Accelerating Carbon Capture using Oxyfuel technology in Cement production

AC^{2}OCem

FINAL Review Report

1. Identification of the project and report

Project title	Accelerating Carbon Capture using Oxyfuel technology in Cement production - AC^{2}OCem
Project ID	299663
Coordinator	University of Stuttgart
Project website	ac2ocem.eu-projects.de
Reporting period	October 2019 – March 2023

Participants

Organisation	**Main contact(s) + E-mail**	**Role in the project**
USTUTT	Jörg Maier joerg.maier@ifk.uni-stuttgart.de	Coordinator
VDZ	Kristina Fleiger Kristina.fleiger@vdz-online.de	Participant
tk Polysius GmbH	Ines Veckenstedt ines.veckenstedt@thyssenkrupp.com	Participant
SINTEF	Mario Ditaranto Mario.Ditaranto@sintef.no	Representative Norway
CERTH	Konstantina Peloriadi peloriadi@certh.gr	Representative Greece
TITAN	Vasileios Michalis v.michalis@titancement.com	Participant
Heidelberg Materials	Francisco Carrasco francisco.carrasco@heidelbergmaterials.com	Participant
Holcim	Mirko Weber mirko.weber@holcim.com	Representative Switzerland
NTNU	Francesco Cherubini francesco.cherubuni@ntnu.no	Participant
Air Liquide	Anna-Maria Pubill Melsió anna-maria.pubill-melsio@airliquide.com	Representative France
TotalEnergies	Laurent Mariac laurent.mariac@totalenergies.com	Participant

Acknowledgements

Accelerating CCS Technologies

AC²OCem is funded through the ACT program (Accelerating CCS Technologies, Horizon2020 Project No 299663).

Financial contributions made from the,

- Research Council of Norway, (RCN), Norway
- Federal Ministry for Economic Affairs and Climate Action (BMWK), Germany
- Swiss Federal Office of Energy (SFOE), Switzerland
- General Secretariat for Research and Development (GSRT), Greece
- French Environment & Energy Management Agency (ADEME), France

are gratefully acknowledged.

The Research Council of Norway

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

ADEME
French Environment &
Energy Management Agency

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Federal Office of Energy SFOE

ΕΣΠΑ
2014-2020
ανάπτυξη - εργασία - αλληλεγγύη
Partnership Agreement
2014 - 2020

European Union
European Structural
and Investment Funds

GSRT
GENERAL SECRETARIAT FOR
RESEARCH AND TECHNOLOGY

Table of Content

2. Executive summary

The aim of the AC²OCem project was to reinforce the decarbonization of European industry by integrating the oxyfuel technology in the cement industry as a cost-efficient carbon capture solution. With the goal of reducing the time-to-market of the oxyfuel technology in the cement sector, the project worked towards advancing the key components of oxyfuel cement plants to TRL6 by performing a series of pilot-scale experiments as well as several detailed analytical studies. This allowed a narrowing of the technological knowledge gaps to support and accelerate the large-scale oxyfuel demonstration plants with the perspective of near-zero CO_2 cement production.

In frame of the AC²OCem project, the 1st generation oxyfuel technology for retrofitting existing plants was investigated, focusing on optimization of the oxyfuel calciner operation and advancing the kiln burner technology for combusting 100 % alternative fuels, including high biogenic share, see Figure 1. In addition to simulation based on a theoretical reference plant and experimental investigations, a retrofitability analysis is performed based on boundary conditions from two cement plants to support the technology transfer from TRL6 to TRL8. The work is complimented with a techno-economic analysis for a guideline on retrofitting the oxyfuel technology in existing cement plants.

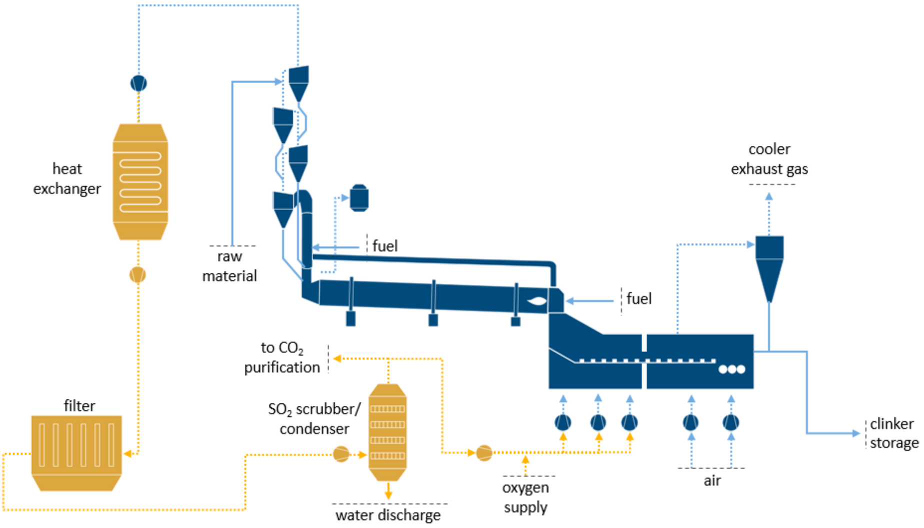


Figure 1: Schematic diagram of a 1st generation oxyfuel cement plant

The innovative 2nd generation oxyfuel technology for new-build cement plants with no flue gas recirculation is studied, facilitating a leap from TRL2 to TRL6 in key technological components, see Figure 2. An unprecedented oxyfuel kiln burner for over-stoichiometric and up to 100 % oxygen combustion is developed and tested in a pilot-scale facility that replicates cement kiln conditions. This process design is assessed and optimized through a techno-economic analysis. The AC²OCem project summarized the environmental sustainability aspects of oxyfuel technologies for retrofitted and new-build cement plants by conducting life cycle assessments.

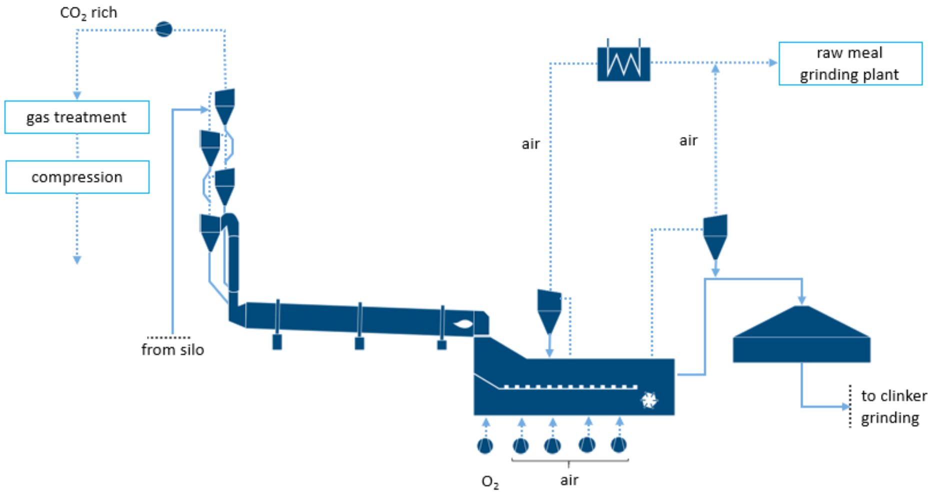


Figure 2: Schematic diagram of a 2nd generation oxyfuel cement plant with no flue gas recirculation

The results of the AC²OCem project are exploited and disseminated in form of journal publications, conference presentations, workshops, blogs etc… to maximize the impact of the outcomes and lessons learned.

Main achievements of the AC²OCem project

1. Pilot-scale experiments with 100 % alternative fuels and experiments with 100 % oxyfuel combustion successfully performed at the combustion facility in USTUTT and simulation model for both cases prepared by CERTH and SINTEF, respectively.
2. Role of moisture addition to control the calcination temperature and impact of flue gas impurities (sulfur) was evaluated. The use of up to 100% alternative fuels in an oxyfuel precalciner was performed.
3. Adapted plant design and recommended operational procedures for retrofit oxyfuel 1st generation technology of Lägerdorf and Slite cement plants. Additionally, model files developed on Aspen Plus for the cement plants (BAT, TITAN), CPU, ASU, 1st generation oxyfuel process
4. Design considerations and analysis of operation for new build cement plants with no recycle ratio and up to 100 % oxygen combustion completed.
5. Establishment of a spreadsheet-based integrated framework for modeling emission inventory summarizing key data required for the environmental impact analysis.

3. Role and contributions of each project partners

The **University of Stuttgart** has been involved in research activities related to combustion for over 50 years. Through several European and national projects, significant experience and know-how has been gathered with regards to combustion technologies (oxyfuel technology) and utilization of solid fuels such as coal, biomass and solid recovered fuels. USTUTT offers experimental facilities ranging from technical-scale to pilot-scale (15 kW to 500 kW) for combustion applications as well as specialized measurement equipment and a well-equipped laboratory for fuel, ash and slag. The experimental facilities of USTUTT are adapted to represent industrially relevant conditions of the cement kiln and calciner.

Within AC^{2}OCem, USTUTT has put their expertise and knowledge of the oxyfuel technology and alternative fuel combustion to integrate these technologies in cement industry. USTUTT was the coordinator of the AC^{2}OCem project, managing and leading two work packages (WPs). WP1 was for the project management, coordination and dissemination. In WP2 'Advanced oxyfuel burner technologies' experimental investigation of the oxyfuel burner technology were performed in a pilot-scale facility at TRL 6. Experiments 1st generation technology with 100 % alternative fuels combustion and for 2nd generation oxyfuel technology with up to 100 % oxygen combustion were performed. In WP3 'Improvement and impact on oxyfuel calciner', the oxyfuel calciner tests were performed by USTUTT in a technical-scale entrained flow reactor relevant to the cement calciners in order to assess and optimize the role of changed flue gas atmospheres on the calcination process.

Holcim is a global leader in innovative and sustainable building solutions. Driven by its purpose to build progress for people and the planet, its 60,000 employees are on a mission to decarbonize building, while improving living standards for all. Holcim offered its expertise in the cement production process to the AC^{2}OCem project by constituting the Swiss subproject. Holcim was providing relevant industry data, e.g. cement plant specific boundary conditions, fuel qualities used, etc. to the different workpackages in AC^{2}OCem. Biomass based fuel used in one of the Holcim operations was shipped to the test facilities for oxyfuel burner tests.

Input and know-how were given to the consortium in order to evaluate the test results with respects to its implementation in cement kilns in a realistic frame. Holcim together with other cement producer partners in AC^{2}OCem provided expertise to perform and evaluate the techno-economic evaluations and life cycle assessment.

Heidelberg Materials is one of the world's largest integrated manufacturers of building materials and solutions with leading market positions in cement, aggregates, and ready-mixed concrete. At the core of its business is its commitment to achieve carbon neutrality.

In AC^{2}OCem, Heidelberg Materials took the role of work package leader in WP4 dedicated to the integration of Oxyfuel generation 1 to existing cement plants. For this purpose, and in other work packages, Heidelberg Materials contributed input data and expertise to support the studies and investigations. Heidelberg Materials also helped assess investigation results from the cement producer's perspective and help contextualize the findings.

SINTEF Energi AS, a research institution in the field of energy, was responsible for the Norwegian part of AC^{2}OCem. SINTEF Energi performed techno-economic evaluation and heat integration of the oxy-fuel CO_2 capture plants considered in the project, as well as a CFD analysis tkP in pilot and full-scale cement kiln configurations.

VDZ: German Cement Work Association (VDZ) with 135 years of experience in energy and resource-efficient cement production is directly linked to more than 70 cement producers worldwide. A broad connection between VDZ and the cement industry will facilitate the knowledge sharing and results dissemination among the end-users. Thus, in WP1, VDZ organized and hosted the Final AC^{2}OCem workshop. The main role of VDZ in the AC^{2}OCem project was related to WP4 and WP5, which includes kiln process simulations for 1st and 2nd generation oxyfuel technology. In WP4, the oxyfuel kiln process was investigated by VDZ in order to find the optimized retrofit options for the two selected cement plants considered for the oxyfuel large-scale demonstration. VDZ was the leader of WP5 that simulated the clinker production process in new-build cement plants erected with the 2nd generation oxyfuel technology and evaluated the potential benefits of this technology for the future cement plants. In addition, VDZ supported the techno-economic study in WP4 and WP5 as well as the LCA in WP6.

Air Liquide as the world largest supplier of industrial gases is actively involved in research and development of oxyfuel and pure oxygen combustion for various types of industry. AL has years of experience in oxygen boosting technologies for cement industry with the target of more-efficient cement production process. Within AC^{2}OCem AL delivered a pilot-scale calciner facility and performed experiments to investigate the role of alternative fuel combustion in an oxy-fuel calciner on the calcination process with the ultimate goal of 100 % alternative fuel combustion in the calciner section. Furthermore, AL is a technology provider for ASU and CPU and supported AC^{2}OCem partners by providing necessary information regarding these units to perform the techno-economic study.

TotalEnergies is among the top 10 largest multi-Energies companies in the world. It has actively participated in the development of carbon capture and storage technologies and gained substantial experience that can be exploited within AC^{2}OCem. TotalEenrgies will support the AC^{2}OCem project scientifically and financially. It will support the techno-economic evaluations, and exploit and disseminate project results in future large-scale carbon capture and storage demonstrations.

Thyssenkrupp Polysius GmbH (tkP) supplies machinery and complete plants as well as a broad range of services for the cement industry and various kinds of other technical processes. tkP delivers proven cement production technology for more than 150 years and is significantly involved in research and development of new solutions. With tkP green technologies, such as oxyfuel technologies, tkP meets the needs of cement industry to achieve carbon neutrality. The main activity of tkP was related to WP3, which were led and tkP performed oxyfuel calcination experiments in the pilot-scale preheater and calciner. Furthermore, tkP has supported the other WP's with its knowledge, experience and appropriate information and data on 1st and 2nd generation oxyfuel; e.g. design information for retrofitted and new-build BAT oxyfuel cement plant incl. CAPEX estimations for them. The proficiency of tkP in cement plant services was utilized.

CERTH (Centre for Research and Technology Hellas) focuses on research topics of solid fuels and their byproducts as well as CO_2 capture technologies (e.g. calcium looping, chemical looping). Over years of activity in the field of energy processes, CERTH has gained substantial insight into 3D CFD simulations and in process modelling using simulation software Aspen Plus®. For WP2 CERTH performed detailed 3D-CFD simulations of SRF particles under oxyfuel conditions. Additionally in the frame of WP4, CERTH with the support of TITAN modeled and simulated the oxyfuel cement process considering the boundary conditions of TITAN’s cement plant. Finally, CERTH’s study focused also on the handling of flue gas impurities and residual streams with regard to CPU operation.

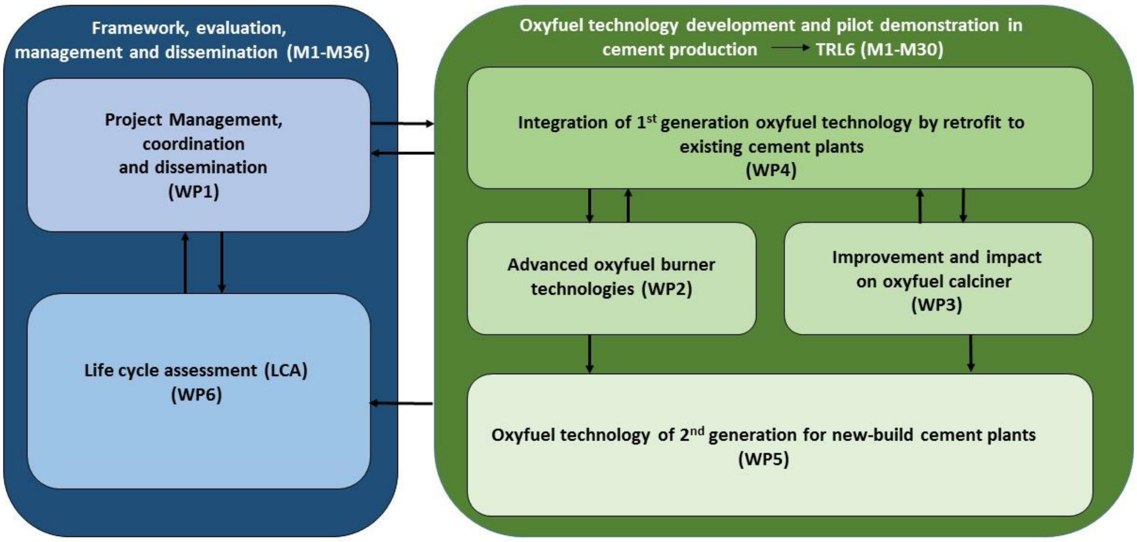
TITAN is an international cement and building materials producer, serving customers in more than 25 countries worldwide through a network of 14 integrated cement plants and three cement grinding plants, based on 120 years of industry experience and driven by its commitment to sustainable growth. TITAN also operates quarries, ready-mix plants, terminals, and other production and distribution facilities and employs about 5,400 people worldwide. Driven by its long-held commitment to improving its environmental footprint and maximizing its positive impact, TITAN is further accelerating its efforts towards net zero acting in bold new ways across its value chain.In AC^{2}OCem TITAN as a cement producer and potential end user of the AC^{2}OCem technology contributed in the project by supplying plant information and providing expertise guide in various tasks with emphasis on the process model development used in the evaluation of oxyfuel operational scenarios.

4. Short description of activities and final results

Describe the activities and final results on work package and overall level, limited to 3 pages per work package. Explain any deviations from proposal/ work plan. Include references to relevant publications, preferentially including hyperlinks.

Present an overview of financial results as well, per partner and per work package.

4.1 Work package level



WP1: Project Management, coordination and dissemination

Task 1.1: Project Management, coordination and communication

The project execution is managed via meetings coordinated by USTUTT. Seven Progress meetings were planned for the AC²OCem project. USTUTT has found it beneficial to host a progress meeting every 6 months to keep the partners updated on work being done in other work packages especially since data transfer between the WPs was important for many partners to achieve their work through the project. During the progress meetings, the partners in the WPs presented the latest updates and results to the rest of the consortium. The presentations from the kick-off meeting and from the progress meetings are uploaded for reference on the project website for the partners.

- 05.12.2019, Kick-off meeting at IFK, University of Stuttgart
- 16-17.06.2020, 1st progress meeting, virtual
- 27-28.01.2021, 2nd progress meeting, virtual
- 14-15.06.2021, 3rd progress meeting, virtual
- 25-26.01.2022, 4th progress meeting, virtual
- 01-02.06.2022, 5th progress meeting at Holcim, Lägerdorf
- 30.03.2023, Final progress meeting, virtual

Throughout the lifespan of the AC²OCem project, partners also organized separate meetings within their WPs where the group discussed results, shared information or handled issues that had occurred and re-set the schedule back to course.

In addition, to counteract the communication issues that came with the Pandemic in 2020, 4 virtual meetings (telcos) were planned (15.01.2020, 05.03.2020, 06.05.2020 and 20.10.2020). The achieved progress, delays and other issues that occurred throughout the year were discussed. This was especially useful as the pandemic hindered the planned schedule and the partners, especially those who were performing experiments in that time, had to re-plan and update their schedules several times. The meeting minutes were noted and uploaded on the project website, in the confidential section for the partners.

A template has been created for deliverables and milestones and has been uploaded to the website. The traffic light report is coordinated by the work package leaders each quarter, and finally edited by USTUTT before submission. The submitted reports are also uploaded to the website for the partners.

D1.1: Project Website publicly available (link)

D1.2: Project progress report (USTUTT) on a quarterly basis starting from M4

D1.3: Project mid-term report

D1.5: Draft of project final report

Task 1.2: Dissemination and exploitation of project results

The disseminated work within the AC^{2}OCem project is listed in §4. The first major collaboration was between a number of AC^{2}OCem members who prepared a paper to be published in the scope of the TCCS-11 conference, where the main outcomes of the project will also be presented during the online conference (June 22-23, 2021).

AC^{2}OCem collaborated with the ANICA project to plan two public workshops. A mid-term workshop was planned by the ANICA consortium and took place on 06.10.2021 (here is a link to the ANICA website for reference: https://act-anica.eu/). The to-date AC^{2}OCem results were presented in the virtual workshop planned by the Technical University of Darmstadt.

VDZ successfully planned and executed the final workshop, a collaboration event between AC^{2}OCem and ANICA. The workshop took place on 7-8.03.2023 in VDZ, Düsseldorf. The AC^{2}OCem partners presented their final results in the public workshop where representatives from relevant institutes companies were invited.

Final AC^{2}OCem workshop: Link

Task 1.3: Increasing public awareness and acceptance regarding CCUS technologies in the industry

Sector

Research shows the most important parameter to reach social acceptance of a new technology, like CCS is knowledge dissemination that is accessible to the public. Awareness of the urgent need to apply carbon capture technology in the cement industry to decrease the CO_2 emissions is the main motivation and a one of the goals of the AC^{2}OCem project. Since the early 2000s, there has been an increase of research into the topic of carbon capture technologies. This is shown in Figure 3 which depicts the number of publications with CCUS or CCS in the title increases from zero publication in 2005 to over 100 publication in 2017. The use of CCUS in the title of publications increased from under 20 between the years of 2012 to 2020 to over 40 in the year 2022. Figure 4 shows the use of keywords ‘carbon capture and storage CCS’ and ‘carbon capture and utilization CCU’ increasing exponentially in the past 30 years.

D1.4: A questionnaire, addressing public knowledge and acceptance in CCS (AC²OCem workshop)

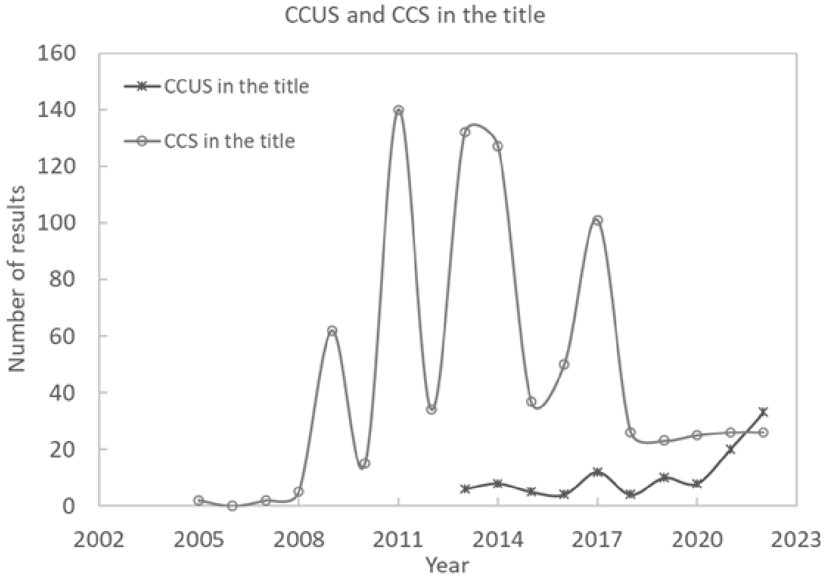


Figure 3: Number of publications in Elsevier with CCS or CCUS in the title from 2005 to 2022

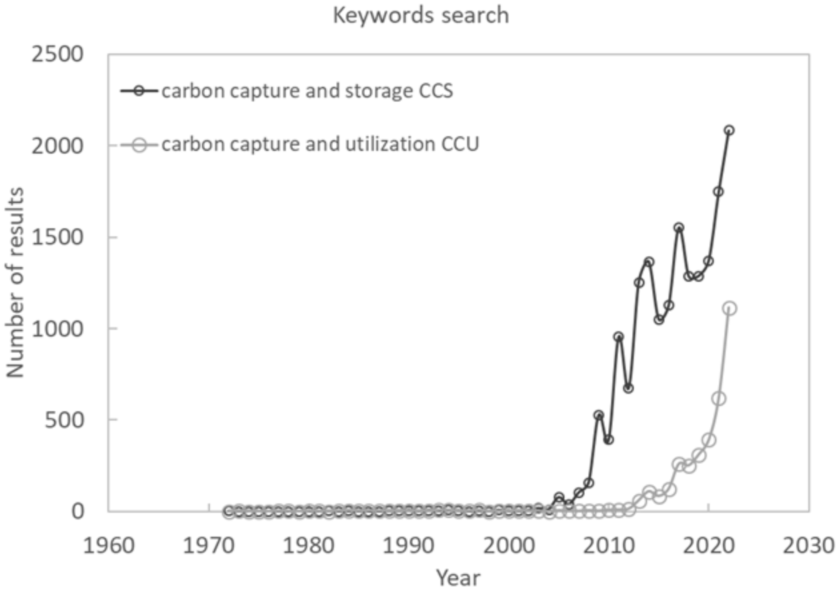


Figure 4: Number of publications in Elsevier with the keywords carbon capture and storage and carbon capture and utilization from the year 1972 to 2022

WP2: Advanced oxyfuel burner technologies

Task 2.1: Pilot-scale demonstration tests of an advanced oxyfuel burner with selected oxygen enrichment for alternative fuel co-combustion up to 100 % (1st generation oxyfuel technology)

This study focuses on substituting fossil fuels with alternative fuels and running a pilot-scale kiln burner in oxyfuel conditions to advance carbon capture utilization and storage (CCUS) technology. Combustion tests are performed in the 500 kW_{th} pilot-scale facility at the University of Stuttgart that has been altered to resemble the burner and combustion conditions in an oxyfuel cement kiln. Coal with air combustion is the reference and alternative fuel including solid recovered fuel (SRF), wood and 90 $\%_{th}$ wood - 10 $\%_{th}$ sludge co-combustion in air and oxyfuel conditions with two varying flue gas recirculation ratios (RR) are studied.

Axial measurements of the flame temperature, heat flux and oxygen and carbon oxide concentrations are measured and evaluated. The O_2 and CO_2 concentration of alternative fuels in oxyfuel conditions at 300 cm from the burner is on average 3±2 vol.-% and 82±5 vol.-%, respectively. The maximum heat flux of coal is at 33 cm from the burner with 260 kW/m^2. The average heat flux for the alternative fuels at 33 cm from the burner is 122±15 kW/m^2 and increases to form a plateau between 100 and 200 cm from the burner at 177±16 kW/m^2.

In comparison to coal, the alternative fuels were milled to larger particle size and have higher volatile content which shifts the char combustion farther from the burner tip. The oxyfuel case with higher RR resembles the air case more, regarding temperature profile, heat flux profile and inlet gas momentum. The stability of the oxyfuel case with higher RR can be optimized by adjusting the swirl angle in the burner. Finally, the combustion of alternative fuels is stable in air and oxyfuel conditions and the flames compared to coal are wider, longer and less intense.

D2.1: Report on pilot-scale demonstration tests of the 1st generation oxyfuel burner with selected oxygen enrichment using high share of alternative fuels (submitted to Journal, will be linked on website)

Task 2.2: CFD simulations of the prototype burner for 1st generation oxyfuel technology

In the framework of AC²OCem project, CERTH conducted CFD simulations of the prototype burner in order to further advance the 1st generation oxy-fuel technology for utilization of high shares of alternative fuels, i.e., SRF, up to 100%. This sophisticated and computationally intensive 3-D CFD model was validated against experimental data performed by USTUTT for two scenarios. The first includes conventional operating conditions (injection of atmospheric air), while the second one oxy-fuel conditions (provision of O_2/CO_2 mixture). The derived results are important for improvement of burner configuration, further development of more accurate process modelling tools for dynamic simulations, and utilization of the developed mathematical model for pilot-scale cases. Based on the results for the first scenario, it can be concluded that the CFD model approximates quite satisfactory the reference values for all the three main parameters under investigation (temperature/dry oxygen/dry carbon dioxide distribution) especially for the points that are far away the burner tip and where the flow is fully developed. Furthermore, despite the difficulties in simulating the complicated phenomena close to the burner, the developed mathematical model presents significant agreement with the reference experimental data in the near-burner region, especially for the temperature and the dry oxygen mole fraction parameters. Significant differences can be observed in the midzone for the temperature and the dry carbon dioxide mole fraction. In order to improve the model behaviour regarding these aspects, future modifications can be performed, including modified kinetic rates of the exothermic homogeneous reactions, investigation of the effect of turbulence on chemistry and the utilization of a more detailed reaction network. For reasons of consistency, the same hypotheses, the same reactions network and the same kinetic rates have also been applied in the case of the oxy-fuel conditions. However, as it is proven by the derived results, this approximation provides a first insight into the occurring process, but it also deteriorates the accuracy as compared to the experimental values. Therefore, it could be a matter of investigation in future projects the conduction of further experiments in order to enhance the model's accuracy. Overall, this work is a first step for the investigation of combustion of high shares of SRF with a prototype burner, especially when conventional conditions are considered. With the implementation of oxy-fuel conditions, the accuracy of the model deteriorates. However, the initial results indicate that the implemented mathematical model can be used as a reference for performing the required simulations for the pilot-scale case or as a baseline for the development of more accurate process modelling tools for dynamic simulations.

D2.2: Report on CFD simulations of 1st generation oxyfuel burner using high shares of alternative fuels

Task 2.3: Pilot-scale demonstration tests of prototype oxyfuel burner with the novel concept of 100 % oxygen and without flue gas recycle (2nd generation oxyfuel technology)

The oxyfuel combustion process can be retrofitted to existing plants and designed for new-build plants, where the plant can be designed with no flue gas recirculation (FGR). A down-scaled kiln burner is tested in oxyfuel conditions with different oxygen-to-fuel ratios in technical and pilot-scale facilities at the University of Stuttgart.

In the technical-scale facility, experiments are conducted to compare a case with synthetic FGR at near-stoichiometric conditions (OXY32) and over-stoichiometric conditions (with λ*3.4), λ* being the oxygen-to-fuel ratio. Experiments in the pilot-scale facility are conducted at varying stoichiometric conditions, λ*2, λ*3 and λ*4.

In both facilities, a reference case with air combustion is conducted. The highest measured temperature in the air, λ*3 and λ*4 cases were 1020 °C, 1321 °C and 1116 °C, respectively. In the oxyfuel cases, after the peak temperature is reached, the temperature profiles stabilize to similar temperatures as measured in the air case. The inlet oxidizer gas concentration and stoichiometry highly affect the CO and NO formation. For all oxyfuel cases, the CO emission rate in the flue gas measurements is below 20 mg/MJ indicating high burnout efficiency. In the technical-scale tests, the NO emission rate at 2.5 m from the burner is lower in the OXY32 case compared to the air case, with 138 and 247 mg/MJ, respectively. The NO emission rate of the λ*3.4 case is 461 mg/MJ, a consequence of no reducing or reburning zone.

The experiments show that the increased over-stoichiometric conditions have a desirable effect on the temperature profile and oxygen can be used as a suitable diluent in comparison to N_2 and CO_2, but NO formation is increased. In the cement production process, this can be solved by designing a reducing zone in the calciner to properly reduce NO.

D2.3: Report on pilot-scale demonstration tests of the 2nd generation prototype oxyfuel burner with the firing concept of up to 100 % oxygen (submitted to Journal, will be linked on website)

Task 2.4: CFD simulation of the prototype burner for 2nd generation oxyfuel technology

CFD-simulations (Ansys Fluent© 19.5) corresponding to the pilot scale furnace and 2nd generation burner tested (case "L4") at the University of Stuttgart have been performed (cf. Task 2.3) where the boundary conditions of the gas outlets of the burner have been modelled with applied velocity profiles. The flame general aspect is well reproduced for the near field behaviour of temperature with peak at the similar position as in the experiments, but as for the SRF simulation of Task 2.2, there is an overestimation of the simulated temperature. The results show that the current CFD model set up is appropriate to simulate second generation oxyfuel combustion with large oxygen excess and has highlighted the possible improvement paths in the modelling.

D2.4: Report on CFD simulations of the 2nd generation oxyfuel kiln burner on pilot- and full-scale

WP3: Improvement and impact on oxyfuel calciner

Task 3.1: Technical-scale parametric study to evaluate the impact of flue gas composition and impurities on calcination under oxyfuel conditions.

This task summarizes the calcination tests conducted within work package 3 (WP3). The term calcination refers to the decomposition of limestone ($CaCO_3$) to lime (CaO) and carbon dioxide (CO_2). In this work the impact of flue gas moisture (H_2O-vapour) and impurities (like KCl and SO_2) are experimentally evaluated.

Temperatures in the range of 840 °C to 860 °C are reported, adequate to reach the required level of calcination of about 90% [1]. Typically, the temperature is monitored at the outlet of the calciner. The temperature range of 880 °C to 900 °C is considered the maximum temperature in current industrial practices. Earlier work established that shift towards higher temperature is to be expected for oxyfuel atmosphere. A shift up to 70°C in comparison to reference air case is reported. The CEMCAP studies established the oxy-fuel temperature in range of 940-960°C, which is fairly higher than current industrial practices. The higher the pCO_2 in the surrounding atmosphere, the higher would be the $CaCO_3$ decomposition temperature, as dictated by the equilibrium thermodynamics. In CEMCAP studies, the atmosphere of 80 vol.-%, dry CO_2 is referred to as oxyfuel cases while the atmosphere of 20 vol.-%, dry CO_2 is the reference air cases [2,3].

The actual temperature may vary with the type of raw meal and the heat transfer conditions in given calciner system, nonetheless the shift is directly linked with the partial pressure of CO_2 therefore is inevitable for oxyfuel atmosphere.

The test with H_2O-vapour variation shows that the H_2O-vapour in bulk gas mixture promote calcination up to certain extent while over excess of H_2O-vapour may have retarding effect.

The test with impurities shows that externally added solid KCl evaporate and leave the system in gaseous form while the gaseous SO_2 was largely captured by CaO to remain in solid phase as $CaSO_4$.

---

[1] S. Becker, R. Mathai, K. Fleiger, G. Cinti, Status Report On Calciner Technology - D8.1, Zenodo, 2016.

[2] M. Paneru, A. Mack, J. Maier, G. Cinti, J. Ruppert, D8.2 Oxyfuel suspension calciner test results, Zenodo, 2018.

[3] European Cement Research Academy, ECRA CCS Project - Report II: TR-ECRA-106, 2009.

D3.1: Report on a technical-scale parametric study of oxyfuel calcination (Link)

Task 3.2: Demonstration of the calcination test under oxyfuel atmosphere in a pilot-scale calciner and pre-heater

This WP consider pilot scale calcination test under oxyfuel atmosphere.

The tests were performed in a pilot scale calciner with pre-heater test facility at the tk Polysius GmbH R&D center.

The objectives of this task were to evaluate the influence of moisture content and temperature on the calcination efficiency under oxyfuel atmosphere. Additionally, the effect of flue gas impurities, like SO_2 (with regard to emission/abatement) and N_2 (with regards to NOx formation) were evaluated under oxyfuel atmosphere.

The test results show that the additional increase of gas moisture further than originating from fuel combustion (coal and alternative fuels), is not reasonable. The further increase of the gas moisture results in neutral or minimal positive influence on the calcination rate. These findings are consistent with the results of USTUTT (WP3.1). Therefore, a moistening concept is not required for industrial sized plants that use coal and/ or alternative fuels.

Sulfur incorporation into the product was lower under oxyfuel conditions than in reference case, but due to the very short residence time and the known calcination kinetics under high CO_2 partial pressure, it can obtain, that in an industrial plant with sufficient residence time, sulfur incorporation could occur to the same extent as under conventional conditions, since the same content of CaO would be available as a reaction partner for sulfur in oxyfuel operation. Regarding SO_2 emissions at preheater outlet, the test conditions did not reflect the conditions realistically expected in an industrial plant at preheater outlet i.e. the outlet temperatures after preheater were too high, which improved the sulfur incorporation in the raw meal under oxyfuel conditions.

Particular attention must be paid to the fuel- and raw meal distribution in order to avoid temperature peaks and thus deposit formation, especially in the area with high O_2 concentrations.

The addition of N_2 did not produce any results, since the temperatures in the tests were too low for the formation of thermal NOx and the combustion of natural gas does not produce NOx emissions. NOx emissions remains below 10ppm during the entire test operation, even under reference air conditions.

D3.2: Report on oxyfuel calcination tests in a pilot-scale calciner and pre-heater (Link)

Task 3.3: Demonstration of up to 100% alternative fuel combustion in a pilot-scale oxyfuel calciner

This task is divided in two different objectives:

1. to show that it is possible to run a cement precalciner in oxy-combustion condition with only Alternative Fuels (AF) as combustible. Tests on the CORALI combustion facility have been carried out.

2. and to show that for better burning the alternative fuel in a cement precalciner working under oxy-combustion conditions, O_2 injections need to be well distributed in the combustion chamber.

The tests realized in the CORALI combustion facility with refuse-derived fuel (RDF) as alternative fuels showed that it was possible to work with up to 100% AF as combustible in conditions close to the ones found in a cement precalciner working in oxy-combustion conditions. It shows that there is no issue linked to the usage of O_2 in a precalciner using AFs. It strengthens the interest of the oxycombustion for cement to capture the CO_2 from the flue gasses. It increases the CO_2 concentration in the fumes, allows it to work in the same conditions as the one currently used and does not limit the quantity of AFs that could be injected in the precalciner when their quality is good enough.

The experiments also showed that a good distribution of the O_2 injection helps to better burn the solid alternative fuels. An O_2 injector in the middle of the AFs injector helps to burn quicker the AFs with low quantity of O_2. Staging the O_2 injection with an O_2 injector near the AF injection and another at a higher place in the combustion chamber also helps the combustion of the AFs but it is important to have the right staging because if it is too high the combustion might be poorer. It is thus interesting to use special injectors like the one used during this study and special O_2 lances that allow the injection of O_2 at the right place.

D3.3: Report on pilot-scale demonstration of up to 100 % alternative fuel combustion in an oxyfuel calciner (Link)

WP4: Integration of 1st generation oxyfuel technology by retrofit to existing cement plants

Task 4.1: Design consideration for retrofitted oxyfuel cement plants

WP4 was devoted to identifying those parameters or topics that need to be addressed when retrofitting existing cement plants with the 1st generation oxyfuel technology. The exercise comprised the assessment of two European cement plants: the Heidelberg Materials Slite plant in Sweden and the Holcim Lägerdorf plant in Germany. These plants serve as a basis for the simulation study to show the influence of differences in plant structure and local boundary conditions on the technical ability to retrofit the 1st generation oxyfuel.

Both plants are operated with a relatively high alternative fuel rate (70-80%) typical for Northern Europe and therefore represent a realistic case even for the near future. The major difference of the plant is the production process influenced by the condition of natural raw material reserve of the plant location. In Slite a typical dry process is used whereas the Lägerdorf plant is operated in a so-called semi-wet process. The natural raw material from the Lägerdorf quarry shows a high moisture content of about 20 %, which influences the pre-treatment of the material prior being fed to the burning process. All available waste heat from the process has to be supplied to the drying unit (hammer mill dryer), making the heat integration in oxyfuel mode a huge challenge. The optimal location of the hammer mill dryer in the process layout played an important role. Although the direct integration is energetically reasonable, the operational risk by false air intrusion is high. In order to avoid dilution of the CO_2 and its negative impact on energy demand of the CPU, this layout has not been further developed. The overall energetic evaluation proved that a sophisticated heat exchanger system could provide enough energy (also in terms of gas volume and temperature) to the drying unit. For this reason, the following layout has been chosen for both plants (Figure 5).

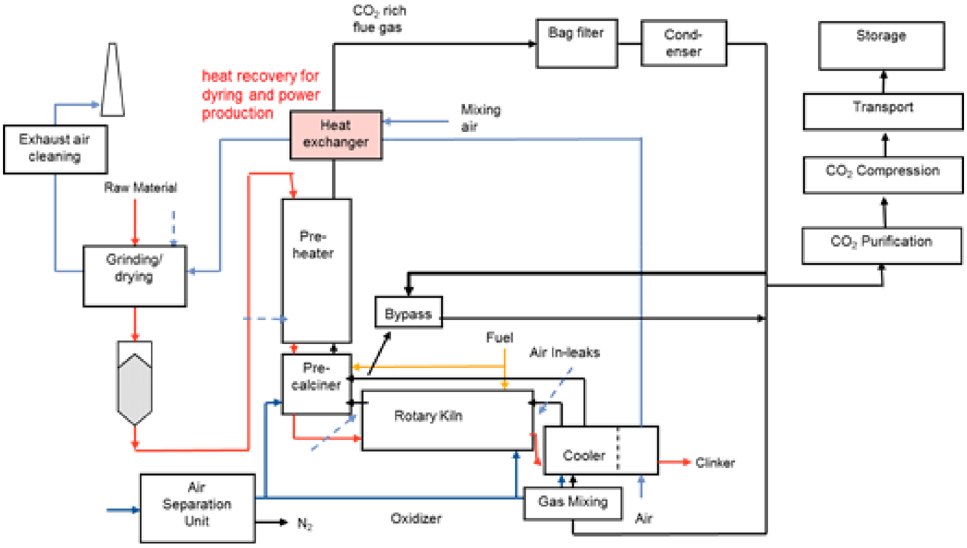


Figure 5: Oxyfuel 1st generation layout for Slite and Lägerdorf plant

D4.1: Waste heat recovery systems for oxyfuel cement plants ([Link](#))

<u>Task 4.2: Process simulations of different flue gas recirculation scenarios and fuel mixes in oxyfuel retrofitted cement plants</u>

The recirculation rate and correspondingly the oxygen concentration in the combustion gases is the most powerful parameter to optimize the oxyfuel operation. It is defined as the volume of total flue gas, which is recycled back to the process. This parameter is important to ensure the lifting of material in the preheater system but also affects the overall energetic performance of the clinker burning process. In general, the thermal energy demand of the clinker burning process can be reduced by decreasing the recirculation ratio by a reduction of flue gas heat losses (Figure 6). However, there is a limit since further decrease would influence the heat available for calcination in the preheater, which would increase the fuel demand there. Another influencing factor is the temperature of the recycled flue gas, which is limited to maximum 120°C to avoid issues with hydraulic equipment below the cooler. In case of Lägerdorf the heat recovery is maximized leading to a cold recirculation.

In case of Slite a minimum recirculation rate of 0.48 has been determined and 0.55 when establishing conventional 21 vol.% O_2 in the combustion gases. The minimum recirculation rate combined with a higher temperature level of flue gas resulted in about 6.6% lower thermal energy demand compared to the air fired reference case. Further, the semi-wet process has a higher heat demand of the flue gases for raw materials drying and therefore in general less flue gas recirculation is possible. This fact leads to a minimum recirculation rate of 0.44 and an increase of 1% thermal energy demand.

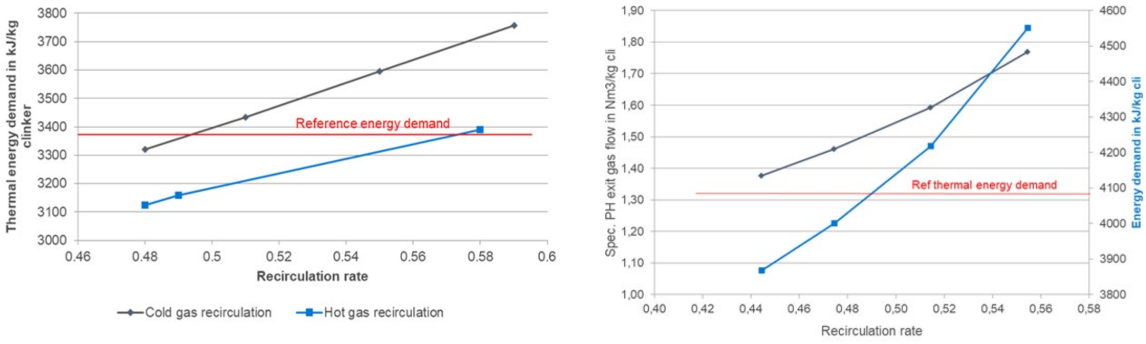


Figure 6: Relationship of thermal energy demand, specific flue gas volume flow and recirculation rate (left: Slite, right: Lägerdorf)

Net carbon removals can be achieved, if biogenic CO_2 is captured and either permanently stored or transferred in long-living products. Based on the current fuel mix both plant options could create this negative emission of 30 to 40 kg CO_2/t cli. Adapting the fuel mix by increasing the biogenic share (e.g. use of sewage sludge) the thermal energy demand is increased due to the lower heat capacity and process integrated drying of the fuels. Simultaneously 100 to 190 kg CO_2 /t cli (100% AFR containing huge share of biomass) of negative emissions could be hypothetically created.

Based on the available information on the reference BAT oxyfuel plant, CERTH developed a process simulation of the typical cement production to ensure consistency within the project. Furthermore, the operation of TITAN's cement plant was simulated in Aspen Plus, based on the operational parameters and values provided from TITAN, which has been successfully validated.

To assess oxyfuel scenarios, CERTH simulated two separate models, of the Air Separation Unit (ASU) and the CO_2 processing unit (CPU) and evaluated the mitigation of flue gas impurities using the CPU. The results provided a comprehensive analysis of the oxyfuel combustion in a cement plant and showed that the oxyfuel process coupled with a CPU can significantly reduce CO_2 emissions from TITAN's plant, while maintaining the quality of the clinker produced.

Task 4.3: Assessments of flue gas impurities and residual streams in the oxyfuel retrofitted cement plant

Impurities which are conventionally discharged via the stack to the environment leave the system at different locations by condensation or in vent streams from the purification unit in oxyfuel operation. While recirculation the flue gas is cooled under water dew point, which also allows the removal of certain impurities as condensates, such as NOx and SOx. In order to purify the CO_2 in the enriched flue gas stream to match the requirements from subsequent processes a CO_2 processing unit (CPU) is required. To a certain extent also impurities will be reduced in this process step. The amount of emissions is important also for the transportation of the final flue gas leaving the oxyfuel and CPU process. The transport specifications are based on the Northern Lights project.

The Slite plant suffers high SO_X emissions due to its natural raw material reserve. Therefore a wet scrubber for $DeSO_x$ is conventionally operated. Without a further removal of SO_x from the flue gas apart from the condensation the impurity level would exceed the allowed limit (10 ppm). Either the wet scrubber is included in the flue gas path or additional reducing agents (such as NaOH/ Na_2CO_3) can be added to the condenser. The NO_x level in the CO_2 product is only below the limit if a properly working SNCR is in place and limits above 200 mg/Nm^3 are not exceeded in both cases. Oxyfuel operation might help to reduce the formation of NO_X due to the lower availability of nitrogen.

The presence of impurities in the flue gases of an oxyfuel cement plant can significantly affect the process efficiency and costs. Cement plant emissions of dust, nitrogen oxides (NOx), and sulfur dioxide (SO_2) require special attention and treatment.

To control the emissions, the feeding of fuels with high metal content into the cement kiln and the use of raw materials with volatile metals should be avoided. Additionally, the usage of dust removing methods is beneficial as the emitted metals are bound to dust to a large extent. The emissions from cement plants which cause greatest concern, and which need to be dealt with are dust, nitrogen oxides (NOx) and sulfur dioxide (SO_2).

The role of the CPU is to process CO_2 from combustion flue gases and purify it to the required specifications. Thus, both the composition of flue gases and the CO_2 product specifications show a strong influence on its design.

The pressure, dehydration, and cryogenic units are key components of a CPU. The pressure unit is used to compress the CO_2 to a high pressure, which makes it easier to transport and store. The dehydration unit is used to remove water and other impurities from the CO_2 stream, which can reduce the efficiency of the capture process. The cryogenic unit is used to cool the CO_2 to a low temperature, which causes it to condense into a liquid that can be stored in underground reservoirs or used for other industrial purposes.

The diagram in Figure 7 displays the process flow of the CPU. The separation of O_2 and CO_2 in this unit relies on the Joule-Thomson effect, which is similar to the ASU operation.

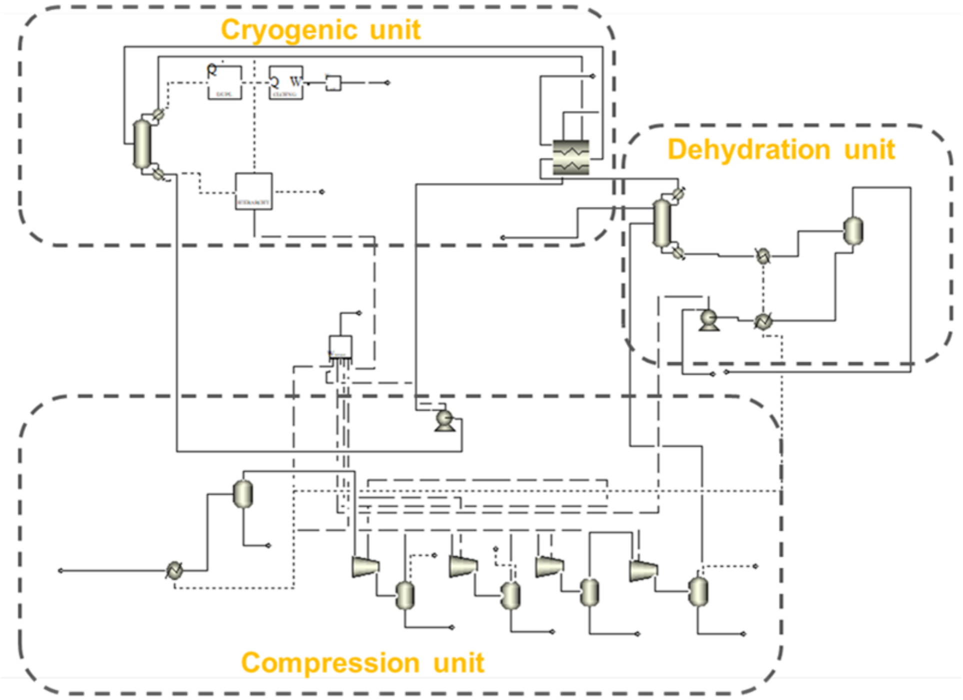


Figure 7: Schematic overview of the CPU

Table 1 indicates that the CPU has successfully achieved impressive results in reducing the impurities in the plant's flue gas stream. The table shows the comparison of CPU results with the Northern Lights limits, which represent the desired limits for CO_2 stream transportation.

Table 1: CPU impurities comparison to Northern Lights limits

	Northern lights limits	CPU results
CO_2 (%)	>95	99,2
NO_X-NO_2 (ppm)	<100	52
SO_X-SO_2 (ppm)	<100	40
DUST-$CACO_3$ (ppm)	<10	2
CO (ppm)	<100	25
HCL (ppm)	<1	0
H_2O (ppm)	50	23
O_2 (ppm)	10	0

Nevertheless, additional purification methods could be used before the CPU unit to further mitigate the impurities.

Task 4.4: Process simulations of the influence of moisture content in the raw material on process design and waste heat recovery

Usually process waste heat from the flue gas is directly used in the drying unit, which is difficult to seal especially in case of retrofit. As shown in Figure 8 the energy demand of the Lägerdorf plant for drying is significantly higher than of Slite plant (or the CEMCAP reference with 6 % raw material moisture). The selection of the plants had a direct influence on the process optimization and design (as discussed in task 4.1 and 4.2).

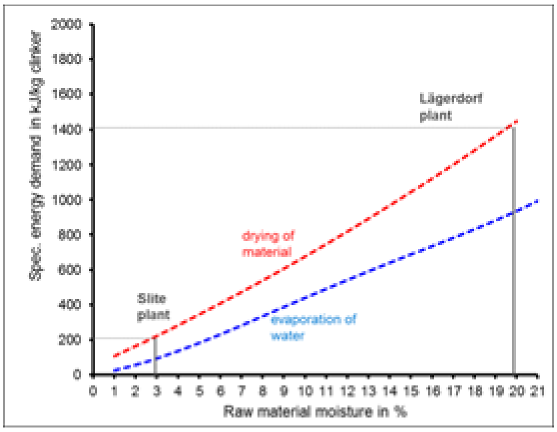


Figure 8: Energy demand for raw material drying for Slite and Lägerdorf plant

Slite plant offers enough waste heat to also react on smaller seasonal fluctuations of raw material moisture. In case of Lägerdorf a material split (kiln meal input to the preheater can be split between the top cyclone stage (No. 3) and the middle stage (No. 2)) is used to react on fluctuation of the raw material moisture. That way less energy is extracted from the gas by the material preheating and the thermal energy demand especially in the calciner rises. The optimal oxyfuel set-point for a recirculation rate of 0.47 is identified at a meal bypass between 30 and 50% (Figure 9).

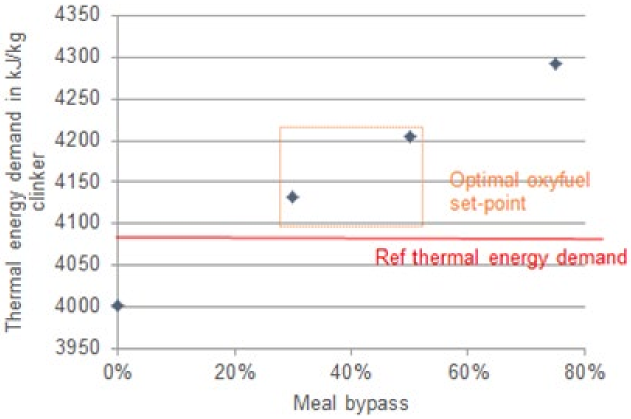


Figure 9: Thermal energy demand for R = 0.47 depending on meal split

D4.4: Report on technical evaluation of retrofitting 1st generation oxyfuel technology to two selected cement plants

Task 4.5: Detection and control of air ingress for plant optimization.

For each oxyfuel process false air intrusion is the major aggressor due to influence on the target of enriching CO_2 to a reasonable level for operating an energy efficient CPU. 6 % false air (related to the total flue gas volume) has been determined as an optimistic and realistic value with regard to sealing the clinker burning process. But it is likely that within the year of kiln operation false air is increased due to wear at the sealings. In case of doubling the false air ingress the CO_2 concentration is reduced from initially 81 vol. % to 71-73 vol. % on dry basis. As a rule of thumb gas supplier AirLiquide named a change of +/- 2% spec. energy demand for each -/+ 1 percentage point CO_2 dry base concentration for design basis of CPU. As a CPU is designed for a dedicated operational point (e.g. for a pessimistic CO_2 concentration) false air influences OPEX and CAPEX of the CPU.

This again clearly shows the need for sophisticated long-living sealings and a good management for false air detection. Against this background the project partners have developed a guideline document (D 4.2) for this purpose, which describes apart from the definitions, typical values, the economic effect and examples for improvement, the methods and techniques to detect false air. The resulting detection strategy (Figure 10) includes the continuous measurement by online measurement of O_2 and CO_2 (common UV, IR or paramagnetic measuring) as direct nitrogen measurement is complex and expensive. After having traced back the intrusion to a certain unit, false air can be further localized by ultrasonic detectors, thermal cameras or absolute pressure measuring devices. After the location of the leak is identified the maintenance department will need to decide if it can be repaired during operation or if it may require a temporary fix until a kiln stop can be scheduled.

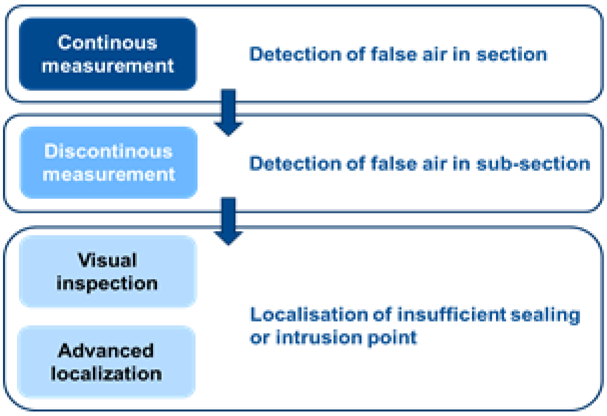


Figure 10: False air detection strategy

D4.2: A guideline for detection and control of air ingress in oxyfuel retrofitted cement plants

Task 4.6: Techno-economic evaluation of a retrofitted oxyfuel cement plant

A techno-economic evaluation of retrofit the 1st generation oxyfuel to two theoretical plants A and B based on the characteristics of Heidelberg Material's Slite cement plant in Sweden and Holcim's Lägerdorf cement in Germany was performed. The costs estimation in D4.6 has been made on average prices and do not reflect the real costs for cement production at both plant locations. A discounted cash flow approach with 8% discount rate and 25 years of plant lifetime was used. The cost estimates correspond to AACE 18R-97 Class 4 estimates with targeted accuracy of -30%/+50%. The evaluation is based on process simulations, public data and literature data for cost of consumables. Capital costs are estimated by various partners in the project.

The increased levelized cost of clinker is shown in Figure 11. The increased levelized cost of clinker shows the difference in levelized cost of clinker for a cement plant including CCS compared to a plant without CCS. Consequently, it is a relative number and not showing the absolute cost for clinker.

The main cost drivers for the process are CAPEX (mainly CPU and core process) and cost of electricity (mainly for CPU and ASU). CAPEX and increased fixed OPEX are very similar for both plants. The main difference between them is the increased variable OPEX in form of increased electricity cost and cost for oxygen, which is also driven by the electricity costs. This is an effect of the difference in the electricity cost in the two countries.

A steam cycle can be included for cases like plant A with low material moisture and large amount of excess heat and high electricity prices. However, it was not advantageous for the two investigated cases with electricity prices fixed for 2019. The cost estimated for the two real plants in this study are significantly higher than costs estimated in previous studies for ideal hypothetical reference plants. This is due to increased understanding of the complexity of modifying existing plants, higher CPU CAPEX, more realism by using replicated existing plants and extended scope by including pipelines and CO_2 buffer tanks.

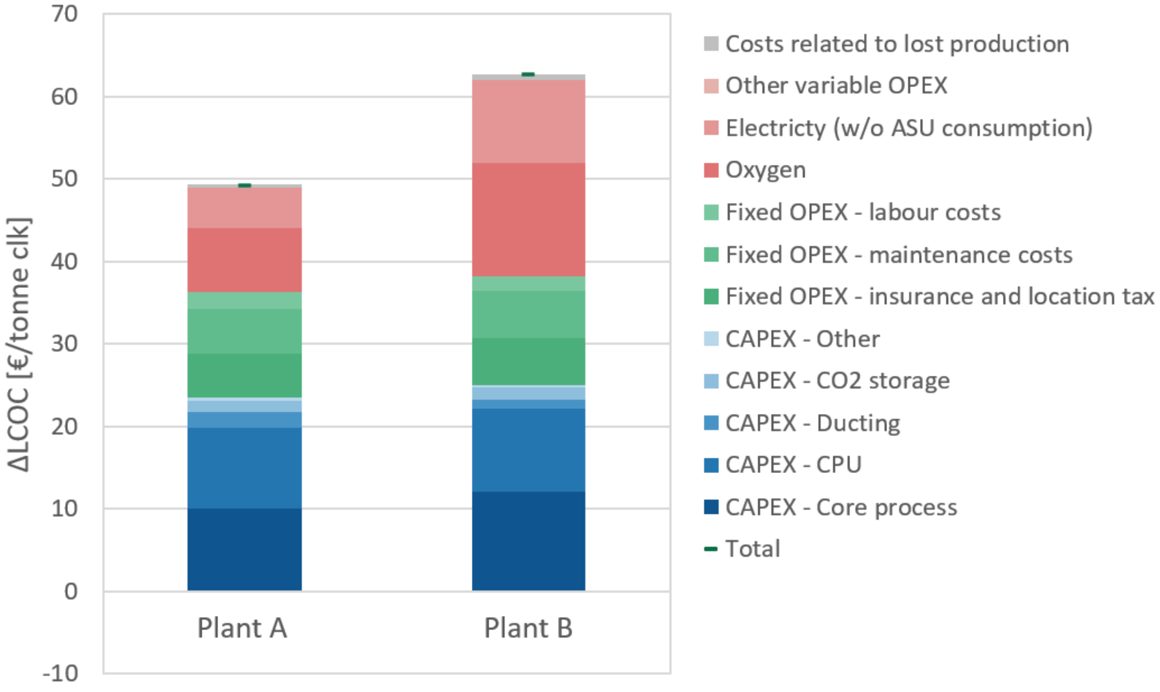


Figure 11: Increased levelized cost of clinker

D4.5: Techno-economic evaluation of retrofitting 1st generation oxyfuel technology to two selected cement plants (Link)

D4.6: A guideline for techno-economic decision-making process for retrofitting oxyfuel cement plants (Link)

WP5: Oxyfuel technology of 2nd generation for new-build cement plants

Task 5.1: Design considerations and process simulations for new-build oxyfuel cement plants

The idea of the 2nd generation oxyfuel layout developed by tkP is to avoid the effort for flue gas recirculation with the aim to reduce CAPEX and OPEX costs. For this purpose, pure oxygen (instead of a mix from recycled gas and oxygen) is provided to a first stage of the cooler (Figure 12). Due to the reduced gas volume flow a tertiary air duct is avoided and the kiln plant geometry especially of the calciner and preheater tower needs to be reduced to adapt the gas velocity.

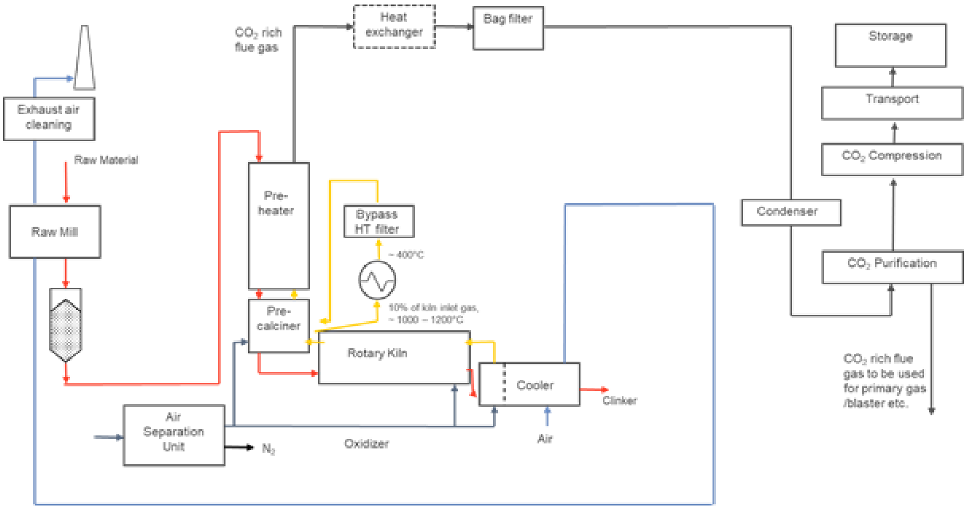


Figure 12: Principle of the oxyfuel technology without flue gas recirculation

That way the kiln atmosphere is dominated by O_2 instead of CO_2/O_2 in case of a flue gas recirculation (Figure 13).

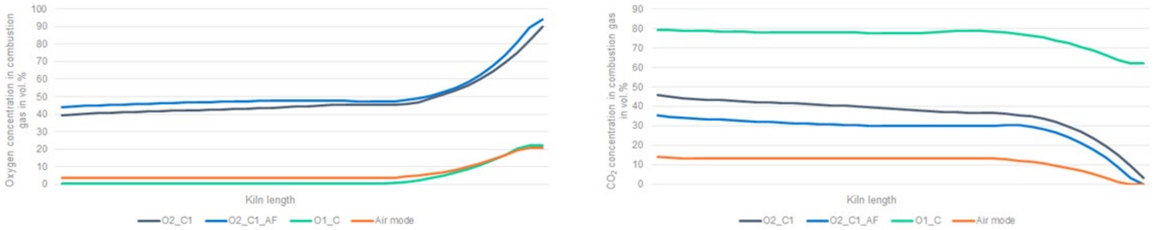
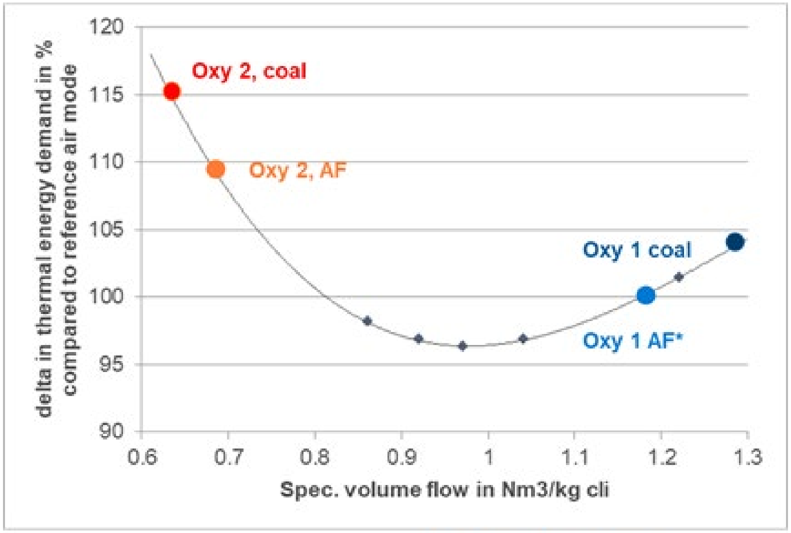


Figure 13: O_2 concentration (left) and CO_2 concentration (right) in the kiln combustion gases (lift side of the diagram kiln inlet and right side of the diagram sintering zone)

A reference plant of 3,000 t/d capacity (as defined in the CEMCAP framework) is used as simulation basis. In addition to the coal fired case the fuel mix was adapted to comprise about 70% of alternative fuels, which reflects the future European fuel mix.

As stated above in WP4 the volume of flue gas influence the thermal energy demand. Energy losses by preheater exhaust gas can be reduced, if less gas is recirculated back to the system. Reduction of exhaust gas volume leads to CAPEX savings due to smaller gas treatment equipment. Though the efficiency of the preheater is improved, lower hot meal temperatures delivered to the calciner have to be covered by increase of fuel feeding to the calciner to deliver the decarbonated hot meal to the kiln at sufficient precalcination rate (Figure 14). This effect is maximized by avoiding any recirculation (2^{nd} generation), which leads to an increase of thermal energy demand of 14.8 % compared to the reference air-mode. Due to the use of alternative fuels (and their process integrated drying) the flue gas volume is increased, which is beneficiary for the operation of a 2^{nd} generation oxyfuel kiln. The difference in thermal energy demand decreases to 9.4% compared to the air-mode reference using the same fuel mix.



* adaptation of recirculation rate assumed

Figure 14: Dependency of thermal energy demand and specific flue gas volume

Since less gas is preheated in the clinker cooler in oxyfuel 2nd generation operation, the cooler efficiency is reduced. In 2nd generation oxyfuel operation, the cooler exhaust gas is used for drying purposes, e.g. raw materials and waste fuels, and excess heat can be used in waste heat recovery (WHR) systems. Due to the lower heat recuperation in the cooler, high amount excess heat from the cooler at high temperature level are available. Subtracting the necessary demand of energy for the drying of the material, a significant potential for power generation exists. For an optimal design of the heat exchange network power output and complexity of the network have been balanced (Figure 15). Two heat exchanger networks were designed one with and one without heat to power cycle. In case without heat to power cycle excess heat from the cooler and preheater are unused. A steam cycle can produce about 7.3 MW power when installed. However, it required a rather complicated heat exchanger network which was just economically for high electricity prices.

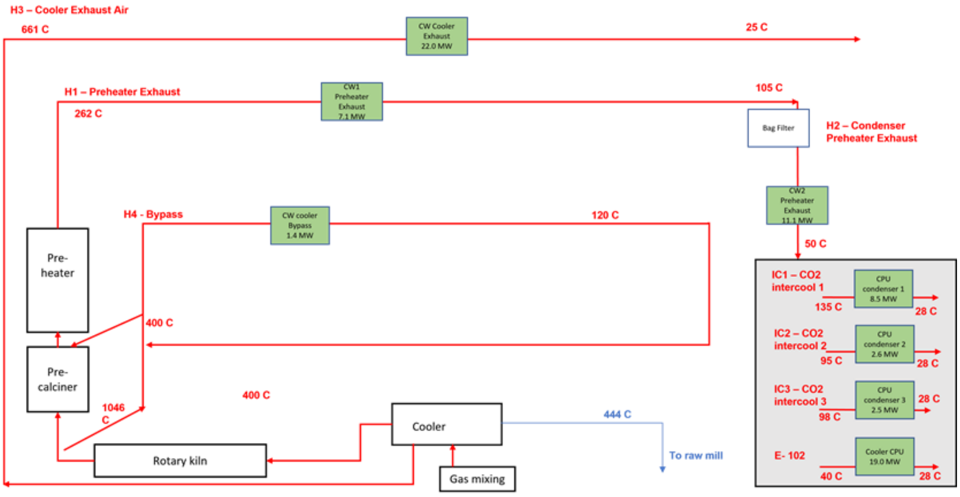


Figure 15: Heat exchanger network

The target of oxyfuel operation is the enrichment of CO_2 to more than 80 vol.% in the flue gases to allow an energy efficient purification. The reference operation in air mode creates a typical CO_2 concentration of 33 vol.% dry in the preheater exit gas. Applying oxyfuel technology with recirculation the CO_2 can be enriched to about 85 vol.% dry. Due to the recirculation of flue gas, false air as well as water vapour can slightly enrich. This can be avoided in case of oxyfuel 2nd generation, which allows an enrichment of CO_2 up to 91 vol.%. Using alternative fuels instead of coal the flue gas composition is changed towards higher moisture contents and slightly less CO_2 concentration due to the changed composition of the fuels. In any case the CO_2 concentration can be enriched up to 89 vol.% in the oxyfuel 2 case.

Due to the increased fuel demand the demand for oxygen rises. In combination with the higher CO_2 generation the additional power demand is similar to the demand of oxyfuel 1st generation, albeit the higher CO_2 concentration is beneficial for the performance of the CO_2 purification step. High enthalpy stream of the cooler exhaust gas allows a more efficient power generation; thus the additional thermal energy demand can be partly recuperated. Including the power generation, the net power demand is about 12.5% lower than for 1st generation oxyfuel kilns.

Table 2: Comparison of thermal and electrical energy demand of Oxyfuel 1st and 2nd generation for 70% alternative fuel use

	Conventional BAT plant	**1st generation oxyfuel**	**2nd generation oxyfuel**
Clinker production [t/h]	124.687	124.065	124.952
Raw meal consumption [t/h]	200.025	200.025	200.025
Spec. thermal energy demand [kJ/kg cli]	3,331	3,343	3,645
Fuel input [MW]	115.4	115.44	126.52
Power consumption for clinker production[1] [MW]	7.5	7.4	7.4
O_2 demand [t/t cli]	0.0	0.331	0.364
O_2 demand [t/h]	0.0	41.07	45.48
ASU power [MW]	0.0	10.19	11.18
CO_2 input to CPU [t/h]	0.0	104.83	109.33
CPU power [MW]	0.0	14.8	13.96
Recycle stream (condenser, fans) [MW]	0.0	1.24	0.75
Total power demand [MW]	7.5	33.63	33.9
Power generation [MW]	0.0	3.8	7.3
Net power consumption [MW]	7.5	29.83	25.9

[1] Does not include cement grinding and shipping/loading.

After consultation with tk Polysius GmbH a second plant layout has been simulated (Figure 16) in order to optimize the thermal energy demand and to decrease the resulting CO_2 emissions from additional fuel combustion. In this layout part of the cooler exhaust air (further called cooler mid-air) is supplied to a preheater cyclone stage, which is gas-tight against the preheater stages operated under oxyfuel conditions. That way the preheating of the material shall be supported to increase the thermal energy efficiency of the process. This process configuration includes one bigger dimensioned cyclone stage and a duct lined with refractory from the cooler back to the preheater leading to higher investment costs.

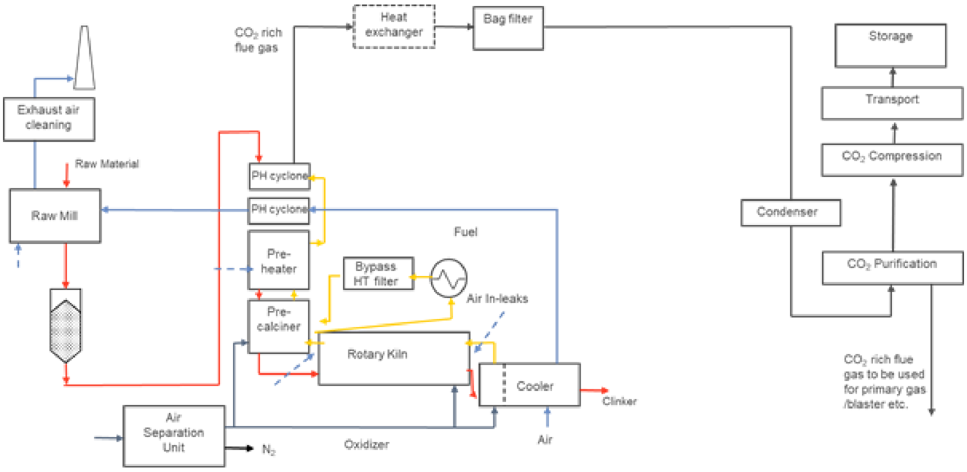


Figure 16: Alternative process configuration including an air-stage to optimize the thermal energy demand

This alternative configuration allowed a reduction of the additional thermal energy from additional 14.8% (Oxyfuel 2nd gen, first configuration) to 10.7% for the coal fired cases. However, the expected positive effect was dampened by the higher wall heat losses of the second configuration. Compared to the reference dimensioned plant wall losses can be reduced by approx. 12% in the first configuration of 2nd generation oxyfuel design. The additional ducting and the larger dimensioned cyclone air-stage increases the wall heat losses by 4-5% compared to configuration 1. Despite that, the complexity of operation, the risk for additional false air and the investment costs rises. For this reason, this configuration has not further been assessed.

Task 5.2: Evaluation of the impact of scale in new-build oxyfuel cement plants

As the clinker-specific energy requirement is directly dependent on the dimension of the clinker kiln, an increase of the kiln capacity is linked to a reduction of specific CO_2 emissions. For higher clinker throughputs the plant components are larger dimensioned and consequently the total heat losses are increased. However, relating to the produced amount of clinker, (specific) heat losses fall with increasing plant size. In this way the thermal energy demand can be reduced. However, the clinker quality and kiln operation is not affected when adapting the fuel input to match the lower specific wall heat losses. Doubling the production capacity to 6,000 t/d of the reference plant the thermal energy demand is reduced by 5.6%. As described above the dimensions of the 2nd generation oxyfuel kiln are smaller, which reduces the effect of wall heat losses on the thermal energy demand. Consequently, the benefit of a higher kiln capacity of 6,000 t/d is lowered to 4.3% savings in thermal energy demand. However, reduction of kiln diameter and reduction of material residence time inside the kiln require industrial proof.

D5.1: Optimized operation of a 2nd generation new-build oxyfuel cement plant

Task 5.3: Evaluation of techno-economic feasibility of new-build 2nd generation oxyfuel cement plants

Techno-economic evaluation of a 1st and 2nd generation oxyfuel reference cement plant was performed. A discounted cash flow approach with 8% discount rate and 25 years of plant lifetime was used. The cost estimates correspond to AACE 18R-97 Class 4 estimates with targeted accuracy of -30%/+50%. The evaluation is based on process simulations, public data and literature data for cost of consumables. Capital costs are estimated by various partners in the project.

Four cases were evaluated (Figure 17):

- 1st generation oxyfuel plant with heat to power cycle,
- 1st generation oxyfuel plant without heat to power cycle,
- 2nd generation oxyfuel plant with heat to power cycle,
- 2nd generation oxyfuel plant without heat to power cycle.

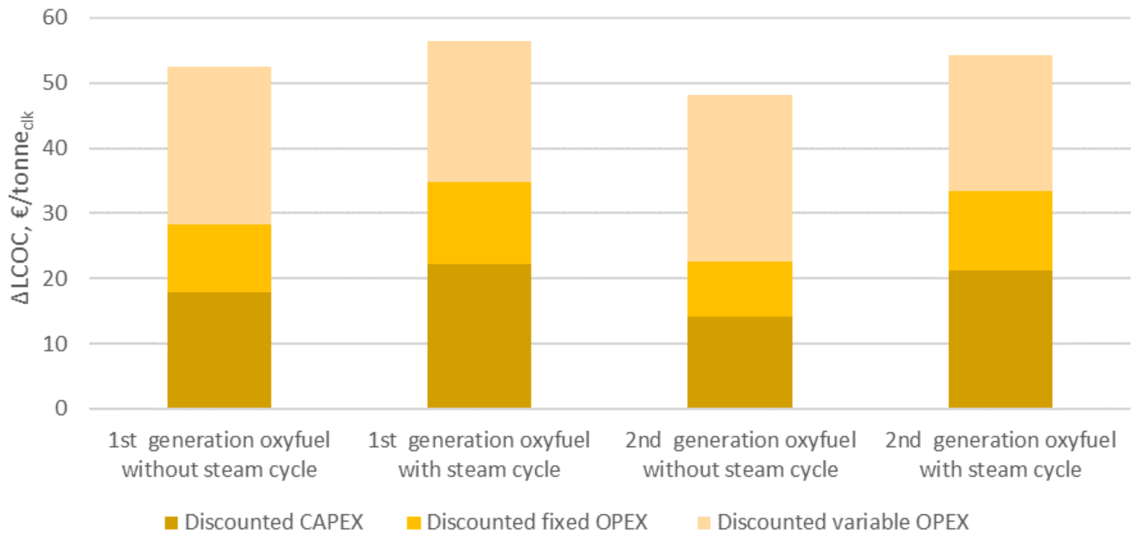


Figure 17: Increased levelized cost of clinker of the four cases evaluated compared to the reference plant without CCS.

In both cases the steam cycle increases the levelized cost of clinker. However, the economic performance of a steam cycle is highly depending on the electricity price. Moreover, the differences between plants with and without steam cycle reduce slightly if the cost of CO_2 avoided is compared.

The 2nd generation oxyfuel plants perform better than the 1st generation oxyfuel plants in terms of increased levelized cost of clinker and CO_2 avoided. The evaluations were made considering Nth of a kind (NOAK) project based on the current knowledge of the technologies. This approach was kept consistent between greenfield and brownfield evaluations. However, in the early stages of commercialization the costs might be higher.

The assessment provides, however, a valuable perspective regarding expected economic performance of these technologies. Nevertheless, there exist an implicit uncertainty regarding these costs. The evaluated KPIs are sensitive to parameters such as electricity cost. Moreover, the overall benefit of retrofitting an existing plant to reduce CO_2 emission, e.g. shorter periods of downtime, should not be dismissed. Moreover, difference in increased levelized costs between 1st and 2nd generation oxyfuel plants are within the error margins of the cost evaluations.

D5.2: Techno-economic feasibility study of 2nd generation oxyfuel cement plants

D5.3: Techno-economic comparative study of 1st and 2nd generation oxyfuel cement plants

WP6: Life cycle assessment (LCA)

Task 6.1: Gathering and synthesis of primary data

This task involves the gathering and synthesis process data, emission inventories, and mass/energy balances of the different life-cycle stages of the clinker production processes investigated in the project. These includes process conditions and efficiencies, consumables, pollutants emission factors, characteristics of the individual technologies and energy and material balances. Process flow diagrams and techno-economic aspects received from Task 4.6 and Task 5.3 are a major data contributor. These interactions with other WPs resulted in a spreadsheet of emission inventory summarizing key data required for the environmental impact analysis allowed the creation of detailed life-cycle inventory models for the different clinker production processes in the different European countries. Also, the reiteration process involving data exchange and creation of life-cycle inventories allowed the construction of a comprehensive integrated framework for the analysis of the clinker production impacts in the different in European countries by combining activity data, emissions metrics and quantification of environmental impacts.

Task 6.2: Life cycle assessment of retrofitted 1st generation and new-build 2nd generation oxyfuel cement plants

These results are presented as the first publication that is the deliverable D6.1 in the AC²OCem project (Cavalett et al., 2022). It was published in June 2022 in Nature Scientific Reports. This publication included:

- Life cycle assessment (LCA) based on real-world data of two state-of-the art cement plants (from Task 6.1), one in Sweden and one in Germany, operating under conventional and retrofitted to oxyfuel CCS conditions. These are benchmarked with a reference cement plant with typical European data.
- Quantification of impacts on climate change (using various climate metrics), human toxicity, fossil depletion potential and water depletion potential.
- Increasing use of alternative fuels with high share of biomass (up to 100%) in the cement plants operating under oxyfuel conditions.
- Impacts with use of biomass from both dedicated energy crops and forest residues.
- Prospective LCA considering the projected changes in the electricity systems in the two respective countries created with a forward-looking background life cycle database based on outputs from Integrated Assessment Models (IAMs).

This study indicates that retrofitting of cement plants with oxyfuel capture technologies can provide significant reductions in the climate change impacts. The use of this CCS technology in combination with increasing use of alternative fuels with high biogenic shares, such as biomass from forest residues or dedicated bioenergy crops like miscanthus, allows achieving negative emissions in the cement clinker production process. Results show that retrofitting the cement plants to oxyfuel reduces climate change impacts between 74% and 91%, while with additional use of biomass as alternative fuel the cement plants reach negative emission between −24 and −169 $gCO_{2eq.}$ per kg of clinker, depending on operational condition, location, and biomass type. Additional emission reduction of -10 (plant in Sweden) and -128 $gCO_{2eq.}$ per kg of clinker (plant in Germany) are expected from the decarbonization of the future electricity systems. These results illustrate the large climate change mitigation potential in the cement sector that can be achieved by the implementation of oxyfuel carbon capture and storage and biomass use as alternative fuel.

The availability of biomass resources is likely to be limited and their sustainable supply needs to be secured. There is potential in existing biomass residues streams or suboptimal agricultural practices, but the competition for these feedstocks is likely to increase in the future. If sustainable biomass supply is not available at the scale that will be needed, the cement production sector cannot achieve substantial negative CO_2 emissions. Future refining and developments in the environmental implications of the large-scale adoption of the oxyfuel capture technology in combination with site-specific availability of biomass resources will be instrumental to identify, manage and prevent potential conflicting implications of the various relevant environmental impact categories.

D6.1: Life cycle assessment of the 1st generation retrofitted and 2nd generation new-build oxyfuel cement plants (Link)

Task 6.3: Quantification of the contributions in terms of net potential for carbon capture and storage of these technological solutions

The quantification of the contributions of investigated oxyfuel technologies in the decarbonization of cement industry in Europe are presented as the second scientific article under submission to an international journal that is the deliverable D6.2. This scientific paper included:

- The construction of a comprehensive model for clinker production combining emission in European countries activity data, emissions metrics and quantification of environmental impacts.
- 10 key decarbonization options (e.g., alternative fuels like biomass, natural gas or hydrogen; technological improvements; clinker substitution; CCS and carbon capture and production of e-fuels, among others), and combinations of them (e.g., alternative fuels and CCS), are assessed and compared in terms of impacts on climate change, fossil fuel use, water consumption, and human health, with an overview of the techno-economic challenges of their implementation.
- Consideration of current and projected clinker production trends.
- Cases with oxyfuel CCS and exploratory 2nd generation oxyfuel CCS technology.
- Projections of future changes in technical and socio-economic conditions are explicitly embedded in our analysis by integrating scenario data from Integrated Assessment Models (IAMs) with LCA background processes
- Quantification of the carbon mitigation potential and spatially differentiated impacts in human heath, water and fossil fuels depletion from the European cement industry.
- Qualitative assessment of synergies and trade-offs between climate change mitigation and other sustainability issues, including techno-economic aspects such as costs, technology maturity level (TML) and challenges of its implementation.

The impacts for the clinker production process vary between 850 ± 16 kg $CO_{2eq.}$ (Norway) and 1154 ± 40 $CO_{2eq.}$ (Estonia) per ton of clinker, while the weighted average impact of European clinker production is 942 ± 23 kg CO_{2eq}. per ton of clinker. Decarbonization options at different levels of maturity offer a potential reduction of climate change impacts between 7 and 137 Mton $CO_{2eq.}$ per year (representing between 5% - 109% of today's annual emissions from cement plants in Europe), with synergies and trade-offs with other environmental impacts. Solutions like higher use of alternative fuels or use of the best available technologies can reduce climate impacts up to 30%, while a mix of complementary measures in a representative decarbonization pathway achieves a mitigation of about 50% by 2050.

Given the peculiarity of the cement industry, where a large portion of CO_2 emissions is due to the calcination process, changing the heat supply source from fossil fuels to renewable fuels has relatively limited mitigation potential (up to about 30%). Other options such as reduced clinker to cement ratio or use of best available kiln technologies can mitigate up to about 20% of today's emissions. Larger emission reductions as required to bring the sector on a net-zero pathway requires a large-scale implementation of carbon capture and storage, with an active management and prevention of potential trade-offs that can occur with other environmental impacts. The implementation of oxy-CCS causes reduced direct emissions of some air pollutants such as NO_x SO_x, CO and particulates at the local level, because they are either produced in lower amounts thanks to an O_2-rich combustion process and/or co-captured alongside CO_2. Lower impacts to human health are thus directly arising from cement plants. At the same time, the higher electricity required for CCS systems can still be associated with emissions of air pollutants damaging human health. This case shows the importance to develop electricity decarbonization in parallel with abatement of other pollutants to secure win-win transitions.

The joint implementation of combined decarbonization options at a pace illustrated by a representative implementation pathway may be not sufficient to meet the zero-emission target as indicated by policy makers and sectoral institutions. Additional mitigation efforts are needed if the net zero targets are to be achieved, and investments are required to overcome existing techno-economic barriers for the implementation of the various decarbonization options. An action plan that takes into consideration the current status of the cement industry in different European countries, which decarbonization option should be prioritized also in light of its co-benefits and trade-offs, and the availability of local resources to be used as alternative fuels can lead to optimal mitigation pathways that can co-deliver climate change mitigation and alleviate other environmental impacts.

D6.2: Investigation of the potential of oxyfuel technology for decarbonization of cement industry in Europe (Intended publication)

4.2 Overall overview of financial results

Financial Progress Table

Partner	WP1 [K€]	WP2 [K€]	WP3 [K€]	WP4 [K€]	WP5 [K€]	WP6 [K€]	Total at Month 42 [K€]	% of total grant/budget
USTUTT	90	548	255	17	-	2	**912**	101%
VDZ	56	-	34	495	26	4	**615**	90 %
tk Polysius GmbH[4]	24	8	278	38	32	1	**381**	100 %
SINTEF	19	209	-	237	228	11	**704**	100 %
CERTH	7	44	-	90	-	-	**141**	100 %
TITAN	12	10	10	38	20	-	**90**	100%
Heidelberg Materials	24	17	-	102	37	15	**195**	100
Holcim	21	39	0	94	62	27	**243**	90 %
NTNU	10	0	0	0	0	347	**357**	100 %
Air Liquide	-	-	198	-	-	-	**198**	
TOTAL Norge	25	0	0	30	0	0	**55**	100 %
TOTAL								

5. Project impact

Comment on the impact of the project, discussing the items below, if relevant for the project. Include a discussion of relevant market and policy developments and their potential impact.

- Contribution to the facilitation of the emergence of CCUS
- Strengthen the competitiveness and growth of European companies
- Other environmental or socially important impacts, such as public acceptance
- Chances for commercializing the technology further
- Gender issues

- **Contribution to the facilitation of the emergence of CCUS**

The AC^{2}OCem project demonstrates the technical and economic feasibility of the oxyfuel technology and lifts the technology maturity. Therefore, the project would put the cement industry in a position to apply this innovative technology on industrial scale when confronting the expectations for CO$_2$ reduction in the time ahead. The results and findings from this project significantly advance the technology for 1st and 2nd generation oxyfuel. This project supports the transition to climate neutrality by developing oxyfuel technology as promising carbon capture technology. This technology is important for the decarbonization of the European cement industry.

---

[4] WP3.2: Additional costs due to a larger scope of adjustments at the test facility and higher equipment rental costs. The total cost of the project exceeded the estimated budget. These additional costs were covered by tk Polysius GmbH.

The AC^{2}OCem project results support the de-risking of this highly integrated technology, that will be applied as the first demonstrators in the cement industry in the coming years. Although the economic analysis depends on various influencing factors and the results show higher cost impacts than previous studies, the AC^{2}OCem project has confirmed that the oxyfuel technology is one of the most promising technological solutions for the cement industry to capture CO_2 from its cement operation.

- **Strengthen the competitiveness and growth of European companies**

Without CCS no carbon neutrality could be achieved in 2050 in the cement industry. This implies no future cement production in Europe. Even the EU Green Deal identifies cement as indispensable product. Carbon leakage and imports from markets which are not part of a carbon trading system, will threaten the corresponding European markets and their respective jobs. Some 50 000 jobs were directly attributed to the European cement industry. Related to cement and concrete about 1.1 m European jobs are indirectly and directly created elsewhere in the economy. Furthermore, for the cement industry to be competitive in the world market, carbon capture costs must be as low as possible. AC^{2}OCem project targets at costs efficiency of one of the most promising capture technologies to support future competitiveness of European cement production

Economy wide, companies participating in AC^{2}OCem results are not only the cement manufacturing market but also equipment suppliers/technology providers for cement and gas supply equipment

- **Other environmental or socially important impacts, such as public acceptance**

Understanding the carbon capture technology and processes increases the social acceptance. AC^{2}OCem knowledge sharing activities support the industry in their communication with society.

- **Chances for commercializing the technology further**

Holcim as a future host of oxyfuel technology is gaining relevant information from the pilot-scale oxyfuel burner and calciner tests that are directly transferred to concrete projects and will be useful in the design and operational considerations of an oxyfuel cement plant. Beside other oxyfuel projects the Holcim C2B project in Germany has been selected by EU to be funded by the European Innovation Fund. In this way, Holcim will use the AC^{2}OCem results beyond the project within the demonstration activities at TRL 8.

As a consortium member of AC^{2}OCem, **Heidelberg Materials** has gained a broader and deeper understanding of the required design considerations but also useful information for the operation of oxyfuel systems. The learnings can concretely be put into practice in the different oxyfuel projects of the company, like the Cl4C project in Mergelstetten based on Oxyfuel Generation 2 as well as other EU funded projects in the European zone.

Air Liquide for its characteristics is at the heart of today’s and tomorrow’s challenges: energy and environmental transition and technological progress. The knowledge acquired during the AC^{2}OCem project brings more robust growth to the group already present in the primary industry. This project has shown that oxygen technology has a true advantage, and it can be one of the potential solutions for the near future. Moreover, this development can be implemented easily in the industrial sites and eases the increase of the usage of alternative fuels all around Europe.

TotalEnergies is very active in CO_2 transport and storage activities but is also promoting the best CO_2 capture technologies for its clients such as cement producers. AC^2OCem project support the de-risking of this highly integrated technology, that will be coming soon in this industry to lower the capture cost. This project strengthens the competitiveness and growth of European companies in CCUS.

tkP, the results and findings within the project are important for the development and implementation of the CI4C and C2B projects as well as for numerous other planned plant modifications of existing cement plants.

TITAN has gained significant improved insight in the first as well as second generation oxyfuel process, which is important for the technoeconomic assessment of available options required for improving the carbon footprint based on carbon capture technologies. TITAN will keep working on the development of the oxyfuel technology through its participation in the HerCCules EU funded project targeting at the implementation of a TRL7-8 oxyfuel calciner at one of its cement plants in Greece.

- **Gender issues**

In the frame of the AC^2OCem consortium members, there have been no known or documented gender equality issues. Nevertheless, it is worth mentioning that for example in Germany, a conscious effort was put into giving female and male candidates an equal opportunity to work on the project in the form of PhD or master students. In France, industrial companies are exerting great effort to hire more women and disabled people. Additionally, the ratio of female to male of the active members in the consortium is 1:2.

6. Implementation

Describe the implementation of the project results in relation to the SET plan Implementation Actions (no 9 on CCUS), Mission innovation research priorities and how you have engaged industry in your work.

The AC^2OCem project addresses the CO_2 emissions from the cement industry and the implementation of oxyfuel technology as a viable capture solution. In the cement industry, around one-third of the CO_2 is produced from fuel combustion and two-thirds is produced as a side product to the main cement production process, by the calcination of limestone raw material. For this reason, *CO_2 mitigation in the cement industry can only be accomplished by implementing carbon capture technologies*.

The results of the AC^2OCem project have successfully demonstrated the oxyfuel technology in retrofitting existing cement plants (1st generation) and the innovative application for new-build oxyfuel plants (2nd generation). The results of the AC^2OCem project have been realized through a series of pilot-scale experiments, simulations, process modeling of existing plants, techno-economic analysis, and life cycle assessments.

The consortium partners have successfully demonstrated the 1st generation oxyfuel combustion technology using 100 % alternative fuels as an energy and cost-efficient retrofit option. The results have shown the possibility of achieving a carbon-negative solution with the Bio-CCUS technology. The project partners demonstrated pilot-scale experimental results as well as simulations of the novel concept for oxyfuel, promoting the oxyfuel technology to the 2nd generation of new-build plants. *This unique concept of the 2nd generation oxyfuel technology with 100 % (excess) oxygen combustion has advanced from TRL 2 to TRL 6*.

The AC^{2}OCem project results directly contribute to several research and innovation (R&I) activities and targets of the ***SET plan Implementation*** Actions no. 9, specifically [5]:

- R&I activity 6: 'Developing next-generation CO_2 capture technologies'
  Target 6: 'At least 3 pilots on promising new capture technologies, and at least one to test the potential of sustainable Bio-CCS at TRL 6-7 study'
- R&I activity 2: 'Delivery of regional CCS and CCU clusters '

Additionally, and in agreement with the ***Mission Innovation*** perspectives [6], AC^{2}OCem results greatly contribute to shrinking the knowledge gaps in oxyfuel technology with the aim of accelerating the time-to-market for the CCUS technology in the cement industry.

The participation of three partners from the cement industry and three technology providers in AC^{2}OCem indicated the strong interest and necessity of the project to support and facilitate future large-scale oxyfuel demonstration in the cement industry. Two Work Packages (WP) of the project were led by industrial partners, WP3 was led by tk Polysius GmbH, and WP4 was led by Heidelberg Materials. Furthermore, two of the three participating cement producers are the owners of the selected plants for the large-scale oxyfuel demonstrations. This ensured the team access to data, boundary conditions and other required information to perform the retrofitability study.

7. Collaboration and coordination within the Consortium

Describe the collaboration and coordination within the Consortium. Comment on the effectiveness of management structures and governance procedures. Add a special focus on the added value of trans-national collaboration on CCUS.

The AC^{2}OCem consortium has 11 partners from 5 European countries. The transnational collaboration was perceived well, and the project was excellently managed by the coordinator and work package leaders. The consortium partners met on a regular basis, with scheduled progress meetings every 6 months. Additionally, the partners involved in tasks together planned regular web meetings. The progress meeting allowed each WP to show the latest updates, connect with members not involved in the WP and discuss the plans for the upcoming 6 months.

Regular contact between the project partners builds trust and allows effective knowledge sharing. This knowledge transfer is crucial between:

- The cement producers and the partners performing the pilot-scale tests have access to the boundary conditions to design the test parameters.
- The partners performing the pilot-scale test and the cement producers with the partners performing the CFD and process modelling
- Cement producers, technology providers and research institutions with the partners performing the TEA and LCA

---

[5] SET-Plan ACTION n°9 - Implementation Plan: SET-PLAN TWG9 CCS and CCU Implementation Plan.

[6] Mission Innovation: Report of the Mission Innovation Carbon Capture, Utilization and Storage; 2019.

8. Dissemination activities (including list of publications)

List published project results and progress/outcomes such as publications, patents, presentations etc. and make sure that these will be available through the project website as well. Use the format specified for the traffic light report.

Describe if and how your industry partners have taken up the results and implemented them. Also describe if you have reached out to other industry actors, stakeholders, policy makers and public in gereral and how these actors have paid attention/shown interest in the work you have been undertaking.

Air Liquide R&D department is in charge to develop differentiating solutions to meet the challenges encountered by the company, while helping to build a sustainable growth and achieve the objective of carbon neutrality by 2050. In the frame of the AC^{2}OCem project, Air Liquide has demonstrated its advantages for an oxyfuel conversion of a cement plant while being used in the R&D platform. The results obtained during this project have already been shared with all the partners of the consortium. This know-how is used by the field employees to discuss with our customers and to help them to improve their processes showing that the usage of oxycombustion for the clinker manufacturing eases the CO_2 capture.

Holcim will use results from the AC^{2}OCem program in their specific CCUS projects & ensure sharing of new know-how within the Group. The outcome is also planned to be summarized at a Holcim Switzerland event later this year ("Fachtagung 2023"), where 150-200 stakeholders from clients, planers, academia and the public are expected.

TotalEnergies will use the results to enrich oxy combustion know-how, not only for cement plants but also waste incinerators, gas boilers, etc.

tkP: For plant suppliers and the cement industry, the results of the project are important.

List of publications and dissemination activities regarding AC²OCem

Type of publication	please specify type of publication if "Oth=Other" is selected	Author/s or speaker/s	Title *with active link if available*	Reference (Journal/issue, event)	Date/ Year	AC²OCem partners involved *(partner short names)*	Others involved (please specify briefly)
O = Oral Presentation	-	Jörg Maier	Accelerating Carbon Capture using Oxyfuel Technology in Cement Production http://www.act-ccs.eu/s/AC2OCEM.pdf	ACT 4th Konowledge Sharing Workshop, Athens, Greece	November 2019	USTUTT	
Oth = Other, please specify	AC²OCem website		http://ac2ocem.eu-projects.de/		December 2019	USTUTT	
O = Oral Presentation		Jörg Maier, Cynthia Kroumian	Oxyfuel technologies for CO2 capture at cement plants	ACT 5th Konowledge Sharing Workshop	November 2020	USTUTT	
Oth = Other, please specify	Announcement at website		https://www.vdz-online.de/wissensportal/forschungsprojekte/ac2ocem-beschleunigung-der-co2-abscheidung-mit-der-oxyfuel-technologie-in-der-zementproduktion	VDZ Website	2020	VDZ	

O = Oral Presentation	-	Kristina Fleiger	EU Project AC^{2}OCem	ECRA CCS Project Steering Committee	29 June 2020	VDZ	
O = Oral Presentation		Mirko Weber, Holcim	Pioneering CCU/S solutions to reduce CO2 – spotlight on Austria's C2PAT initiative: Mirko Weber and Joseph Kitzweger, LafargeHolcim	Cemtech Online Conference: "Decarbonising the cement industry Pathways to a sustainable future"	21-24 September 2020	LafargeHolcim	Link
Oth = Other, please specify	Peer reviewed paper + oral presentation	Cynthia Kroumian, Kristina Fleiger, Ines Veckenstedt, Mari Voldsund, Otávio Cavalett, Simon Roussanaly, Joerg Maier, Volker Hoenig, Konstantina Peloriadi, Günter Scheffknecht	DESCRIPTION OF THE WORK AND PRELIMINARY RESULTS OF THE AC^{2}OCEM PROJECT IN FACILITATING CARBON CAPTURE TECHNOLOGY IN THE CEMENT INDUSTRY USING OXYFUEL COMBUSTION	TCCS-11 - Trondheim Conference on CO2 Capture, Transport and Storage	June 21-23, 2021	USTUTT, VDZ, tkP, SINTEF, NTNU, CERTH	-

SPa = Peer reviewed Paper	-	Otavio Cavalett	(in preparation) Deployment of bio-CCS: case study on the cement sector	IEA Bioenergy	2021	NTNU	-
SPa = Peer reviewed Paper		Cavalett, O., Watanabe, M. D. B., Fleiger, K., Hoenig, V. & Cherubini, F.	LCA and negative emission potential of retrofitted cement plants under oxyfuel conditions at high biogenic fuel shares	Nature Science Reports **12**, 1–14	June 2022	VDZ	
SPa = Peer reviewed Paper	Intended publication	Cavalett, O., Watanabe, M. D. B., Voldsund, M., Roussanaly, S. & Cherubini, F.	Paving the way for a sustainable decarbonization of the European cement industry	Unspecified international journal	June 2023	Sintef	
SPa = Peer reviewed Paper		Andersson, Leif Erik; Voldsund, Mari; Subramanian, Avinash Shankar Rammohan; Anantharaman, Rahul; Fleiger, Kristina; Carrasco, Francisco; Weber, Mirko	Heat integration for oxyfuel cement plants	Computer-aided chemical engineering	2023	SINTEF, VDZ,SINTEF, NTNU, Holcim, HeidelbergMaterials	
B = Blog		Voldsund, Mari; Ditaranto, Mario; Bakken, Jørn	Second-generation oxyfuel technology: Accelerating CCS in the cement industry	SINTEF Blogg	2021	SINTEF	
O = Oral Presentation		Mirko Weber, Holcim	Carbon Capture - Ein integraler Bestandteil der Dekarbonisierung bei Holcim	24. HOLCIM FACHTAGUNG 2023	06.09.2023	Holcim	

Oth = Other, please specify	Oral Presentation + Abstract	Voldsund, Mari; Anantharaman, Rahul; Andersson, Leif Erik; Carrasco, Francisco; Fleiger, Kristina; Paul, Jourdaine; Mariac, Laurent; Roussanaly, Simon; Subramanian, Avinash; Veckensted, Ines; Weber, Mirko	Techno-economic Evaulation of Oxyfuel CO2 Capture in European Cement Plants	GHGT-16	25.10.2022	SINTEF, VDZ, NTNU, Holcim, HeidelbergMaterials, Air Liquide, TOTALEnergies, thyssenkrupp	
A = Abstract		Reyes-Lúa, Adriana; Voldsund, Mari; Anantharaman, Rahul; Andersson, Leif Erik; Carrasco, Francisco; Fleiger, Kristina; Paul, Jourdaine; Mariac, Laurent; Roussanaly, Simon; Subramanian, Avinash; Veckensted, Ines; Weber, Mirko	Techno-economic Evaluation of Second Generation Oxyfuel CO2 Capture in a Cement plant	TCCS-12 - Trondheim Conference on CO2 Capture, Transport and Storage	June 2023	SINTEF, VDZ, NTNU, Holcim, HeidelbergMaterials, Air Liquide, TOTALEnergies, thyssenkrupp	
Po = Poster	Poster Presentation + Abstract	Konstantina Peloriadi, Dimitrios Fakis, Aristeidis Nikolopoulos, Vasileios Michalis, Panagiotis Grammelis	Mitigation of flue gas impurities in oxyfuel cement plants	GRC Permanently Removing CO2	April 2022	CERTH, TITAN	
Po = Poster		Konstantina Peloriadi, Dimitrios Fakis, Aristeidis Nikolopoulos, Vasileios Michalis, Panagiotis Grammelis	Carbon Capture using Oxyfuel Technology in Cement Production	GRC Transformative Science for the New Carbon Economy	May 2023	CERTH, TITAN	

PoPa = Poster and Paper		Konstantina Peloriadi, Dimitrios Fakis, Aristeidis Nikolopoulos, Panagiotis Grammelis	Assessment of flue gas impurities in oxyfuel retrofitted cement plants	TCCS-12 - Trondheim Conference on CO2 Capture, Transport and Storage	June 2023	CERTH	
O = Oral Presentation		Cynthia Kroumian	Oxyfuel burner technology	AC^{2}OCem Final Workshop, Link	March 2023	USTUTT, CERTH, SINTEF	Link
O = Oral Presentation		Ines Veckenstedt	Impact on oxyfuel calciner	AC^{2}OCem Final Workshop, Link	March 2023	tk, USTUTT, AL	Link
O = Oral Presentation		K. Peloriadi & F. Carrasco	Integration of 1st gen oxyfuel technology to existing cement plants	AC^{2}OCem Final Workshop	March 2023	Heidelberg, CERTH	Link
O = Oral Presentation		K. Fleiger & L. Andersson	Oxyfuel technology for new built plants	AC^{2}OCem Final Workshop	March 2023	VDZ, SINTEF	Link
O = Oral Presentation		O. Cavalett & A. Reyes-Lua	TEA and LCA	AC^{2}OCem Final Workshop	March 2023	SINTEF, NTNU	Link
SPa = Peer reviewed Paper		C. Kroumian, J. Maier, G. Scheffknecht	Experimental evaluation of rich oxyfuel combustion characteristics in varying over-stoichiometric conditions	Under review (international journal)	2023	USUTT	

Annex: AC^{2}OCem final financial report

Project name: Accelerating Carbon Capture using Oxyfuel technology in Cement production - AC^{2}OCem
Project number: 299663
Actual cost per country / per organisation

Country	ACT funding	Other public funding	Private funding, R&D institution	Ptivate funding, industry	In-kind, R&D institution	In-kind industry	Other funds	Total after 42 months per org	Total after 42 months per country
Germany (K€)									**2104**
USTUTT	900	-	-	-	12.4	-	-	912.4	-
VDZ	492.2	-	-	-	123.1	-	-	615.3	-
tk Polysius GmbH[7]	171.5	-	-	-	-	209.6	-	381.2	-
Heidelberg Materials	84	-	-	-	-	112	-	195	-
Norway (K€)	**791**	**-**	**-**	**240**	**30**	**55**	**-**	**-**	**1116**
SINTEF	447	-	-	240	17	-	-	704	-
NTNU	344	-	-	-	13	-	-	357	-
TOTAL Energies	-	-	-	-	-	55	-	55	-
Greece (K€)	**200**	**-**	**-**	**31.5**	**-**	**-**	**-**	**-**	**231.5**
CERTH	141.5	-	-	-	-	-	-	141,5	-
TITAN	58.5	-	-	31.5	-	-	-	90	-
Swizerland (K€)	**97**	**-**	**-**	**146**	**-**	**-**	**-**	**-**	**243**
Holcim	97	-	-	146	-	-	-	243	-
France (K€)	**99**	**-**	**-**	**99**	**-**	**-**	**-**	**-**	**198**
Air Liquide	99	-	-	99	-	-	-	198	-
Total per funding									

---

[7] tk Polysius GmbH: WP3.2: Additional costs due to a larger scope of adjustments at the test facility and higher equipment rental costs. The total cost of the project exceeded the estimated budget. These additional costs were covered by tk Polysius GmbH."