyfuel technology is based on carrying out the combustion process with oxygen, which yields a high-concentration CO_2 stream (Figure 2A). In contrast to the post-combustion technologies, the oxyfuel technology is an integrated technology, which necessitates some alterations in the cement kiln. According to (Anantharaman et al. 2018), no additional fuel consumption is needed after converting the kiln to oxyfuel combustion. Also, several components of the conventional cement plant can still be used for the retrofitted plant. The main additional components are the Air Separation Unit (ASU) and the auxiliary equipment needed for providing the oxygen to the burners. Also, as the oxyfuel technology yield a CO_2 stream with a relatively low purity (Murugan et al. 2020), an additional compression and purification unit (CPU) would be needed (based on the required purity for transportation and storage) (Kolster et al. 2017). The technology is also subject to modifications and updates in order to improve the performance. For example, while the oxygen is normally mixed with the flue gas in the conventional version of the oxyfuel technology (so called first-generation), a pure oxygen stream will be employed in the second-generation, which can lead to higher efficiency and cost savings (Volosund et al. 2021; Kroumian et al. 2021; Pikkarainen et al. 2014).

Figure 2A. Oxyfuel combustion

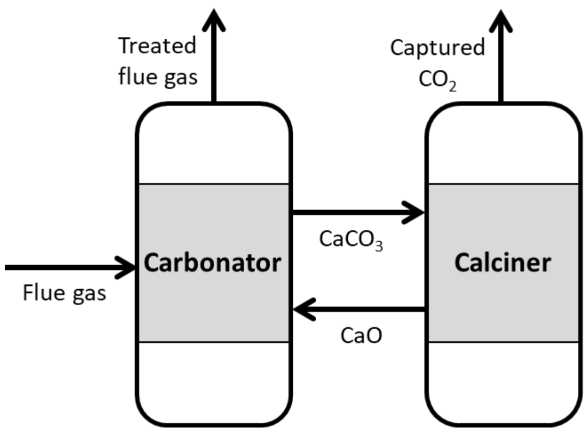


Source: Author's own visualisation

Calcium Looping

The concept of calcium looping carbon capture is based on the chemical reactions of carbonation and calcination (CaCO3 <--> $CaO + CO_2$). As shown in Figure 3A, the flue gas firstly enters the carbonation chamber (carbonator), where the carbon dioxide in the flue gas reacts with the calcium oxides and forms stable calcium carbonates ($CaO + CO_2$ --> $CaCO_3$) (600-700 degree) (Valverde et al. 2014). The treated flue gas is then released to the atmosphere and the calcium carbonates are then transferred to the calcination chamber (calciner) (900 degree). The calcium carbonates are then calcined to generate a pure carbon dioxide stream and calcium oxide, which is then transferred again to the carbonator to act as a CO_2-sorbent. The technology can be designed in two configurations; tail-end or integrated. While the calciner module is integrated into the cement production process (i.e. in the main calciner system) in the integrated version, the tail-end configuration does not require any retrofitting as the technology deal with the flue gas from the kiln. However, the later configuration has a lower energy efficiency. Similar to the other capture technologies, different operating conditions and parameters are being investigated (Ortiz et al. 2015; Diego et al. 2016; Arias et al. 2017; Lena et al. 2018; Hornberger et al. 2021; Moreno et al. 2021). For example, some studies suggest different sorbents (e.g. dolomite), due to their superior performance (Perejón et al. 2016). The integration of calcium looping with oxyfuel combustion has been also investigated in order to capture more carbon dioxide (Arias et al. 2018; Anantharaman et al. 2018).

Figure 3A. The calcium looping technology

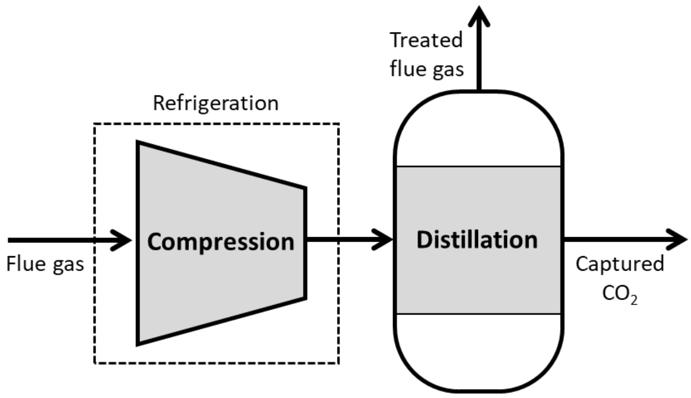


Source: based on Romano et al. (2013); Lena et al. (2018); Arias et al. (2017)

Cryogenic Carbon Capture & Membrane-assisted CO_2 Liquefaction:

The cryogenic carbon capture is a post-combustion technology based on physical separation at low temperatures (Font-Palma et al. 2021). Herein, the different boiling points of the flue gas components are used to segregate the CO_2 stream in a phase different than the other gases (liquid or solid). The flue gas is first pretreated and then refrigerated at very low temperatures (–100ºC:–135ºC). Accordingly, the CO_2 will be transformed to the solid phase and can be separated from the flue gas (Figure 4A). The capture efficiency can be controlled by varying the parameters (e.g. temperature and pressure). As the process involves several cooling and warming cycles, the energy efficiency can be increased by using heat exchangers. There are various configurations and designs in the literature, each claims a superior performance (Liu et al. 2020; Hoeger et al. 2021; Keshavarz et al. 2019; Baxter et al. 2018; Baxter et al. 2009). Besides cryogenic carbon capture, membrane-assisted CO_2-liquefaction is also a capture method that uses low temperatures and phase separation (Bouma et al. 2017). Herein, the membranes are firstly used to yield a CO_2 stream in a moderate concentration (Baker et al. 2018). In the second step, a coldbox is used to cool this stream down to –54º C, which is then send to a vapour-liquid separator to accomplish the CO_2 capture process (Anantharaman et al. 2018).

Figure 4A. Cryogenic carbon capture

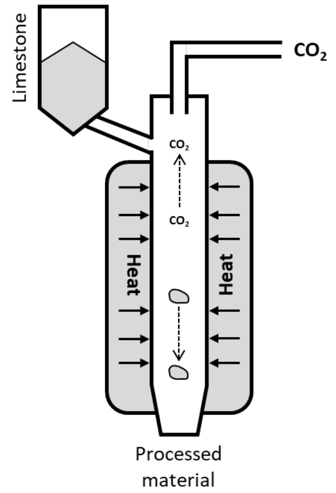


Source: based on Liu et al. (2020); Hoeger et al. (2021); Keshavarz et al. (2019); Baxter et al. (2018); Baxter et al. (2009)

Direct separation

While the preceding technologies capture the CO_2 from the flue gas, the concept of direct separation is quite unique as it is based on capturing the process CO_2 before it is diluted. In order to achieve that, the technology is designed to carry out the calcination process indirectly in an isolated environment (LEILAC 2021a). As shown in Figure 5A, the calcination tube is heated from the outside surface. In the first version of the technology, natural gas burners have been used as an energy source. While the raw meal or limestone passes through the tube from top to down, the calcination process is executed via radiative and conductive heat transfer (Hills et al. 2017). Eventually, the calcined materials can be collected from the bottom and the high-concentration CO_2 can be collected at the top. As the technology is relatively uncomplex and does not need additional energy to separate the CO_2 from the flue gas, it is claimed to have low energy penalty, and lower OPEX and CAPEX than other carbon capture technologies (LEILAC 2021b). However, it should be highlighted that the technology can only capture the process emissions. Therefore, the rest of the emissions (i.e. fuel emissions) still need to be captured by other techniques. According to (LEILAC 2020), these remaining fuel emissions can be eliminated via electrification or using renewable fuels. An ambitious goal could be also using biomass as energy input along with other post-combustion capture technologies, which can result in negative emissions. As will be discussed later, only one pilot project has been carried out, which was an important milestone to address some doubts and challenges such as the steel stability and performance at high temperatures (approximately 1000ºC) (Sceats 2017), energy consumption, process and safety (Winskell 2021).

Figure 5A. The LEILAC technology

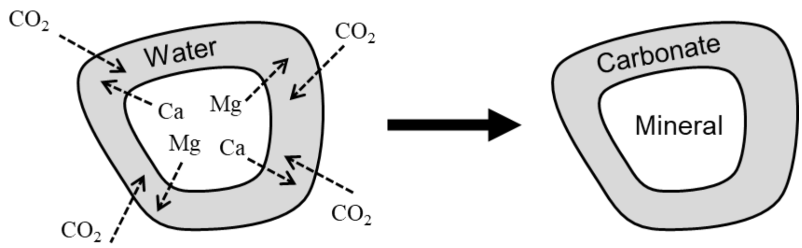


Source: based on LEILAC (2021a); Hills et al. (2017)

Carbonation & Mineralization

Besides geological storage, some alternatives can be also used for permanent carbon sequestration. Carbonation and mineralization are two sequestration techniques that make use of the oxides in the cementitious materials and natural minerals, respectively. Similar to the calcium looping technology, this process is the reverse of calcination ($M^{+}O + CO_2 \rightarrow M^{+}CO_3$). The reaction of concrete compounds (e.g. CSH and CAH) with CO_2 in an aqueous environment results in carbonates, which are stable compounds (Kaliyavaradhan and Ling 2017). Similarly, natural minerals such as serpentine, olivine and wollastonite also contain oxides, which can react with CO_2 and yield carbonates (Figure 6A) (Sanna et al. 2012; Gerdemann et al. 2007). Similar to the preceding technologies, the literature contains various versions and designs of the process (e.g. static and dynamic) (Iizuka et al. 2004; Iizuka et al. 2013; Zhan et al. 2013; Skocek et al. 2020). The main components are the curing chamber, where the reaction takes place, and some auxiliary equipment such as tanks and controllers. Herein, the CO_2 sequestration capacity depends on the properties of the material to be carbonated (e.g. cement content and surface area) and the curing conditions (e.g. temperature, pressure and humidity). The described principle is quite analogous for the minerals, concrete waste and precast concrete, which has been so far investigated on lab and pilot scales. In terms of ready-mix concrete (RMC), there are already some industrial applications based on another concept. The technology of CarbonCure depends on adding a small amount of CO_2 to the concrete, which result in a nano-scale carbonation. As a result, the concrete properties are improved and less cement is needed (Monkman and MacDonald 2017; Monkman and Cail 2019). Additionally, the concrete wash water is carbonated and can be added to the concrete. Combinedly, both effects (i.e. cement savings and CO_2 sequestration) result in lower carbon footprint (Monkman et al. 2018; Monkman and Thomas 2021).

Figure 6A. Mineralization/carbonation process



Source: based on Reddy et al. (2019)