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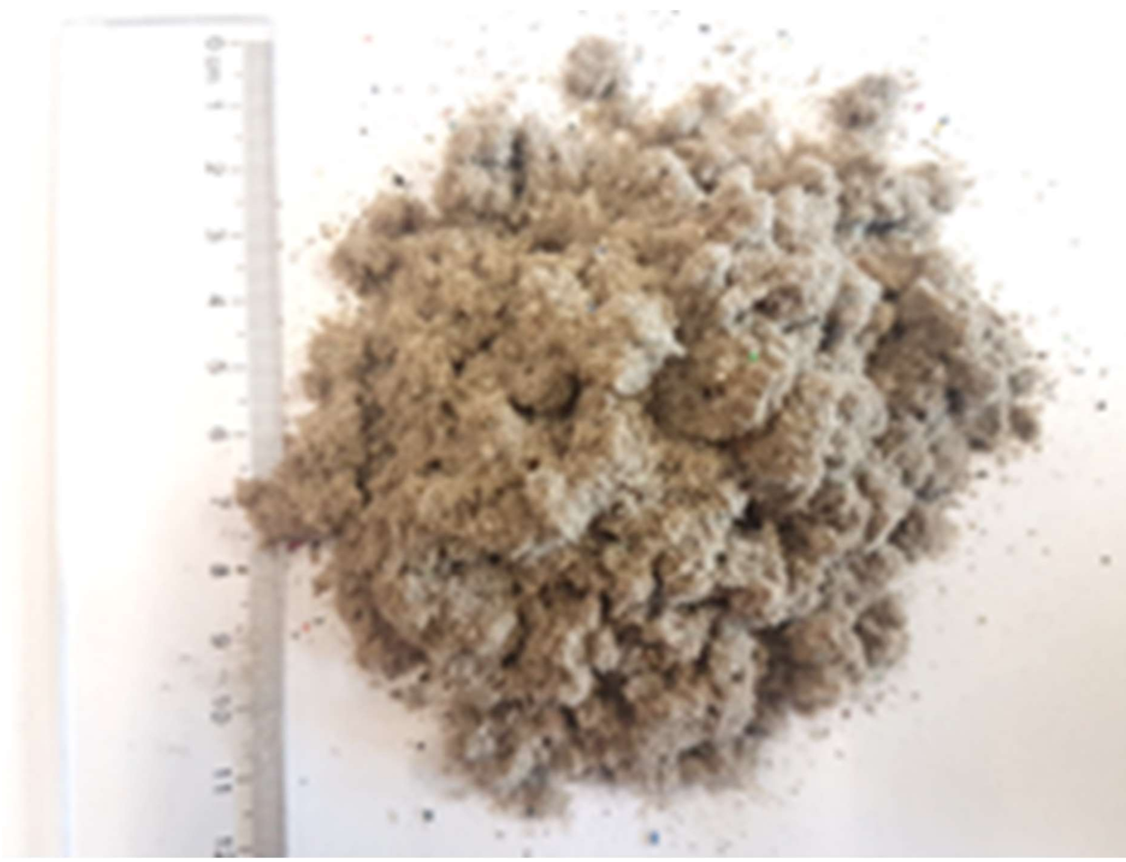
AC2OCem

Accelerating Carbon Capture using Oxyfuel Technology in Cement Production



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Zusammenfassung

Für das Projekt AC2OCEM - Accelerating Carbon Capture using Oxyfuel technology in Cement production - wurde ein starkes Konsortium von elf Partnern aus fünf europäischen Ländern, darunter Norwegen, Deutschland, die Schweiz, Frankreich und Griechenland, zusammengestellt. Es bringt Universitäten und Forschungsinstitute (Universität Stuttgart, VDZ, SINTEF Energy Research, Center for Research and Technology-Hellas CERTH und Norwegian University of Science and Technology NTNU), industrielle Endnutzer (Heidelberg Materials, Holcim, TITAN und TOTAL) und Technologieanbieter (ThyssenKrupp Polysius und Air Liquide) zusammen. Das Projekt wurde im Rahmen des ACT-Programms (Accelerating CCS Technologies, Horizon2020 Project No 299663) finanziert. Der Schweizer Beitrag von Holcim Technology wurde vom Schweizer Bundesamt für Energie BFE unterstützt.

Das Projekt AC2OCem befasste sich mit den CO2-Emissionen der Zementindustrie und der Einführung der Oxyfuel-Technologie als praktikable Abscheidungslösung.

Die Zementproduktionsindustrie ist die zweitgrösste industrielle CO2-Emissionsquelle. Die Scope-1-CO2-Emissionen einer Zementproduktionsstätte haben zwei Quellen: Etwa ein Drittel des CO2 entsteht bei der Verbrennung von Brennstoffen und zwei Drittel werden als Nebenprodukt des Hauptprozesses der Zementherstellung durch die Kalzinierung von Kalksteinrohmaterial erzeugt. Während der erste Teil möglicherweise durch den Einsatz von biogenen Brennstoffen, Elektrifizierung und/oder Wasserstoff in Zukunft vermieden werden kann, gilt der zweite Teil als "schwer zu vermindern". Aus diesem Grund kann die CO2-Minderung in der Zementindustrie nur durch den Einsatz von Technologien zur Kohlenstoffabscheidung (CCUS) erreicht werden.

Ziel des AC2OCem-Projekts war es, die Dekarbonisierung der europäischen Industrie durch die Integration der Oxyfuel-Technologie in der Zementindustrie als eine der kosteneffizientesten Lösungen zur CO2-Abscheidung zu fördern. Die Grundidee der Oxyfuel-Technologie besteht darin, Verbrennungsluft durch Sauerstoff zu ersetzen, um den Stickstoff aus der Luft im System zu vermeiden und das CO2 für eine effiziente Abscheidung in einer Reinigungseinheit (CPU) vorzukonzentrieren.

Mit dem Ziel, die Markteinführung der Oxyfuel-Technologie im Zementsektor zu verkürzen, arbeitete das Projekt an der Weiterentwicklung der Schlüsselkomponenten von Oxyfuel-Zementanlagen. Neben Demonstrationstests umfasste das Projekt mehrere analytische und theoretische Studien einschliesslich Aspen-Simulation und CFD-Modellierung. Dies ermöglichte eine Verringerung der technologischen Wissenslücken zur Unterstützung und Beschleunigung der grosstechnischen Oxyfuel-Demonstrationsanlagen mit der Aussicht auf eine CO2-arme Zementproduktion.

Um die Technologie zu beschleunigen, untersuchte das Projekt AC2OCem die Anwendung der Oxyfuel-Technologie in bestehenden und neu gebauten Zementanlagen. Im Rahmen des AC2OCem-Projekts wurde die so genannte Oxyfuel-Technologie der ersten Generation, bei der das Abgas teilweise in den Brennbereich zurückgeführt wird, um die Gasmengen im System in einem ähnlichen Bereich wie beim konventionellen Luftbetrieb zu halten, für die Nachrüstung bestehender Anlagen untersucht - mit Schwerpunkt auf der Optimierung des Oxyfuel-Kalzinatorbetriebs und der Weiterentwicklung der Ofenbrennertechnologie für die Verbrennung von 100 % alternativen Brennstoffen, einschliesslich eines hohen biogenen Anteils. Der Versuchsaufbau stand im Einklang mit den Strategien zur Erhöhung des Anteils alternativer Brennstoffe von Holcim Schweiz (>85% bis 2030 gegenüber 51% 2021) und von Cemsuisse (60% Biomasse, 100% alternative Wärmeenergie bis 2050). Neben Simulationen auf der Grundlage einer theoretischen Referenzanlage und experimentellen Untersuchungen in mehreren Versuchsanlagen wird eine Nachrüstbarkeitsanalyse auf der Grundlage von Randbedingungen zweier spezifischer Zementwerke durchgeführt, um den Technologietransfer von TRL6 zu TRL8 zu unterstützen. Ergänzt wurde die Arbeit durch eine techno-ökonomische Analyse für einen Leitfaden zur Nachrüstung der Oxyfuel-Technologie in bestehenden Zementanlagen.

Darüber hinaus wurde im Rahmen des Projekts die innovative Oxyfuel-Technologie der 2. Generation für neu zu errichtende Zementanlagen ohne Rauchgasrückführung untersucht. Ein noch nie dagewesener Oxyfuel-Ofenbrenner für eine überstöchiometrische und bis zu 100 %ige Sauerstoffverbrennung wird entwickelt und in einer Pilotanlage getestet, die die Bedingungen in einem Zementofen nachbildet. Dieses Prozessdesign wird durch eine techno-ökonomische Analyse bewertet und optimiert.

Es wurde eine technisch-wirtschaftliche Bewertung einer Oxyfuel-Anlage der 1. und 2. Generation durchgeführt, die auf das 3000 tato-Referenzzementwerk angewendet wurde. Die nivellierten Kosten des Klinker-Deltas verglichen mit einem Zementwerk ohne CCUS liegen zwischen 49 und 63 Eur/t Klinker und die Kosten für vermiedenes CO2 bei 67 bis 83 Eur/t für die beiden Oxyfuel-Nachrüstungen der ersten Generation.

Die in dieser Studie für die beiden Anlagen der ersten Generation geschätzten Kosten sind deutlich höher als die Kosten, die in früheren Studien für ideale hypothetische Referenzanlagen geschätzt wurden. Dies ist auf ein besseres Verständnis der Komplexität der Änderung bestehender Anlagen, höhere CPU CAPEX, mehr Realismus durch die Verwendung nachgebauter bestehender Anlagen, allgemein höhere Kosten für Rohstoffe und einen erweiterten Umfang durch die Einbeziehung von Pipelines und CO2-Puffertanks zurückzuführen.

Die Oxyfuel-Anlagen der 2. Generation schneiden etwas besser ab als die Oxyfuel-Anlagen der 1. Generation in Bezug auf die höheren Klinkerkosten und die vermiedenen CO2-Emissionen, dies ist jedoch Gegenstand von Sensitivitätsanalysen und detaillierten Untersuchungen.

Die wirtschaftlichen Ergebnisse reagieren sehr empfindlich auf die getroffenen Annahmen, daher führte das Projektteam bestimmte Sensitivitätsanalysen zu diesen Kostenzahlen durch, z. B. zu den Stromkosten, der CO2-Intensität des Stroms, dem Investitionsdelta, den Ausfallzeiten bei der Klinkerproduktion oder der Rohmaterialfeuchte. Die Stromkosten spielen eine wichtige Rolle, der erwartete Strombedarf steigt von 8 MW (BAT-Anlage ohne CO2-Abscheidung) auf über 33 MW (Zementanlage mit Oxyfuel-Kohlenstoffabscheidung der zweiten Generation).

Im Rahmen des AC2OCem-Projekts wurden schliesslich die ökologischen Nachhaltigkeitsaspekte von Oxyfuel-Technologien für nachgerüstete und neu gebaute Zementwerke durch die Durchführung von Lebenszyklusanalysen zusammengefasst. Der Einsatz dieser CCS-Technologie in Kombination mit dem zunehmenden Einsatz alternativer Brennstoffe mit hohem biogenen Anteil ermöglicht es, negative Emissionen bei der Zementklinkerherstellung zu erreichen.

Die Ergebnisse des AC2OCem-Projekts werden in Form von Zeitschriftenveröffentlichungen, Konferenzvorträgen, Workshops, Blogs usw. verwertet und verbreitet, um die Wirkung der Ergebnisse und der gewonnenen Erkenntnisse zu maximieren. Zu den wichtigsten Höhepunkten der Verbreitungsarbeit des Konsortiums gehörten die Trondheim Carbon Capture and Storage Conference TCCS-11, ein abschliessender AC2OCem & ANICA-Workshop in den Räumlichkeiten des VDZ in Düsseldorf, die ghgt-16-Konferenz in Lyon und eine öffentliche Holcim "Fachtagung"-Veranstaltung in Zürich.

Die Ergebnisse des AC2OCem-Projekts wurden durch eine Reihe von Experimenten im Pilotmassstab, Simulationen, Prozessmodellierung und CFD, techno-ökonomische Analysen und Lebenszyklusanalysen erzielt. Die Konsortialpartner haben erfolgreich die Oxyfuel-Verbrennungstechnologie der ersten Generation unter Verwendung von 100 % alternativen Brennstoffen als energie- und kosteneffiziente Nachrüstungsoption demonstriert. Die Ergebnisse haben gezeigt, dass es möglich ist, mit der Bio-CCUS-Technologie eine kohlenstoffnegative Lösung zu erreichen.

Die Projektpartner haben experimentelle Ergebnisse im Pilotmassstab sowie Simulationen des neuartigen Konzepts für Oxyfuel der 2. Generation für Neuanlagen demonstriert. Dieses einzigartige Konzept mit 100 %iger (überschüssiger) Sauerstoffverbrennung ist von TRL 2 auf TRL 6 gestiegen.

Résumé

Pour le projet AC2OCEM - Accelerating Carbon Capture using Oxyfuel technology in Cement production - un consortium solide de onze partenaires de cinq pays européens, dont la Norvège, l'Allemagne, la Suisse, la France et la Grèce, a été constitué. Il réunit des universités et des instituts de recherche (Université de Stuttgart, VDZ, SINTEF Energy Research, Center for Research and Technology-Hellas CERTH et Norwegian University of Science and Technology NTNU), des utilisateurs finaux industriels (Heidelberg Materials, Holcim, TITAN et TOTAL) et des fournisseurs de technologie (ThyssenKrupp Polysius et Air Liquide). Le projet a été financé dans le cadre du programme ACT (Accelerating CCS Technologies, Horizon2020 Project No 299663). La contribution suisse de Holcim Technology a été soutenue par l'Office fédéral de l'énergie OFEN.

Le projet AC2OCem s'est intéressé aux émissions de CO2 de l'industrie du ciment et à la mise en œuvre de la technologie de l'oxycombustion en tant que solution de capture viable.

L'industrie du ciment est la deuxième plus grande source d'émissions industrielles de CO2. Les émissions de CO2 d'un site de fabrication de ciment ont deux sources : environ un tiers du CO2 provient de la combustion de combustibles et deux tiers sont des produits secondaires du processus principal de production de ciment, par la calcination de la matière première, le calcaire. Si la première partie peut être évitée en utilisant des combustibles biogènes, l'électrification et/ou l'hydrogène à l'avenir, la seconde partie est considérée comme "difficile à réduire". C'est pourquoi la réduction des émissions de CO2 dans l'industrie du ciment ne peut se faire qu'en mettant en œuvre des technologies de capture du carbone.

L'objectif du projet AC2OCem était de renforcer la décarbonisation de l'industrie européenne en intégrant la technologie de l'oxyfuel dans l'industrie du ciment comme l'une des solutions de capture du carbone les plus rentables. L'idée de base de l'oxyfuel est de remplacer l'air de combustion par de l'oxygène, afin d'empêcher l'azote de l'air dans le système et de pré-concentrer le CO2 pour une capture efficace dans une unité de purification (CPU).

Dans le but de réduire le délai de mise sur le marché de la technologie de l'oxycombustion dans le secteur du ciment, le projet s'est efforcé de faire progresser les composants clés des cimenteries oxycombustion. Outre les essais de démonstration, le projet a couvert plusieurs études analytiques et théoriques, y compris la simulation Aspen et la modélisation CFD. Cela a permis de réduire les écarts de connaissances technologiques afin de soutenir et d'accélérer les usines de démonstration d'oxyfuel à grande échelle dans la perspective d'une production de ciment proche de zéro CO2.

Afin d'accélérer la technologie, le projet AC2OCem a étudié l'application de la technologie de l'oxyfuel aux cimenteries existantes et aux nouvelles cimenteries. Dans le cadre du projet AC2OCem, la technologie oxyfuel dite de première génération, où les gaz d'échappement sont partiellement recirculés dans la zone de combustion pour maintenir les volumes de gaz dans le système dans une gamme similaire à celle du fonctionnement à l'air conventionnel, a été étudiée pour la modernisation des usines existantes - en se concentrant sur l'optimisation du fonctionnement du calcinateur oxyfuel et en faisant progresser la technologie du brûleur du four pour brûler 100 % de combustibles alternatifs, y compris une part élevée de biogène. La configuration expérimentale était conforme aux stratégies d'augmentation des combustibles alternatifs de Holcim Suisse (>85 % d'ici 2030 contre 51 % en 2021) et de Cemsuisse (60 % de biomasse, 100 % d'énergie thermique alternative d'ici 2050). En plus de la simulation basée sur une usine de référence théorique et des recherches expérimentales dans plusieurs installations expérimentales, une analyse d'adaptabilité est réalisée sur la base des conditions limites de deux cimenteries spécifiques pour soutenir le transfert de technologie de TRL6 à TRL8. Le travail a été complété par une analyse technico-économique en vue d'une ligne directrice sur la modernisation de la technologie de l'oxycombustion dans les cimenteries existantes.

En outre, la technologie innovante d'oxycombustion de deuxième génération pour les nouvelles cimenteries sans recirculation des gaz de combustion a été étudiée dans le cadre du projet. Un

brûleur de four oxyfuel sans précédent pour une combustion surstœchiométrique et jusqu'à 100 % d'oxygène est développé et testé dans une installation pilote qui reproduit les conditions des fours à ciment. Cette conception de procédé est évaluée et optimisée par le biais d'une analyse technico-économique.

L'évaluation technico-économique d'une oxyfuel de 1ère et 2ème génération appliquée à la cimenterie de référence de 3000 tpj a été réalisée. Le coût nivelé du delta de clinker par rapport à une cimenterie sans CCUS se situe entre 49 et 63 Eur/t cli et le coût du CO2 évité entre 67 et 83 Eur/t pour les deux cas d'amélioration de l'oxyfuel de 1ère génération.

Les coûts estimés pour les deux usines de première génération dans cette étude sont nettement plus élevés que les coûts estimés dans les études précédentes pour les usines de référence hypothétiques idéales. Cela est dû à une meilleure compréhension de la complexité de la modification des installations existantes, à des dépenses en capital plus élevées, à un plus grand réalisme grâce à l'utilisation d'installations existantes reproduites, à un coût généralement plus élevé des matières premières et à l'extension du champ d'application grâce à l'inclusion des pipelines et des réservoirs tampons de CO2.

Les usines d'oxycombustion de deuxième génération sont légèrement plus performantes que les usines d'oxycombustion de première génération en termes d'augmentation du coût du clinker et de CO2 évité, ce qui est toutefois sujet à des sensibilités et à des études détaillées.

Les résultats économiques sont très sensibles aux hypothèses retenues, c'est pourquoi l'équipe du projet a effectué certaines analyses de sensibilité sur ces chiffres de coûts, comme le coût de l'électricité, l'intensité en CO2 de l'électricité, le delta des investissements, le temps d'arrêt de la production de clinker ou l'humidité des matières premières. Le coût de l'électricité joue un rôle important, les besoins prévus en énergie électrique passant de 8 MW (usine BAT sans capture du carbone) à plus de 33 MW (cimenterie avec capture du carbone par oxyfuel de deuxième génération).

Le projet AC²OCem a finalement résumé les aspects de durabilité environnementale des technologies d'oxycombustion pour les cimenteries rénovées et nouvellement construites en réalisant des évaluations du cycle de vie. L'utilisation de cette technologie de CSC, combinée à l'utilisation croissante de combustibles alternatifs à forte proportion biogénique, permet d'obtenir des émissions négatives dans le processus de production de clinker.

Les résultats du projet AC2OCem sont exploités et diffusés sous forme de publications, de présentations lors de conférences, d'ateliers, de blogs, etc. afin de maximiser l'impact des résultats et des enseignements tirés. Parmi les points forts du travail de diffusion du consortium, citons la conférence de Trondheim sur le captage et le stockage du carbone (TCCS-11), un atelier final AC2OCem et ANICA dans les locaux du VDZ à Düsseldorf, la conférence ghgt-16 à Lyon et un événement public Holcim "Fachtagung" à Zürich.

Les résultats du projet AC2OCem ont été obtenus grâce à une série d'expériences pilotes, de simulations, de modélisations de processus et de CFD, d'analyses technico-économiques et d'évaluations du cycle de vie. Les partenaires du consortium ont démontré avec succès la technologie d'oxycombustion de première génération utilisant 100 % de combustibles alternatifs en tant qu'option de modernisation énergétique et économique. Les résultats ont montré la possibilité de parvenir à une solution neutre en carbone avec la technologie Bio-CCUS.

Les partenaires du projet ont démontré des résultats expérimentaux à l'échelle pilote ainsi que des simulations du nouveau concept d'oxycombustion, promouvant ainsi la technologie de l'oxycombustion pour la deuxième génération de nouvelles centrales. Ce concept unique de combustion à 100 % d'oxygène (en excès) est passé du TRL 2 au TRL 6.

Summary

For the project AC2OCEM - Accelerating Carbon Capture using Oxyfuel technology in Cement production – a strong consortium was put together with eleven partners from five European countries including Norway, Germany, Switzerland, France and Greece. It combines universities and research institutes (University of Stuttgart, VDZ, SINTEF Energy Research, Center for Research and Technology-Hellas CERTH and Norwegian University of Science and Technology NTNU), industrial end users (Heidelberg Materials, Holcim, TITAN and TOTAL) and technology providers (ThyssenKrupp Polysius and Air Liquide). The project was funded as part of the ACT program (Accelerating CCS Technologies, Horizon2020 Project No 299663). The Swiss contribution by Holcim Technology was supported by the Swiss Federal Office of Energy SFOE.

The AC2OCem project addressed the CO2 emissions from the cement industry and the implementation of oxyfuel technology as a viable capture solution.

The cement production industry is the second largest industrial CO2 emission source. The scope 1 CO2 emissions of a cement manufacturing site has two sources: around one third of the CO2 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. While the first part can be avoided by using biogenic fuel, electrification and/or hydrogen in future, the second part is considered as “hard to abate”. For this reason, CO2 mitigation in the cement industry can only be accomplished by implementing carbon capture technologies.

The aim of the AC2OCem project was to reinforce the decarbonization of European industry by integrating the oxyfuel technology in the cement industry as one of the most cost-efficient carbon capture solution. The basic idea of oxyfuel is to replace combustion air by oxygen, in order to prevent the nitrogen from the air in the system and to pre-concentrate the CO2 for an efficient capturing in a purification unit (CPU).
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. Beside demonstration tests the project covered several analytical and theoretical studies including Aspen simulation and CFD modelling. 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 CO2 cement production.

To accelerate the technology, the AC2OCem project investigated applying the oxyfuel technology on existing and new-build cement plants. In the frame of the AC2OCem project, the so-called 1st generation oxyfuel technology, where exhaust gas is partially recirculated back to the burning area to keep the gas volumes in the system in a similar range than in conventional air operation, was investigates for retrofitting existing plants - focusing on optimization of the oxyfuel calciner operation and advancing the kiln burner technology for combusting 100 % alternative fuels, including high biogenic share. The experimental setup was in line with the strategies on alternative fuel increase by Holcim Switzerland (>85% by 2030 vs. 51% 2021 baseline) and by Cemsuisse (60% biomass, 100% alternative thermal energy by 2050). In addition to simulation based on a theoretical reference plant and experimental investigations in several experimental facilities, a retrofitability analysis is performed based on boundary conditions from two specific cement plants to support the technology transfer from TRL6 to TRL8. The work was complimented with a techno-economic analysis for a guideline on retrofitting the oxyfuel technology in existing cement plants.

Furthermore, the innovative 2nd generation oxyfuel technology for new-build cement plants with no flue gas recirculation has been studied within the project. 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.

Techno-economic evaluation of a 1st and 2nd generation oxyfuel applied to the 3000 tpd reference cement plant was performed. The Levelized cost of Clinker delta to a cement plant without CCUS is between 49 and 63 Eur/t cli and the cost of avoided CO2 at 67 to 83 Eur/t for the two 1st generation oxyfuel retrofits cases.

The cost estimated for the two plants 1st generation retrofits 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, general higher cost for raw materials and extended scope by including pipelines and CO2 buffer tanks.

The 2nd generation oxyfuel plants perform slightly better than the 1st generation oxyfuel plants in terms of increased clinker cost and CO2 avoided, this is however subject to sensitivities and detailed investigations.

The economic results are very sensitive towards the assumptions taken, therefore the project team was running certain sensitivity analyses on these cost figures, like electrical power cost, CO2 intensity of power, capex delta, clinker production downtime or raw material moisture. Electricity cost plays an important role, the expected electrical power requirements raises from 8 MW (BAT plant w/o carbon capture) to above 33 MW (cement plant incl. 2nd generation oxyfuel carbon capture).

The AC²OCem project finally summarized the environmental sustainability aspects of oxyfuel technologies for retrofitted and new-build cement plants by conducting life cycle assessments. The use of this CCS technology in combination with increasing use of alternative fuels with high biogenic shares, allows achieving negative emissions in the cement clinker production process.

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. Some key highlights of the dissemination work of the consortium included the Trondheim Carbon Capture and Storage Conference TCCS-11, a final AC2OCem & ANICA workshop at the VDZ premises in Düsseldorf, the ghgt-16 conference in Lyon and a public Holcim “Fachtagung”-event in Zürich.

The results of the AC2OCem project have been realized through a series of pilot-scale experiments, simulations, process modeling and CFD, 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 with 100 % (excess) oxygen combustion has advanced from TRL 2 to TRL 6.

Main findings

- Pilot-scale experiments with 100 % alternative fuels in main burner and calciner under oxyfuel combustion conditions successfully performed.
- Tests confirmed that the higher the partial pressure of CO2 in the surrounding atmosphere, the higher is the CaCO3 decomposition temperature. Water vapour promoted calcination however any additional water in the exhaust gas will have to be condensed and treated upstream the carbon purification unit.
- The retrofiliability of conventional cement plants to 1st generation oxyfuel lines have been demonstrated for two specific sites. The recirculation rate and correspondingly the oxygen concentration in the combustion gases is the most powerful parameter to optimize the oxyfuel operation in respect to thermal energy demand and flue gas volume.

- Simulations of the CPU has shown the importance of customized design and optimization of the CPU with pressure, dehydration, and cryogenic units in order to achieve high CO2 capture rates and purities while minimizing energy requirements for capture and storage.
- Cement plant impurities like dust, nitrogen oxides (NOx), and sulfur dioxide (SO2) require special attention and treatment.
- False air is one of the biggest technical risk for oxyfuel. a guideline on false air was developed.
- The techno-economic results for the Levelized cost of Clinker delta is between 49 and 63 Eur/t cli and the cost of avoided CO2 at 67 to 83 Eur/t for the two 1st generation oxyfuel retrofits cases.
- The 2nd generation shows a higher CO2 enrichment potential of about 90%dry CO2, depending on fuel mix, with the benefit of a more efficient CPU compared to the 1st generation, on the other hand the heat consumption will be elevated, so that finally the additional power demand is similar.
- The 2nd generation oxyfuel plants perform slightly better than the 1st generation oxyfuel plants in terms of increased levelized cost of clinker and CO2 avoided, subject to sensitivities.
- The Life Cycle Assessment indicated that 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, allows achieving negative emissions in the cement clinker production process.

Contents

Abbreviations

AC2OCem	Accelerating Carbon Capture using Oxyfuel Technology in Cement Production
AF	Alternative Fuels
ASU	Air Separation Unit
BAT	Best Available Technology
CAC	Cost of Avoided CO2
CBAM	Carbon Border Adjustment Mechanism
CERTH	The Centre for Research & Technology Hellas
CFD	Computational Fluid Dynamics
CCUS	Carbon Capture, Utilization and Storage
CPU	CO2 Processing Unit
DSS	Dried Sewage Sludge
FGR	Flue Gas Recirculation
HTEC	Holcim Technology
IAM	Integrated Assessment Models
IFK	Institut für Feuerungs- und Kraftwerkstechnik (University Stuttgart)
LCA	Life cycle assessment
LCOC	Levelized Cost of Clinker
NOAK	Nth of a kind
RDF	Refuse-Derived Fuel
RR	Flue Gas Recirculation Ratio
SFOE	Swiss Federal Office of Energy
SRF	Solid Recovered Fuels
SNCR	Selective Non-Catalytic Reduction
TKIS	Thyssen Krupp Industrial Solutions
TML	technology maturity level (TML)
TRL	Technical Readiness Level
USTUTT	University Stuttgart
VDZ	Verein Deutscher Zementwerke
WP	Workpackage

1 Introduction

1.1 Background information and current situation

For the project AC2OCEM - Accelerating Carbon Capture using Oxyfuel technology in Cement production – a strong consortium was put together with eleven partners from five European countries including Norway, Germany, Switzerland, France and Greece. It combines universities and research institutes (University of Stuttgart, VDZ, SINTEF Energy Research, Center for Research and Technology-Hellas CERTH and Norwegian University of Science and Technology NTNU), industrial end users (Heidelberg Materials, Holcim, TITAN and TOTAL) and technology providers (ThyssenKrupp Polysius and Air Liquide). The project was funded as part of the ACT program (Accelerating CCS Technologies, Horizon2020 Project No 299663). The Swiss contribution by Holcim Technology was supported by the Swiss Federal Office of Energy SFOE.

The AC2OCem project aimed to underpin the decarbonization of Europe by integrating oxyfuel technology in the cement production process as one of the most cost-effective carbon capture solutions. The cement production industry is the second largest industrial CO2 emission source by releasing about 2.2 Gt CO2 per year, equivalent to 27 % of the total CO2 emissions in the industry sector.

In Switzerland the cement industry contributes to 36% (2.5 Mt) of the CO2 emissions in the Swiss industrial sector in 2015 [3] related to the six cement plants with a total production capacity of about 5 Mt of cement annually. The Swiss cement plants show in average a lower CO2 footprint than on a European and global level, thanks to a modern dry clinker manufacturing process, to the relatively low clinker factor and due to the relatively high share of alternative fuels including biomass.

Even if in future fuel related CO2 can be further reduced, by means of using biomass, electrification and/or hydrogen, the raw material based CO2 from the decarbonization process of limestone, which is typically in the range of 2/3 of the emissions, remains as the “hard to abate” share. That’s why CCUS is considered as unavoidable to decarbonize the industry.

In Holcim climate action is at the core of the strategy. 2030 and 2050 net-zero targets have been validated by the Science Based Targets initiative (SBTi) across all three scopes. Holcim commits to reduce gross Scope 1 and 2 GHG emissions by 25 percent per ton of cementitious materials by 2030 from a 2018 base year and was among the first companies with 2050 net-zero targets across three scopes. Holcim describes the different measures on this journey in the “Holcim climate report 2023”, available on holcim.com.
CCUS is an integral part of this journey. Holcim is developing or assessing a range of CCUS technologies and pathways to give the maximum flexibility across the global footprint and to reduce capital investment requirements. The Holcim Group has several CCUS pilot projects and prepares the first full scale CCUS implementations. The company targets an installed CCUS capacity of 5 Mt/year by 2030 and committed a 2.0 billion CHF Capital Expenditure in CCUS excluding public funding by 2030. The EU supports the development by funding several of the European Carbon Capture projects by Holcim.

Holcim Switzerland shares the vision of producing climate neutral and completely recycled building materials by 2050. They were pioneering with resource-saving product offerings like Susteno cement or Evopact concrete and are working on various decarbonization projects, the various actions are described in the report “Für eine nachhaltig gebaute Zukunft”, available on holcim.ch. Holcim Switzerland is collaborating with universities and technology developers in various CCUS projects to evaluate efficient solutions for the three Holcim cement plants in Switzerland with the aim to have one of these projects realized before 2030 with a capacity of at least 20’000 t CO2/year.

Different technologies for Carbon Capture are considered in order to specify the best option for each plant and it’s boundary conditions:

Post combustion solutions aim to capture CO_2 in the exhaust gas of a traditional kiln system at the "end of the pipe." The most advanced post-combustion solution is based on liquid solvents such as amines, e.g. monoethanolamine (MEA). The CO_2 in the exhaust gas is absorbed by the solvent, and the CO_2-rich liquid is then sent to the regenerator where the CO_2 is released in a concentrated form. The solvent is reintroduced to the absorption column. Other post-combustion approaches include CO_2 separation by membranes and adsorption processes.
Amine based scrubbers have been demonstrated in large scale in other industries like power, however show rather high energy consumption in the cement environment. The required steam to desorb the CO_2 and recover the reagent is not available in cement plants and the waste heat that can be used is by far not sufficient. Additional steam generation will cause additional CO_2 formation and therefore reduces the efficiency and cost related to CO_2 avoided.
Therefore other postcombustion approaches, which are rather electrical based (adsorption, cryogenic, membranes) might be advantageous in this respect, maturity level of some of these technologies are however lower.

Integrated processes like the oxyfuel approach are very promising alternatives for the cement industry. Hereby air for combustion in the cement manufacturing process is replaced by oxygen to prevent nitrogen in the system and receive a concentrated CO_2 exhaust stream. The oxyfuel concept for the cement production had been the topic of discussion for the past few years in several research studies [1,2]. The great potential of full oxyfuel as a technologically and economically suitable solution for carbon capture in the cement industry was endorsed.

To accelerate the CCS technology development the AC2OCem project was created. The idea was to investigate applying the oxyfuel technology on existing and new-build cement plants. The project differentiates between the 1st generation oxyfuel with flue gas recirculation for the cement plant revamping and the 2nd generation with no circulation for the new built approach.
While it is not expected that the Swiss cement demand will increase substantially [3] there might still be replacement projects with new kiln lines, however for Switzerland the oxyfuel revamping concept is most probably of higher relevance given that 5 of the 6 Swiss cement plants are dry process preheater kiln systems.

The combustion conditions in the two concepts are different. While in the 1st generation scheme the recirculated fluegas enriched in CO_2 is mainly replacing the nitrogen (N_2) in the combustion air, the 2nd generation works with an overstochiometric oxygen flow in the main combustion area in the rotating kiln.

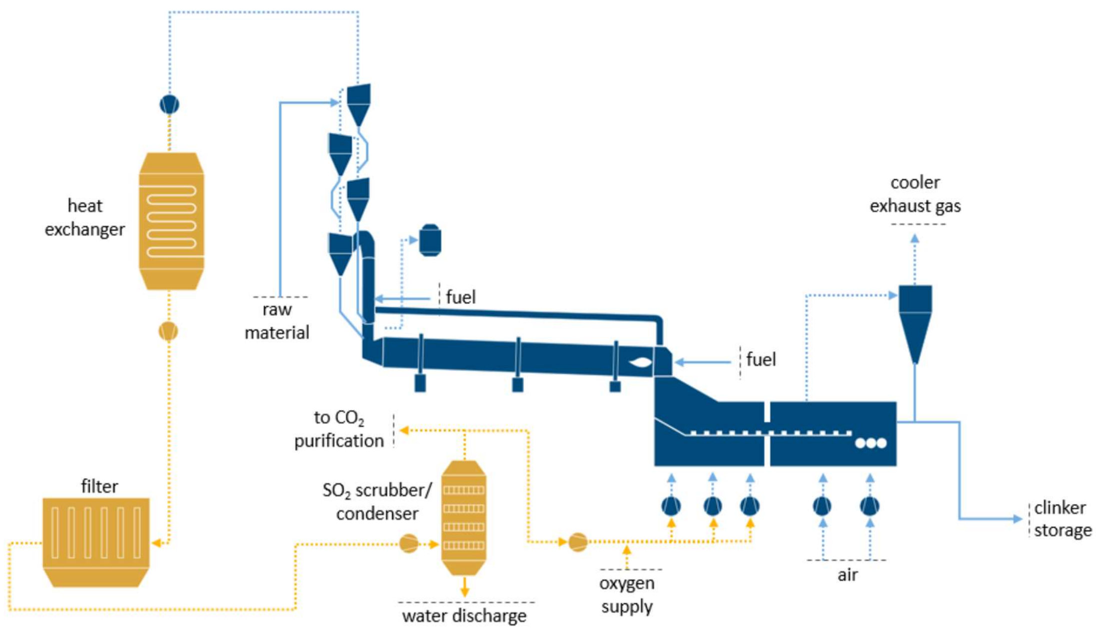


Figure 1: Schematic diagram of a 1st generation oxyfuel cement plant (source: ThyssenKrupp Polysius)

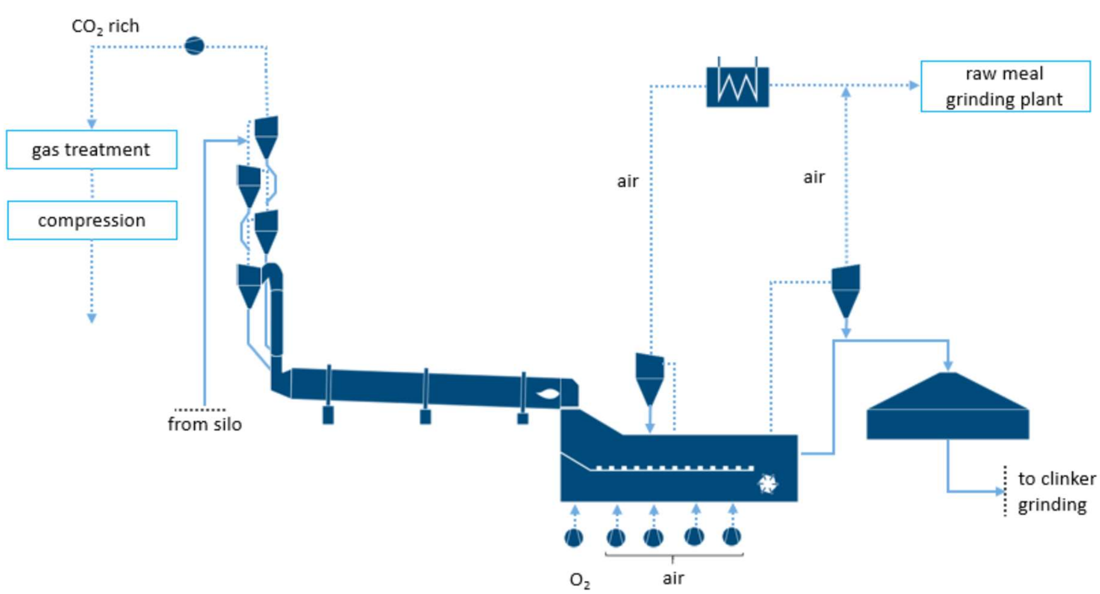


Figure 2: Schematic diagram of a 2nd generation oxyfuel cement plant with no flue gas recirculation (source: ThyssenKrupp Polysius)

While previous studies on CCUS [2] were focusing on traditional fuels, within the frame of the AC2OCem project alternative fuels was combusted in an oxyfuel atmosphere with the perspective of neutral or even negative CO2 cement production - aligned with Holcim strategy on alternative fuel increase and the Cemsuisse roadmap (60% biomass, 100% alternative thermal energy by 2050).

The EU selected several oxyfuel projects in the cement industry for Innovation Fund grants. This underpins the relevance of the technology in the industry. The AC2OCem project partners Heidelberg Materials and Holcim are hosting some of these large scale oxyfuel projects – ensuring that the AC2OCem results will directly influencing the concrete demonstration on industrial scale.

1.2 Purpose of the project

The project objectives are defined based on the existing knowledge on an oxyfuel cement process obtained via previous and ongoing carbon capture projects in the cement industry. This will allow a narrowing of the technological gaps for promoting the oxyfuel technology to accelerate the large-scale demonstration with the perspective of net zero CO2 cement production. In the project, it was the approach to advance the oxyfuel technology for cement industry by the assessment of key technical aspects to expedite the large-scale implementation of oxyfuel CO2 capture technology for retrofitted cement plants and to promote a novel oxyfuel concept for new-build plants, which was achieved by demonstration tests and analytical and theoretical studies.

The oxyfuel technology for coal power plants has already reached a high technical readiness level (TRL 8); however, this technology for cement plants requires further research and higher maturity levels. The AC2OCem project promotes the oxyfuel technologies for the cement industry with distinct technology readiness levels. The 1st generation oxyfuel technology for retrofitting applications have been investigated in previous and ongoing projects, where specific key components have reached TRL 6 prior to AC2OCem, though the technology was not yet fully ready for deployment at an industrial scale. In the frame of the AC2OCem project, the combustion of up to 100 % alternative fuel in oxygen enriched atmospheres has been studied. In addition to experimental activities, comprehensive process modelling of 1st generation oxyfuel, considering operational data from cement plants, contributes to the demonstration and ultimately commercialization of oxyfuel cement production.

The groundbreaking 2nd generation oxyfuel technology, mainly for newly-build kiln lines, was introduced for the first time in the AC2OCem project. The flue gas recirculation rate is reduced down to zero with the ultimate goal of an even more cost-effective CCUS solution. The concept is formulated prior to the project. Within the project, a new kiln burner is designed to handle alternative fuel combustion with up to 100 % oxygen, the burner was tested at a pilot-scale facility, leveraging the technology from TRL 2 to TRL 6. Moreover, basic experimental studies on the calcination process had been conducted at TRL 6 for the calciner under the altered oxyfuel regime.

1.3 Objectives

The key targets of the AC2OCem project had been defined as follows:

- Developing a novel oxyfuel concept, promoting this technology to the 2nd generation for new-build cement plants
- Experimental and analytical investigations of the 2nd generation oxyfuel technology, associated with a high reduction potential of energy demand, CAPEX and OPEX
- Expediting the 1st generation oxyfuel technology to market by retrofitability analysis of two cement plants, supporting the technology transfer from TRL 6 to TRL 8

- Advancing the 1st generation oxyfuel technology for utilization of high shares of alternative fuels, boosting CO_2 negative cement plants (Bio-CCS), by demonstration tests at pilot-scale facilities
- Optimization of the oxyfuel cement process with the ultimate goal of lowering the CO_2 avoidance cost
- Providing a guideline for the techno-economic decision-making process of retrofitting oxyfuel in cement plants
- Developing a comparative techno-economic study on 1st generation retrofitted and 2nd generation new-build oxyfuel cement plants to support the future decarbonized cement industry
- Addressing the environmental sustainability aspects of oxyfuel cement plants through life cycle assessments
- Increasing public awareness and acceptance regarding the deployment of CCUS in energy-intensive industries
- Spreading the acquired knowledge and outcome among the public organizations and the cement industry within and beyond the project

2 Description of facility

A technical-scale oxy-combustion facility (50 kW) at the university in Stuttgart was employed to characterize the combustion behavior of diverse alternative fuel samples, mainly solid recovered fuels (SRF) and biomass in the form of dried sewage sludge (DSS) and wood. Pilot-scale oxyfuel burner technology was investigated using the oxy-combustion facility (500 kW) at the University of Stuttgart, which was adopted to emulate a cement kiln burner. The down-fired combustion chamber is 7 m in length and 0.8 m in inner diameter.

Parametric study on calcination took place in an electrically heated entrained flow reactor located at the University of Stuttgart. The reactor is heated electrically and is capable also of providing concurrent feeding of raw material and fuel with air preheating to obtain similar operation conditions as in a typical cement plant calciner.

Air Liquide operates a 1 MWth technical rig ("CORALI") dedicated to the simulation of a cement calciner. The facility was operated in the frame of the AC2OCem project to develop new oxyfuel combustion technologies and to study the combustion of solid alternative fuels in different operation conditions. The bottom fire chamber can go up to 950 °C and is fuel flexible (solid, liquid and gaseous fuels possible) with a maximum particle size of 10 mm. Calcination conditions on fluidized bed conditions can be simulated thanks to the injection of fireclay and the decarbonization using CO2 injection. The facility allows measurements of temperature, heat flux, flame visualization, flue gas analysis, ash and unburnt analysis.

ThyssenKrupp Industrial Solutions operates a technical pilot plant that consists of a preheater and a calciner installation with a 4-stage cyclone preheater and a calciner length of ~10 m. The inner diameter is 100 mm, characteristic feed rates are in a range of 40 kg/h and the natural gas fired calciner had been modified to operate in a staged combustion scheme under oxyfuel conditions. Calciner operation under oxyfuel conditions with preheating of material, especially under wet conditions, simulated flue gas recirculation or no flue gas recirculation gas matrix and their effect on calcination efficiency and calcination temperature.

Beside the facilities for the experimental part of AC2OCem two cement plants had been selected in the frame of the project in order to study the retrofitting of these sites to the oxyfuel technology. Beside the site of "Slite" in Sweden, nominated by Heidelberg Materials, Holcim selected the Lägerdorf cement plant in North Germany. There is an ongoing project on the use of CO2 and funding was granted for the oxyfuel carbon capture in that plant, which significantly increases the likelihood of a full-scale realization of the technology based on the investigation within AC2OCem.
A full-scale pilot will be an important step for later multiplication, also in the Swiss cement plants. The Holcim plant in Germany operates with high raw material moisture, which represents an extreme case, allowing the AC2OCem results to be translated to any other modern cement plant, including the Swiss sites. It also fires a substantial amount of alternative fuels, the thermal substitution rate is in a typical range for western and central European sites.

3 Procedures and methodology

Beside the demonstration tests using the facilities according chapter 2 of this report the project covers several analytical and theoretical studies including Aspen simulation and CFD modelling. Beside a techno-economic analysis a life cycle assessment related to the oxyfuel technology was part of the project.

In general, the work is divided into the following main activities:

- Project management with focus on establishing clear management and results exploitation strategies.
- Experimental investigations of oxyfuel burner technology for 1st and 2nd generation oxyfuel cement plants.
- Experimental investigations of oxyfuel calciner.
- Process simulations and techno-economic evaluations of the 1st generation oxyfuel technology for retrofitted cement plants.
- Process simulations and techno-economic evaluation of the 2nd generation oxyfuel technology for new-build cement plants.
- Life cycle assessment of oxyfuel technology for 1st and 2nd generation oxy-fuel cement plants.
- Exploitation and dissemination of project results.

The topics have been distributed to six work packages according to the sketch below.

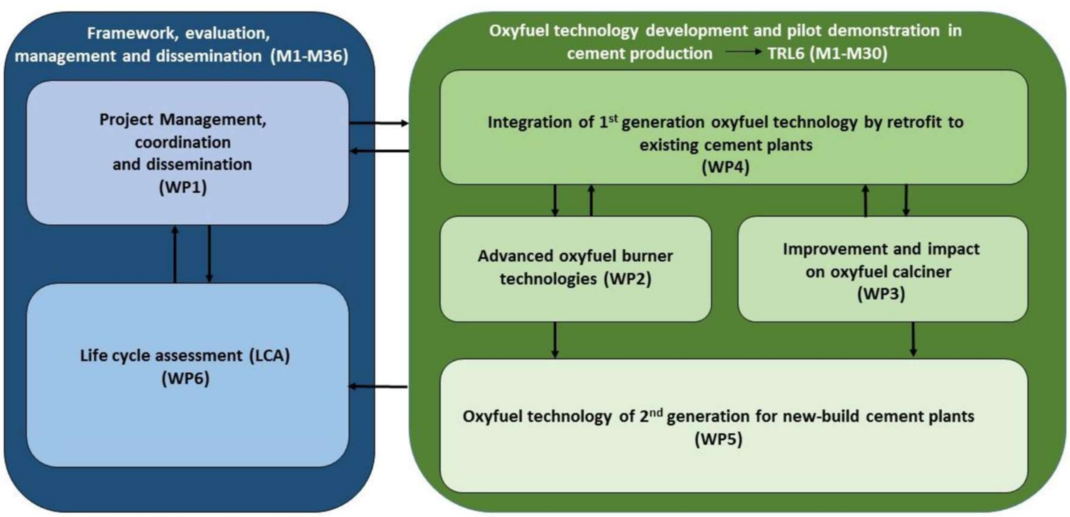


Figure 3: Workpackages within the AC2OCem project.

WP 1: Project management, distribution and utilization. (Leader: USTUTT, Partners: TKIS, SINTEF, CERTH, TITAN Cement, HeidelbergMaterials, Holcim, VDZ)

Objectives:

- Organization and administration for a successful fulfillment of the project goals through transparent, team-oriented group work based on defined individual tasks.
- Establishment of communication channels between the consortium partners and the responsible Norwegian authorities
- General dissemination tasks, increase topic awareness

Specific tasks with Holcim involvement:

- To improve the transfer of knowledge and experience gained in the project, VDZ was organizing a final AC2OCem seminar - in addition Holcim summarized the main outcome at the public event “24th Holcim Fachtagung”, see below.
- Holcim was participating in progress meetings, traffic light reports, mid term report, interim meetings and reporting with the the Swiss Federal Office of Energy SFOE etc.
- Holcim was reviewing AC2OCem specific publications and presentations
- Holcim organized one of the progress meetings on site in the cement plant in Lägerdorf, Germany
- Internal stakeholder engagement incl the Holcim affiliates Geocycle, and Group Companies in Switzerland and Germany

WP 2: Advanced oxyfuel burners and combustion concepts for high proportions of alternative fuels (Leader: USTUTT, Partners: TKIS, SINTEF, CERTH, TITAN Cement, Holcim)

Objectives:

- Development and testing of a new, advanced prototype of an oxyfuel burner and combustion concept to evaluate the innovative oxyfuel combustion concept with 100% oxygen and without CO2 recirculation - the developments and tests on a pilot scale with the new burner prototype leading to the achievement of TRL 6.
- Use of up to 100 % SRF fuel (Solid Recovered Fuel) of relevant qualities with up to 50 % biogenic content in an optimized oxyfuel burner with targeted oxygen enrichment.
- Adaptation and validation of combustion models for the combustion of high proportions of SRF in an oxygen-enriched atmosphere and CFD simulations to optimize combustion in the cement kiln.
- Evaluation of the emission behaviour and identification of necessary measures to avoid or minimize emissions.

Specific tasks with Holcim involvement:

- Holcim was providing relevant fuel qualities data for the testing of burner concepts and firing conditions of the 1st and 2nd oxyfuel generation through pilot tests at the IFK in Stuttgart.
- Holcim with the support of its daughter company Geocycle was organizing fuel samples from a cement plant for the tests at Stuttgart
- Holcim accompanied the test planning and execution at the pilot plant in Stuttgart and contributed to the evaluation and interpretation of results, considering specific boundary conditions of the cement plants.

WP 3: Improvements and influences on the oxyfuel calciner (leader: TKIS, partners: USTUTT, VDZ)

Objectives:

- Evaluation of the role of flue gas moisture level in the calciner to reduce and control the calcination temperature. Theoretical and experimental calcination tests will be performed up to pilot-scale in a process relevant environment (TRL 6).
- The impact of process conditions and flue gas impurities like sulfur and chlorines on calcination reaction will be evaluated at technical- and pilot-scales.
- Based on the results a moisture injection concept and process control strategy for retrofitted and new-build cement plants will be developed.
- Evaluation of oxyfuel calcination process with up to 100 % alternative fuel combustion in an oxyfuel calciner.

Holcim was officially not involved in the development of this work package, still giving some input within the general progress meetings and in the reporting phase.

WP 4 Implementation of 1st generation oxyfuel technology in a retrofitted existing cement plant (leader: HeidelbergMaterials, partners: CERTH, Holcim, TITAN Cement, TKIS, VDZ, USTUTT, SINTEF)

Objectives:

- Process modelling and simulation of retrofitted oxyfuel cement plants with regard to several scenarios for flue gas recirculation/recirculation of impurities and raw meal qualities to optimize the overall performance and energy demand of the plant under oxyfuel conditions
- Optimization of a retrofitted oxyfuel cement plant by localization and control of false air inflow
- Design considerations and retrofitting of oxyfuel cement plants
- Techno-economic evaluation of retrofitted cement plants

Specific tasks with Holcim involvement:

- Holcim provided advice and knowledge required for the adaptation of a retrofitted oxyfuel cement plant and reviewed concepts and simulation results.
- Selection criteria elaboration for case studies, taking into account specific boundary conditions corresponding to Holcim plants in Switzerland.
- Plant specific data and general input for the simulation and the techno-economical evaluation was provided, reviewing of results
- Experience sharing on false air fighting, typical values and potential further optimization, elaboration of guidelines to control and minimize false air

WP 5 Advanced 2nd generation oxyfuel technology for newly built cement plants (Leader SINTEF Partners: VDZ, Holcim, HeidelbergMaterials, TKIS)

Objectives:

- Optimization of the design and infrastructure of a newly constructed oxyfuel cement plant
- Design considerations for newly constructed oxyfuel cement plants
- Upscaling of the oxyfuel cement plant from 3,000 tons/day to 6,000 tons/day
- Techno-economic evaluation of a newly constructed oxyfuel cement plant

Specific tasks with Holcim involvement:

- Design considerations for newly constructed oxyfuel cement plants and scaling: Holcim provided necessary input data (boundary conditions, operating parameters, etc.) for the process simulation, taking into account company-specific design criteria for new plants.

- Input data and evaluation of techno-economic evaluation

WP 6 Life cycle analysis (comparative analyses) (Head: NTNU, partners: VDZ, Holcim, HeidelbergMaterials, TITAN Cement)

Objectives:

- Life cycle analysis of retrofitted and newly constructed oxyfuel cement plants
- Quantification of the contribution of oxyfuel cement plants to the decarbonization of the cement industry

Specific tasks with Holcim involvement:

- Holcim participated in the life cycle analysis by providing data required by other partners (e.g. thermal energy demand, raw materials and flue gas characterization, CO2 losses, etc.).Review and interpretation of results

4 Results and discussion

4.1 Workpackage 1 – Project Management, coordination and dissemination

The university of Stuttgart had the lead on project management. Progress meetings have been organized every six months to keep the partners updated on work being done in other work packages especially since data transfer between the workpackages was important for many partners to achieve their work through the project. Including the kick-off meeting in total seven progress meetings had been carried out, two of them as face-to-face meetings.
Holcim was organizing and hosting the 5th progress meeting in its cement plant in Lägerdorf in Germany, giving the consortium members the opportunity to get a tour in a cement plant. Other planned in person meetings had to be changed to a virtual approach due to the Corona crisis during the project timeframe. Throughout the lifespan of the AC2OCem project, partners also organized separate meetings within their workpackages where the group discussed results, shared information or handled issues that had occurred and re-set the schedule back to course.

The traffic light reports were coordinated by the workpackage leaders each quarter, and finally edited by the University of Stuttgart before submission.

The published deliverables related to workpackage 1:

D1.1: Project Website https://ac2ocem.eu-projects.de
D1.5: Project final report (link)

Holcim was having three project review meetings with the funding agency in Switzerland, the Swiss Federal Office of Energy SFOE, based on presentations summarizing the progress and results and one extended interim report dated December 5th 2021. Holcim Technology Ltd as the funding recipient was coordinating the work with other Holcim Group companies, in particular Holcim Switzerland, Holcim Germany and Geocycle.

The disseminated work within the AC2OCem project is listed in the ERANET final report in detail (link). Some highlights include the following events:

- AC2OCem members prepared a paper to be published in the scope of the Trondheim Carbon Capture and Storage Conference (TCCS-11) conference, where the main outcomes of the 1st phase of the project were presented during the online conference on June 22nd and 23rd 2021 (link to paper).

- AC2OCem collaborated with the ANICA project (https://act-anica.eu/) to plan two public workshops. A mid-term workshop was planned by the ANICA consortium and took place on 06.10.2021. The to-date AC2OCem 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 AC2OCem and ANICA. The workshop took place on March 7th and 8th 2023 at the VDZ building in Düsseldorf. The AC2OCem partners presented their final results in the public workshop where representatives from relevant institutes and companies were invited. The event was organized in a hybrid mode, in person and online participation was possible.

Picture 1: On site participants AC2OCem & ANICA workshop.

- The AC2OCem progress and results have been presented at several ACT Knowledge Sharing Workshops
- The “Techno-economic Evaluation of Oxyfuel CO2 Capture in European Cement Plants” of AC2OCem was presented at the GHGT-16 conference in Lyon in October 2022 (link to presentation).
- Holcim shared highlights of the AC2OCem project at the public event “24th Holcim Fachtagung” on September 6th 2023 in Zürich.

Picture 2: Presentation AC2OCem Highlights at the 24th Holcim Fachtagung

Awareness of the urgent need to apply carbon capture technology in the cement industry to decrease the CO2 emissions was one of the main motivations and goals of the AC2OCem project. Since the early 2000s, there has been an increase of research into the topic of carbon capture technologies. the use of keywords ‘carbon capture and storage CCS’ and ‘carbon capture and utilization CCU’ increasing exponentially in the past 30 years, shown in the graph below.

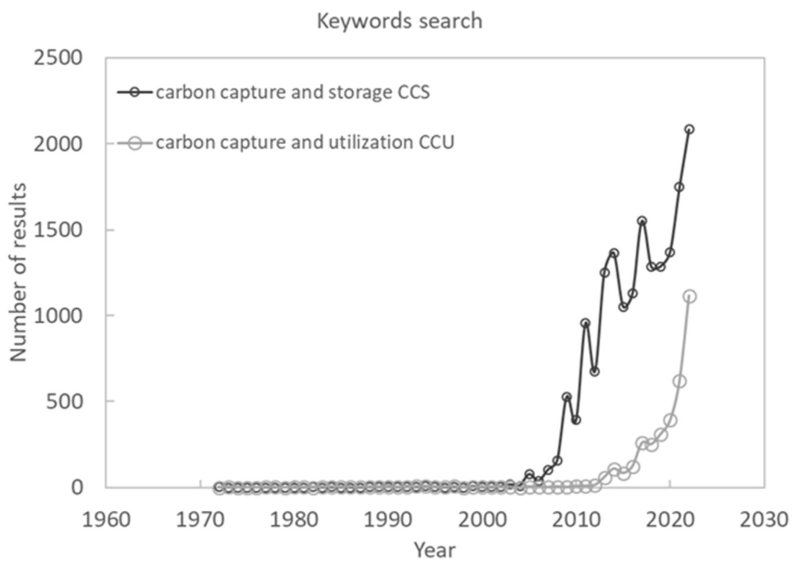


Figure 4: Number of publications in Elsevier with the keywords carbon capture and storage and carbon capture and utilization from the year 1972 to 2022

4.2 Workpackage 2 - 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)

The first task within the 2nd workpackage focused on substituting fossil fuels with alternative fuels and running a pilot-scale kiln burner in oxyfuel conditions. Combustion tests were performed in the 500 kWth 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 was the reference. Alternative fuel including solid recovered fuel (SRF), wood and the co-combustion of 90 % wood with 10 % dried sludge were tested in air and oxyfuel conditions and with two varying flue gas recirculation ratios (RR). The RR was adjusted by increasing the CO2 concentration in the inlet gases.

SRF is the most common alternative fuel used in European cement plants, including plants in Switzerland. Holcim with the support of its daughter company Geocycle was organizing samples of the dried sewage sludge fuel used in a German cement site for the tests at the university in Stuttgart and ensured applying fuel specifications that are representative for Western European cement plants including Switzerland. Since the aim was to increase as much as possible the biogenic share in the fuelmix to lower the carbon footprint the AC2OCem consortium decided to also test a fuel mix with a higher biogenic source rate. 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 experimental setup was therefore in line with the strategies on alternative fuel increase by Holcim Switzerland (>85% by 2030 vs. 51% 2021 baseline) and by Cemsuisse (60% biomass, 100% alternative thermal energy by 2050).

Foremost, the experiments have shown that the combustion of SRF - a rather inhomogeneous fuel mixture, wood and sludge was stable during air and oxyfuel conditions, the fuel composition and particle size led to a wider and longer flame in comparison to the localized and short coal flame. The tests showed that under oxyfuel conditions, flue gas RR plays a major role in controlling flame temperature and momentum at the burner. The variation of the flue gas RR has shown that oxyfuel combustion of alternative fuels with higher oxyfuel RR resembles air combustion conditions more than the low RR cases. Optimizing the burner could aid in further stabilizing the combustion conditions in the high RR case, by increasing the momentum and enhancing mixing conditions to improve the combustion rate at the near burner region. Achieving constant CO2 concentrations at the end of the combustion chamber is important since the energy efficiency of the Carbon Purification Unit (CPU) is dependent on the CO2 concentration.

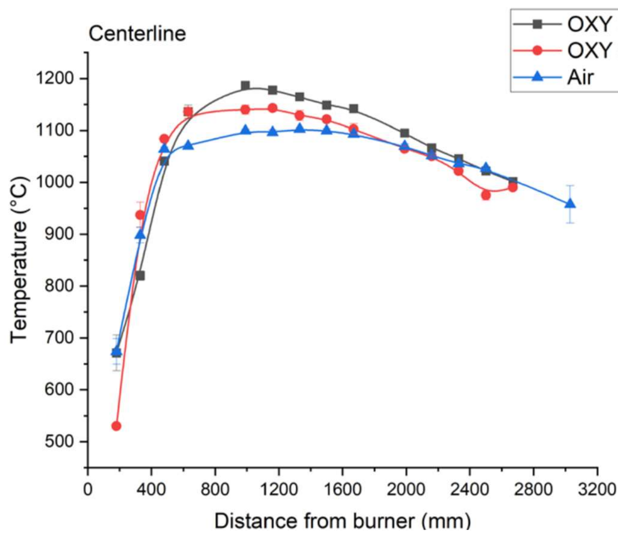


Figure 5: Temperature profile measured from the burner along the centerline of the furnace. Air mode (Air 21% O2) and Oxyfuel modes OXYXX with XX% O2) (University Stuttgart)

Detailed results are found in deliverable D2.1: Report on pilot-scale demonstration tests of the 1st generation oxyfuel burner with selected oxygen enrichment using high share of alternative fuels (publication planned).

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. The 3-D CFD model was validated against experimental data performed for two scenarios. The first includes conventional operating conditions (injection of atmospheric air), while the second one oxy-fuel conditions (provision of a O2/CO2 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, oxygen and carbon dioxide distribution) especially for the points that are far away from 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.

With the implementation of oxyfuel conditions, the accuracy of the model deteriorated. 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, specific modifications heave been discussed (kinetic rates, effect of turbulence on chemistry, more detailed reaction network, etc.

The task is summarized in the deliverable D2.2: Report on CFD simulations of 1st generation oxyfuel burner using high shares of alternative fuels (publication planned)

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)

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.

Experiments in the technical scale were conducted to compare a case with synthetic flue gas recirculation FGR at near-stoichiometric conditions (OXY32) representing the 1^{st} generation oxyfuel and over-stoichiometric conditions representing the 2^{nd} generation (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. The cases with λ*3 and 4 are most important since generally 2/3 of the heat input in a modern cement kiln line is done in the calciner area, i.e. under oxyfuel condition this over-stoichiometry is required at the main burner in the rotary kiln.

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 – sowing the excess oxygen is in fact having the cooling effect as expected and as required.

The inlet oxidizer gas concentration and stoichiometry highly affect the carbon monoxide (CO) and nitrous oxide (NO) formation. For all oxyfuel cases, the CO emission rate in the flue gas measurements is below 20 mg/MJ indicating high burnout efficiency. The NO emission rate of the λ*3.4 is elevated by 18%, 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 N2 and CO2, 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 again and or to inject ammonia water to enhance the NO to N2 reaction – therefore the result is not alarming. All the Holcim plants in Switzerland are equipped with Selective Non-Catalytic Reduction Technologies (SNCR) for NOx control.

The report of the deliverable D2.3 summarizes the task: Report on pilot-scale demonstration tests of the 2nd generation prototype oxyfuel burner with the firing concept of up to 100 % oxygen (publication in preparation).

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

CFD-simulations corresponding to the pilot scale furnace and 2nd generation burner test (case λ*4) at the University of Stuttgart (Task 2.3) have been performed 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 behavior of temperature with peak at the similar position as in the experiments, but as for the simulation with SRF of Task 2.2, there is an overestimation of the simulated temperature. The results showed 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.

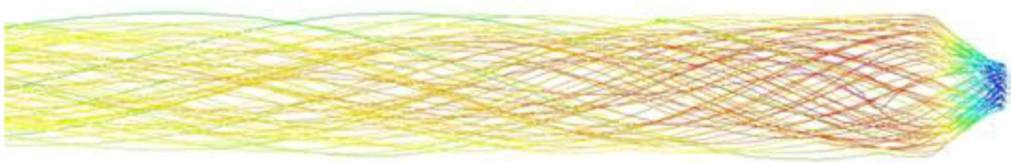


Figure 7: Fluid streamlines colored by temperature in a rotary cement kiln operated in oxy fuel combustion mode simulated in the AC2OCem project. Burner on the right-hand side, rich CO2 flue gases exiting the kiln on the left-hand side

4.3 Workpackage 3 - Improvement and impact on oxyfuel calciner

Holcim was not part of this workpackage.

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

While the workpackage 2 was focusing on the main flame in the rotating part of a modern kiln system this workpackage was dealing with the calcination, the second combustion area in the cement manufacturing system. The term calcination refers to the decomposition of limestone (CaCO3), the main raw material in the cement manufacturing process, to lime (CaO) and carbon dioxide (CO2). In this work the impact of flue gas moisture and impurities like KCl and SO2 were experimentally evaluated.

Earlier work established that a shift towards higher temperatures is to be expected for oxyfuel atmosphere. A shift up to 70°C in comparison to reference air case is reported. The CEMCAP studies [2] established the oxyfuel temperature in a temperature range of 940-960°C, which is fairly higher than current industrial practices. The higher the partial pressure of CO2 in the surrounding atmosphere, the higher would be the CaCO3 decomposition temperature, as it is dictated by the equilibrium thermodynamics.
Higher temperatures may increase risks of build-up creation and with this the need for cleaning, which is in an oxyfuel environment a particular challenge (reduction of CO2 concentration by false air intrusion).

The idea of this task was to check if a higher moisture or inserts level – reducing the partial pressure of CO2 - may restrict the temperature increase. Earlier investigation showed that a better decomposition of the raw material was obtained in case of steam dilution - attributed to better heat transfer.

The test with H2O-vapour variation showed that the water vapour in bulk gas mixture in fact promoted calcination up to certain extent while over excess of water vapour may have retarding effect. It was at least questioned if moisture increase is finally beneficial since the water needs to be condensed and treated further downstream the process what comes with a cost. Furthermore, Holcim has ambitious targets of water withdrawal reduction in operation.

The test with impurities showed that externally added solid KCl evaporate and leave the system in gaseous form while the gaseous SO2 was largely captured by CaO to remain in solid phase as CaSO4 – even supported by the addition of KCl. This potentially has a positive effect on SO2 going to gaseous phase which typically need to be treated prior to enter a carbon capture unit, on the other hand it may have negative effects on deposits formation due to sulfur accumulation in the kiln system, however longer time observations are needed to further comment.

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

This workpackage considered pilot scale calcination test under oxyfuel atmosphere. The tests were performed in a pilot scale calciner with pre-heater test facility at the Thyssenkrupp 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 SO2 (with regard to emission/abatement) and N2 (with regards to NOx formation) were evaluated under oxyfuel atmosphere.

The test results confirmed 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. Furthermore - as mentioned above - any additional water in the exhaust gas will have to be condensed and treated upstream the carbon purification unit. These findings are consistent with the results of the WP 3.1. Therefore, a moistening concept is not required for industrial sized plants that use coal and/or alternative fuels.

Regarding SO2 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. 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 O2 concentrations.

The addition of N2 did not show the production of additional NOx, since the temperatures in the tests were too low for the formation of thermal NOx and the combustion of the natural gas used does not produce significant fuel NOx emissions. NOx emissions remained below 10ppm during the entire test operation, even under reference air conditions.

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

In this workpackage it was shown that it is possible for an oxyfuel cement based precalciner to work with alternative fuel (AF) in the fuel mix and even with 100% of AFs if the AFs characteristics are good enough to reach enough temperature in the calciner. The tests have been realized in the “CORALI” combustion facility of Air Liquide with refuse-derived fuel (RDF) however with other material having a similar heat value it is expected to be possible to reach the same results. The high concentration of CO2 in the combustion is not an issue to burn the AFs. Cement producers won’t have to change their fuel mix while changing from air- to oxy-combustion therefore. It is expected that they can even envision to further increase the AFs share in the fuel mix. It is important to have a proper mix of AFs with enough heat value to work with 100% AFs.

The experiments also showed that a good distribution of the O2 injection helps to better burn the solid alternative fuels. An O2 injector in the middle of the AFs injector helps to burn quicker the AFs with low quantity of O2. Staging the O2 injection with an O2 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.

4.4 Workpackage 4 - Integration of 1st generation oxyfuel technology by retrofit to existing cement plants

Task 4.1: Design consideration for retrofitted oxyfuel cement plants

The fourth workpackage 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%), which is typical for many Europe cement plants and therefore represent a realistic case even for the near future. The thermal substitution target in Holcim Switzerland is 85% by 2030. The major difference of the plants is the production process influenced by the condition of natural raw material reserve of the plant location.

In Slite a 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 challenge. The optimal location of the raw mill in the process layout plays an important role. Although the direct integration is energetically reasonable, the operational risk by false air intrusion is high. Due to environmental and safety reasons cement plants are operated with a slight negative pressure to prevent leakage of hot material and gases, however with the drawback of increased cold air entrainment risks. In order to avoid dilution of the CO2 and its negative impact on energy demand of the CPU, the layout with the raw mill connected has not been further developed. In previous studies [2] the impact of false air on the oxyfuel system had been simulated, see task 4.5.

Even for Lägerdorf with the high raw material moisture 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 (see figure below). This basic layout can be transferred to any other modern dry cement kin systems, as five of the six clinker lines operated in Switzerland. There is only one semi dry system that would require a different approach.
Within the workpackage different approaches for waste heat recovery has been discussed. Based on the analysis it can be recommended to use an organic Rankine cycle for the heat-to-power generation in the oxyfuel cement plant.

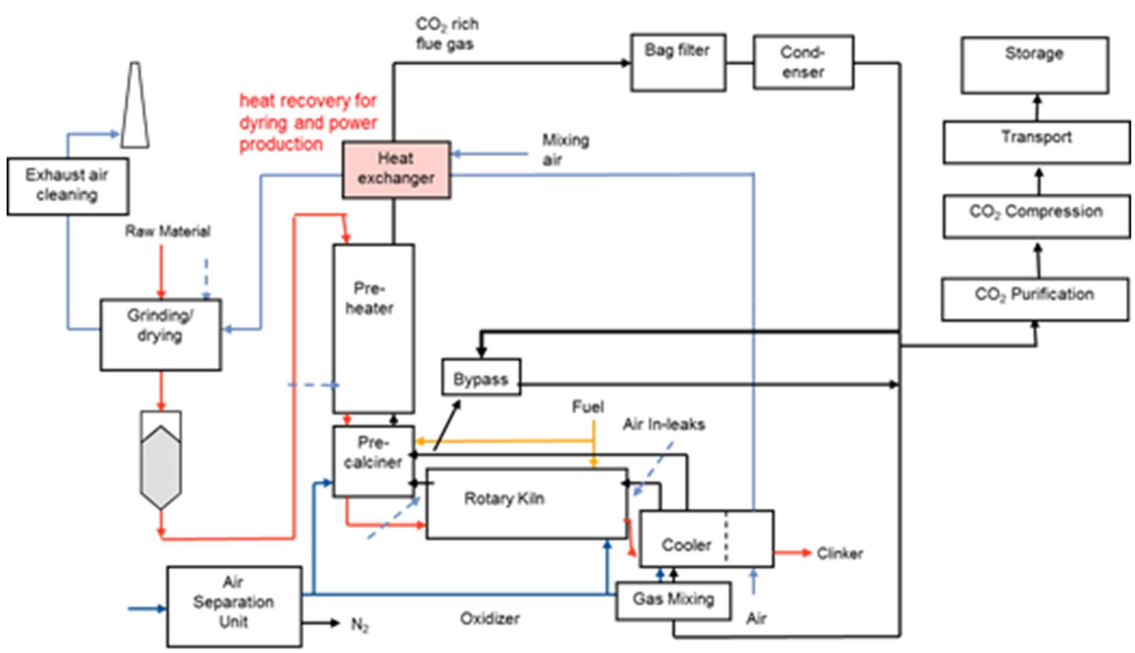


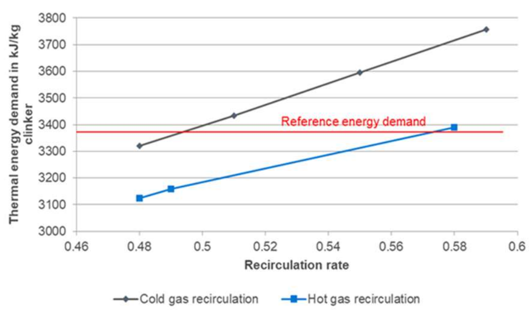
Figure 8: Oxyfuel 1st generation layout for the AC2Ocem case studies

The report D4.1 deals with the waste heat recovery systems for oxyfuel cement plants (Link)

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

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 cycled 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. 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.% O2 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 in Lägerdorf 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.



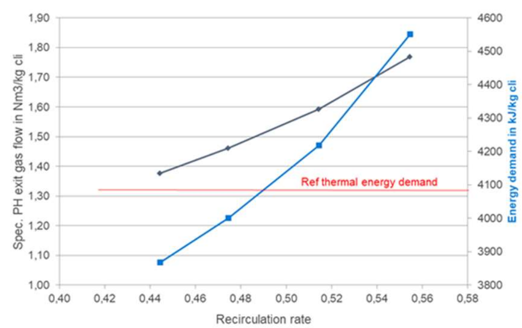


Figure 9: Relationship of thermal energy demand, specific flue gas volume flow and recirculation rate (left: Slite, right: Lägerdorf)

Net carbon removals can be achieved, if biogenic CO2 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 CO2/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 CO2 /t cli (100% AFR containing huge share of biomass) of negative emissions could be hypothetically created, see also workpackage 6.

Based on the available information on the reference best available technology (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 CO2 processing unit (CPU) and evaluated the mitigation of flue gas impurities using the CPU. The importance of customized design and optimization of the CPU with pressure, dehydration, and cryogenic units is highlighted, which can achieve high CO2 capture rates and purity while minimizing energy requirements for capture and storage. 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

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

Impurities which are conventionally discharged via the stack as emissions to the environment leave the system at different locations in the water condensate or in vent streams from the purification unit when operating in oxyfuel mode. The recirculated flue gas is cooled below water dew point, this allows the removal of certain impurities as condensates, such as NOx and SOx. In order to further 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 impurities will be reduced further in this process step. The CO_2 quality specifications used in AC2OCem are based on the published values by the Northern Lights project.

The Slite plant suffers from high SOX formation due to its natural raw material reserve. Therefore a wet scrubber for DeSOx is conventionally operated. To achieve the allowed sulfur impurity level the wet scrubber is included in the flue gas path in oxyfuel and potentially additional reducing agents (such as NaOH/ Na_2CO_3) are added to the condenser. The NOx level in the CO_2 product is only below the limit if a properly working SNCR is in place and limits above 200 mg/Nm3 are not exceeded. Oxyfuel operation might help to reduce the formation of NOx due to the lower availability of nitrogen.

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 the figure below 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.

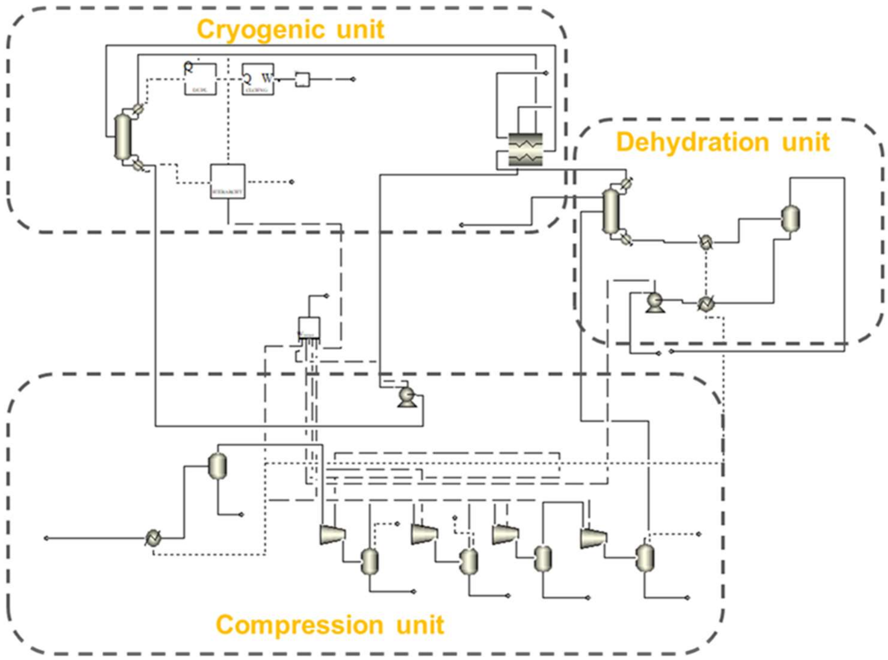


Figure 10: Schematic overview of the CPU

The table below 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.

	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 or to react on different input concentrations or more stringent product specifications.

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 in the flue gas is directly used in the raw mill, the material's drying unit, which is difficult to seal especially in case of a retrofit. The specificities of the plants had a direct influence on the process optimization and design (as discussed in task 4.1 and 4.2).

The 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 3 and the middle stage 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 top cyclone meal bypass between 30 and 50%.

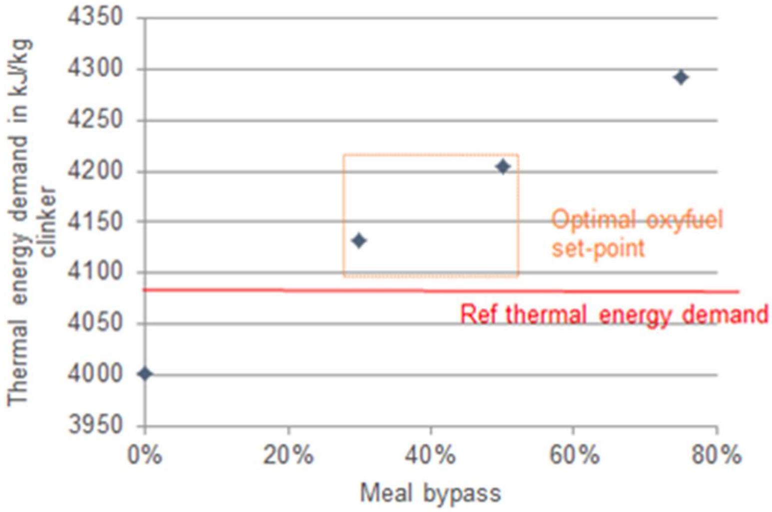


Figure 11: Thermal energy demand for R = 0.47 depending on meal split

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

As previously discussed, false air intake is one of the biggest technical risk for an oxyfuel kiln line due to influence on the target of enriching CO2 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 CO2 concentration is reduced from initially 81 vol. % to 71-73 vol. % on dry basis.

As a rule of thumb the gas supplier and AC2OCem consortium partner AirLiquide named a change of +/- 2% specific electrical energy demand for each -/+ 1 percentage point CO2 dry base concentration for design basis of CPU. Previous studies [2] simulated that the thermal energy demand raises by 0.8 to 1.3% per 2% false air ratio, at the same time the electrical demand of the CPU increases by 2.7 to 3.5%. Experiences from the AC2OCem members from cement industry regarding false air at the critical equipment were taken into consideration to simulate the achievable CO2 concentrations at the purification unit inlet.

As a CPU is designed for a dedicated operational point (e.g. for a pessimistic CO2 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, 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 includes the continuous measurement by online measurement of O2 and CO2 (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.

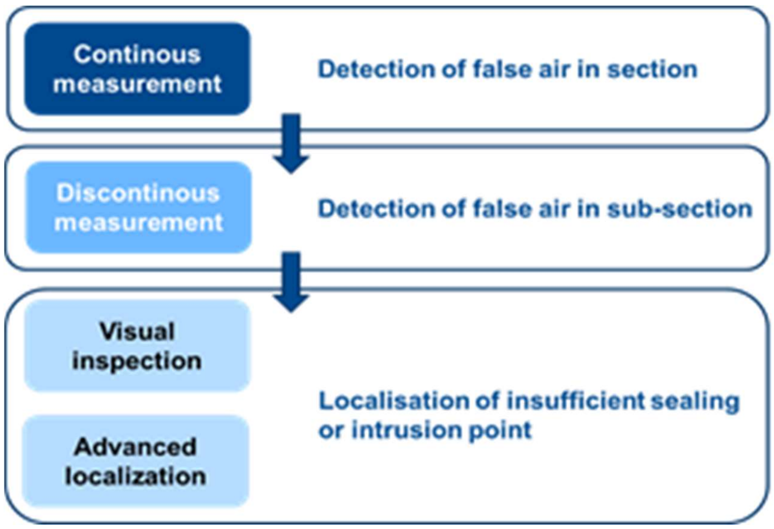


Figure 12: False air detection strategy

Tighter control of the clinker burning process and the use of modern sealing technologies are essential but may not be enough. To achieve even higher levels of tightness, some of the currently available sealing technologies may need to be adapted and redesigned to operate in oxyfuel conditions.

- Sealing with gas seems to be possible; graphite seals can also be adapted for gas flushing.

- Reducing the negative pressure of the system and the gas circulation would limit the driving force of the false air entry.

- Blowers can be sealed with a special seal between the impeller shaft and the housing.

- The occurrence of build-ups should be minimized (quality of the fuel, chemical additives). In addition, more shock blowers with CO_2 can be installed instead air cannons or manual poke openings.

Target for an oxyfuel kiln should be the reduction of false air to less than 6%.

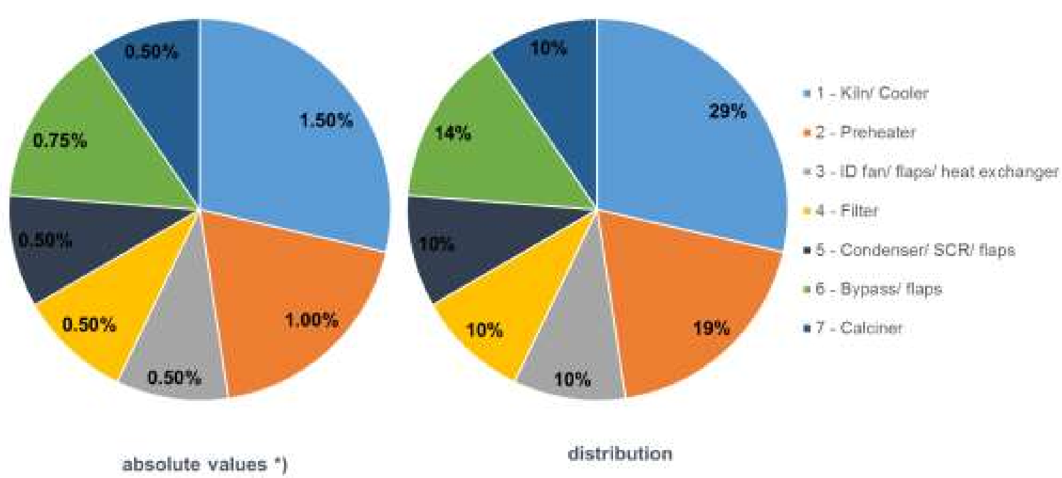


Figure 13: Optimized false air of a modern cement kiln split by source

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 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 the AC2COCem 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 (LCOC), shown in the figure below, covers 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 modifications) 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 for waste heat recovery for electrical power production 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.

With the average electrical energy cost in Switzerland of 112 CHF/MWh (according to GGS (link) on 2019 basis) the impact of power more than doubles compared to the Sweden based case in AC2OCem (plant A): The roughly 7 Euro/t CO2 avoided for electricity would raise to >15 CHF/tCO2 in Switzerland. With the cost of CO2 avoidance between 49 and 63 Euros/t and an estimated cost of CO2 transport and sequestration of 68 CHF/t CO2 (58-78 according [4], seems rather optimistic) the overall abatement cost is in the range of 125 CHF/t CO2, which is slightly higher than the estimated cement industry decarbonization cost of 113 CHF/ tCO2 in [4].

The project was running certain sensitivity analyses on these cost figures, like electrical power cost, CO2 intensity of power, capex delta, clinker production downtime or raw material moisture.

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, general higher cost for raw materials and extended scope by including pipelines and CO2 buffer tanks.

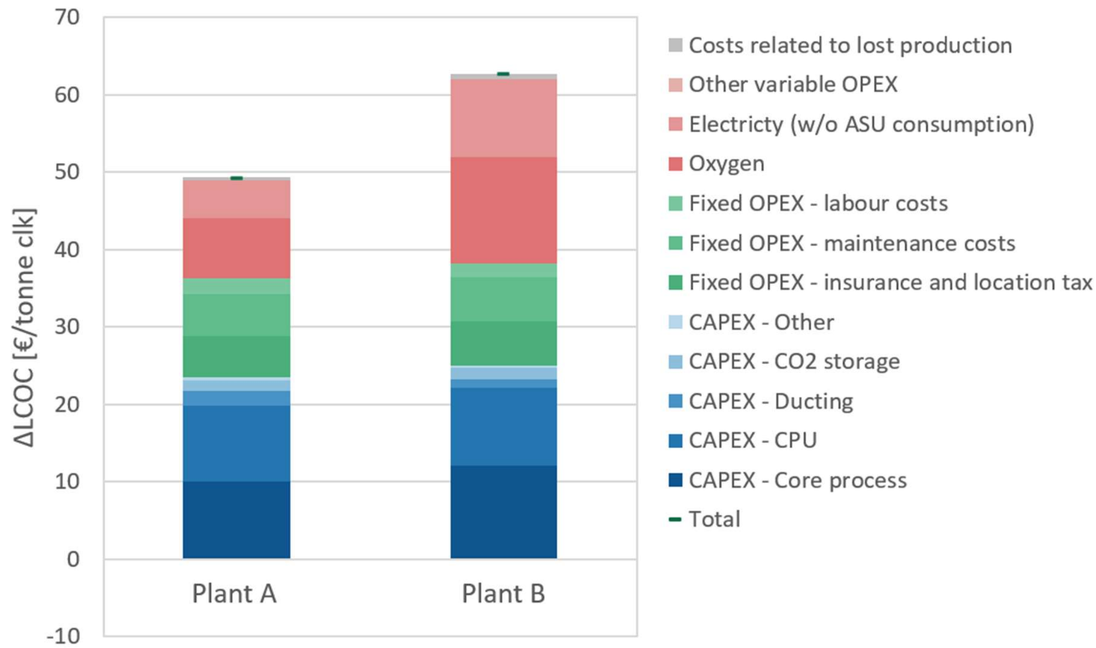


Figure 14: Increased levelized cost of clinker for the two case studies

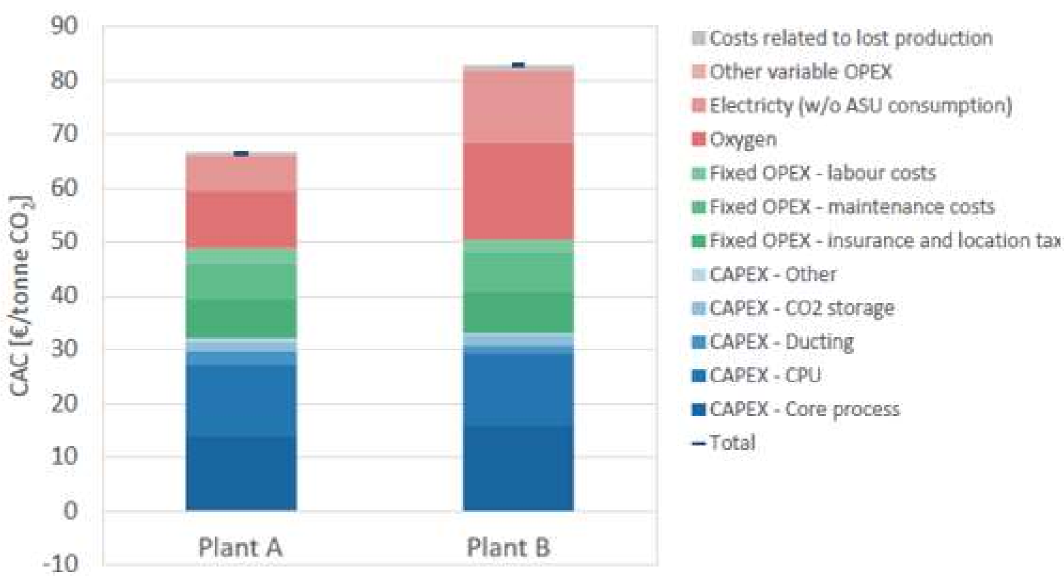


Figure 15: Cost of avoided CO2 for the two case studies

The preliminary results were presented at the ghgt 15 conference in Lyon in October 2022 (link to presentation).

4.5 Workpackage 5 - 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 thyssenkrupp Polysius 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. 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.

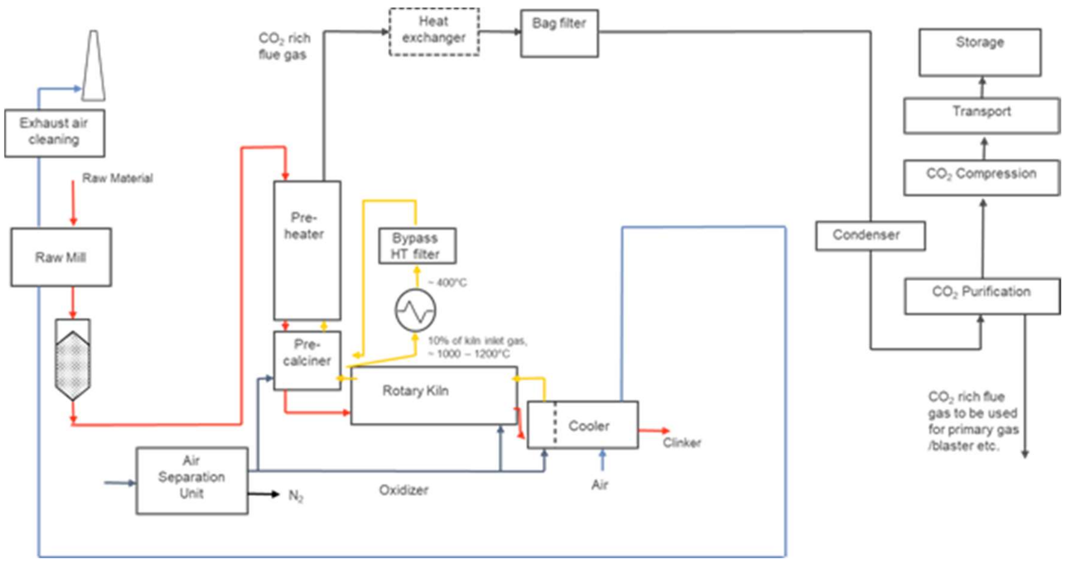


Figure 16: Principle of the oxyfuel technology without flue gas recirculation

That way the kiln atmosphere is dominated by O2 instead of CO2/O2 in case of a flue gas recirculation.

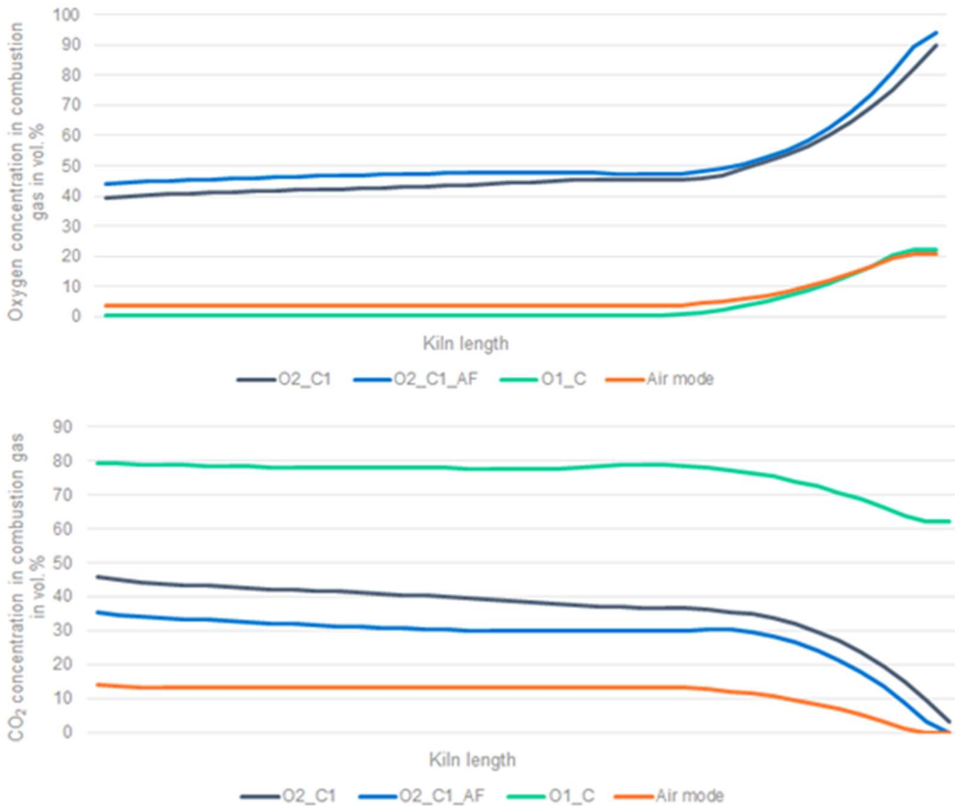


Figure 17: O2 concentration (top) and CO2 concentration (bottom) in the kiln combustion gases (left side of the diagram being the kiln material inlet and right side of the diagram sintering zone / cooler side)

A reference plant of 3,000 t/d capacity (as defined in the CEMCAP [2] 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 workpackage 4 the volume of flue gas influences 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. This effect is maximized by avoiding any recirculation (2nd 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 2nd generation oxyfuel kiln. The difference in thermal energy demand decreases to 9.4% compared to the air-mode reference using the same fuel mix.

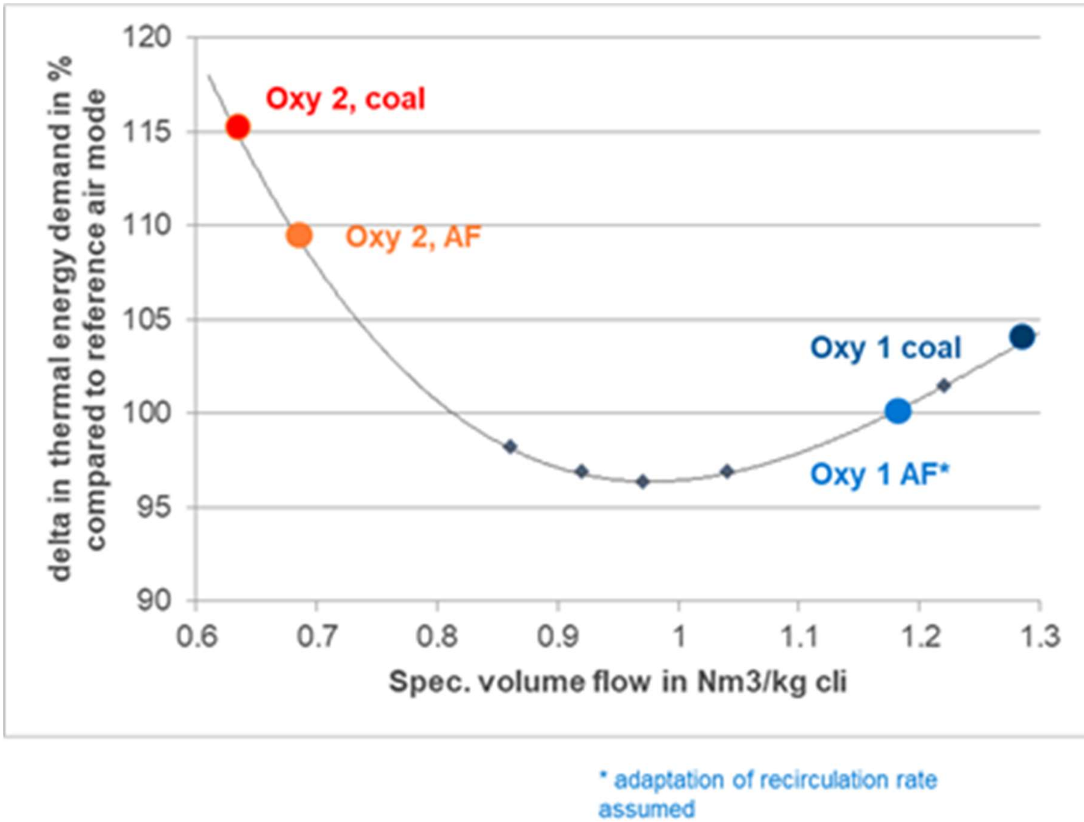


Figure 18: Dependency of thermal energy demand and specific flue gas volume (Oxy 1 means Oxyfuel 1st generation, Oxy 2 means Oxyfuel 2nd generation)

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 is 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. 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.

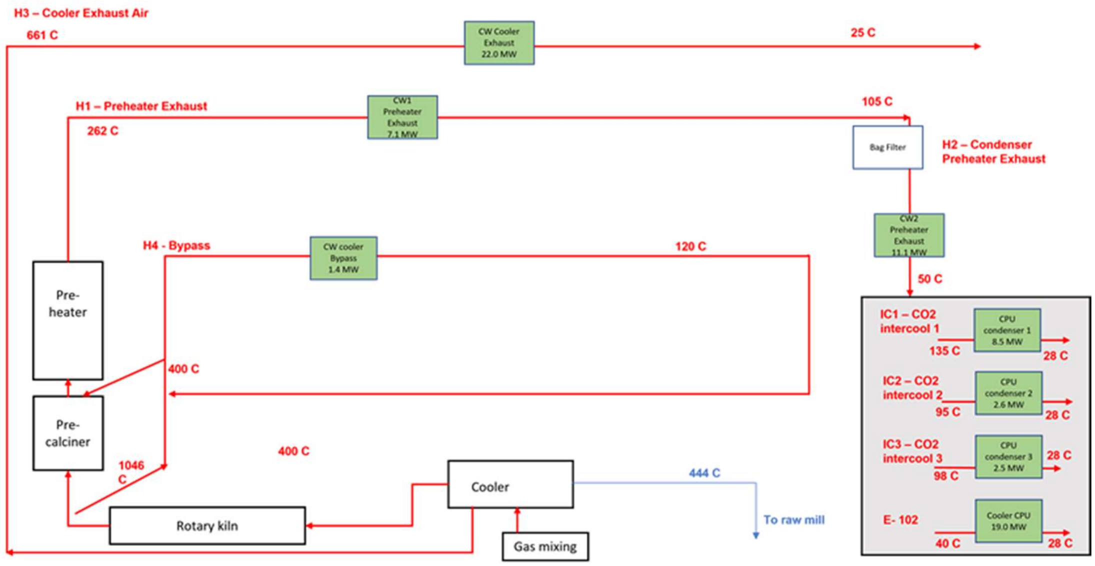


Figure 19: Heat exchanger network

There is already a large experience with cement flue gas waste heat recovery systems in Holcim. In Switzerland all three cement plants of Holcim have systems installed to prevent wasting energy.

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 (1st generation) 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.

	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

A second plant layout has been simulated (figure below) in order to optimize the thermal energy demand and to decrease the resulting CO2 emissions from additional fuel combustion. In this layout part of the cooler exhaust air (so 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.

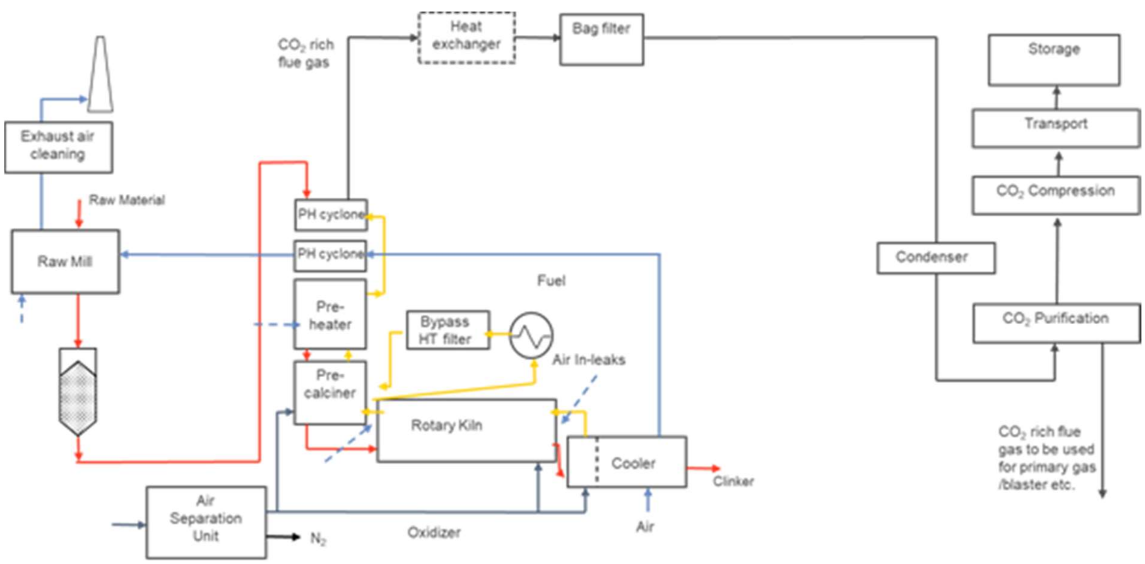


Figure 20: Alternative process configuration including an air-stage to optimize the thermal energy demand

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 CO2 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 are 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 specific 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.

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 applied to the 3000 tpd 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:

- 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.

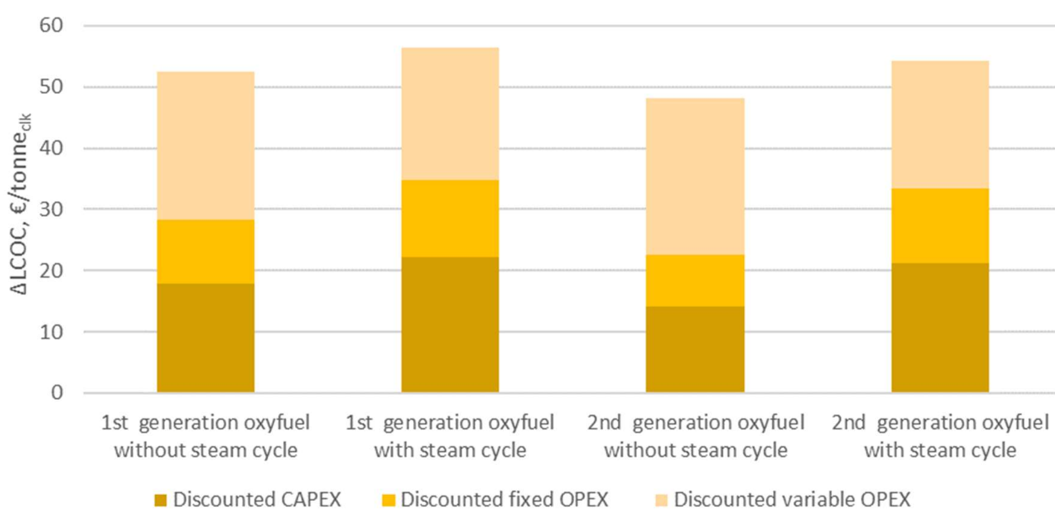


Figure 21: Increased levelized cost of clinker of the four cases evaluated compared to the reference plant without CCS.

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 CO2 avoided is compared.

The 2nd generation oxyfuel plants perform slightly better than the 1st generation oxyfuel plants in terms of increased levelized cost of clinker and CO2 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 CO2 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 and will require a case by case evaluation.

4.6 Workpackage 6 - Life cycle assessment (LCA)

Task 6.1: Gathering and synthesis of primary data

This task involved the gathering and synthesis of process data, emission inventories, and mass- and energy balances of the different life-cycle stages of the clinker production processes investigated in the AC2OCem 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 the tasks 4.6 and 5.3 are a major data contributor.

This 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. 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 indicated 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 gCO2eq. per kg of clinker, depending on operational condition, location, and biomass type. Additional emission reduction of -10 (plant in Sweden) and -128 gCO2eq. 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 cement industry is replacing already today a high ratio of the fossil fuels by alternative materials, the thermal substitution by Holcim in Switzerland is above 50%, and the trend goes to higher substitution. The alternative fuels, like municipal or industrial wastes or old tires used today in Europe already contains a certain share of biogenic carbon, 100% biomass fuels are materials like dried sewage sludge, animal meal or waste wood.
Applying oxyfuel to the cement plants in Switzerland would lead to a CO2 reduction of almost 2.5 Mio t CO2/year. (based on Emissionshandelsregister 2022). With the objected biogenic share of biomass (acc. Cemsuisse 60% thermal substitution in 2050) a net carbon removal by the Swiss cement sector is possible. Taking the key data from AC2OCem (90% capture rate) and assuming one third of the emissions arising from the thermal input about 110% removal is achievable.

Alternative Fuels, in particular the ones with higher biogenic share typically contain higher moisture and a lower heat value, which is raising the thermal energy demand. Furthermore these fuels raises the risk of operational issues like process fluctuations, which can have a negative impact on the carbon capture plant efficiency. Therefore the 100% biomass case is rather a hypothetical.

Furthermore 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 CO2 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 mentioned above is summarizing the findings: “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 CO2eq. (Norway) and 1154 ± 40 CO2eq. (Estonia) per ton of clinker, while the weighted average impact of European clinker production is 942 ± 23 kg CO2eq. per ton of clinker. Decarbonization options at different levels of maturity offer a potential reduction of climate change impacts between 7 and 137 Mton CO2eq. 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 CO2 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 NOx SOx, CO and particulates at the local level, because they are either produced in lower amounts thanks to an O2-rich combustion process and/or co-captured alongside CO2. 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 mentioned above is intended to be published under the title "Investigation of the potential of oxyfuel technology for decarbonization of cement industry in Europe."

5 Conclusions & Outlook

Main Conclusions

Pilot-scale experiments with 100 % alternative fuels under oxyfuel combustion conditions were successfully performed. Beside the most common alternative fuel (SRF), dried sewage sludge fuel used in a Holcim Germany cement site was used for the tests at the university in Stuttgart.
The experiments have shown that the combustion of SRF - a rather inhomogeneous fuel mixture, wood and sludge was stable during air and oxyfuel conditions. The tests showed that under oxyfuel conditions, flue gas recirculation rate plays a major role in controlling flame temperature and momentum at the burner. Optimizing the burner could be necessary in further stabilizing the combustion conditions if the recirculation rate is high. Achieving constant CO2 concentrations at the end of the combustion chamber is important since the energy efficiency of the Carbon Purification Unit (CPU) is dependent on the CO2 concentration.
The experiments representing the second generation oxyfuel with no gas recirculation but an overstochiometric oxygen feed were showing that after the peak temperature is reached, the temperature profiles stabilize to similar temperatures as measured in the air case – demonstrating 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 N2 and CO2, which is key for the 2nd generation oxyfuel.
Overall the tests showed high burnout efficiencies, the nitrogen oxides have been slightly increased (+18%) due to the higher oxygen availability and therefore the lack of reducing conditions in the flame.

The experiments have been accompanied with a CFD simulations of the prototype burner and validated against the test data. The models were appropriate although slightly deviating for oxyfuel modes. Nevertheless the derived results are important for improvement of burner configuration, further development of more accurate process modelling tools for dynamic simulations.

In other test campaigns the **impact of flue gas moisture and impurities on the calcination under oxyfuel conditions** were experimentally evaluated. The tests confirmed that the higher the partial pressure of CO2 in the surrounding atmosphere, the higher is the CaCO3 decomposition temperature. The test with water vapour variation showed that the water in the gas in fact promoted calcination up to certain extent while over excess of water may have retarding effect. It is still not considered as reasonable to raise moisture since any additional water in the exhaust gas will have to be condensed and treated upstream the carbon purification unit.
SO2 was largely captured by CaO to remain in solid phase as CaSO4 – even supported by the addition of KCl. This potentially has a positive effect on SO2 going to gaseous phase and with this to the CPU where it would need to be removed from the gases.
The addition of N2 did not show the production of additional NOx, since the temperatures in the tests were too low for the formation of thermal NOx and the combustion of the natural gas used does not produce significant fuel NOx emissions.
100% alternative fuel tests in the calciner were successful too. The high concentration of CO2 in the combustion is not an issue to burn the AFs. Cement producers won't have to change their fuel mix while changing from air- to oxy-combustion therefore. It is expected that they can even envision to further increase the AFs share in the fuel mix. The experiments also showed that a good distribution of the O2 injection and high calorific fuels are key.

The **retrofiliability of conventional cement plants to 1st generation oxyfuel lines** have been investigated for two specific sites the Heidelberg Materials Slite plant in Sweden and the Holcim Lägerdorf plant in Germany. The concept for both plants – despite the differences in raw material moisture – was chosen to minimize the false air entrainment by decoupling the raw mill. This basic layout can be transferred to any other modern dry cement kin systems, as five of the six clinker lines operated in Switzerland. Simulations showed that the recirculation rate and correspondingly the oxygen concentration in the combustion gases is the most powerful parameter to optimize the oxyfuel

operation in respect to thermal energy demand and flue gas volume. Net carbon removals can be achieved, if biogenic fuel-based CO2 is captured for both plants.
Simulations of the CPU has shown the importance of customized design and optimization of the CPU with pressure, dehydration, and cryogenic units in order to achieve high CO2 capture rates and purities while minimizing energy requirements for capture and storage. Cement plant impurities like dust, nitrogen oxides (NOx), and sulfur dioxide (SO2) require special attention and treatment. A certain removal of impurities such as NOx and SOx happens by condensation, additional reducing agents (such as NaOH/ Na2CO3) need to be added to the condenser if the inlet concentrations are elevated. Additional purification methods might be needed before the CPU unit to further mitigate the impurities or to react on different input concentrations or more stringent product specifications.
While the plant with lower raw material moisture has enough heat the other plant operates a material split (partial preheater bypass) to generate more heat in the offgas. The optimal oxyfuel recirculation rate determined in the project by simulations depend on the heat needed for raw materials and on the meal bypass in particular.
False air is one of the biggest technical risk for oxyfuel. In case of doubling the false air ingress the CO2 concentration is reduced from initially 81 vol. % to 71-73 vol. % on dry basis with major negative consequences on the CPU design and/or operation. As a rule of thumb a change of 2% specific electrical energy demand for each percentage point CO2 dry base concentration is expected (design basis). The consortium developed therefore a guideline on false air, which describes apart from the definitions, typical values, the economic effect and examples for improvement, the methods and techniques to detect false air. To achieve high levels of tightness – less than 6% false air has been determined as a target for oxyfuel -, some of the currently available sealing technologies may need to be adapted and redesigned to operate in oxyfuel conditions, e.g. by sealing gas, reduction of negative pressure in the system, special seals, shock blowers using CO2.
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 has been made on average prices and do not reflect the real costs for cement production at both plant locations. The main cost drivers for the process are CAPEX (mainly CPU and core process modifications) and cost of electricity (mainly for CPU and ASU). 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. A steam cycle for waste heat recovery for electrical power production can be included for cases like plant A with low material moisture and large amount of excess heat and high electricity prices. The results for the Levelized cost of Clinker delta is between 49 and 63 Eur/t cli and the cost of avoided CO2 at 67 to 83 Eur/t. The power cost, which was fixed to 2019 levels can influence the figures significantly. This result is substantially higher costs than the figures estimated in previous studies for an 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, general higher cost for raw materials and extended scope by including pipelines and CO2 buffer tanks.

The **investigation regarding the 2nd generation oxyfuel** were based on a generic new-built reference plant. The idea of this oxyfuel layout is to avoid the effort for flue gas recirculation with the aim to reduce CAPEX and OPEX costs. Simulation showed that due to the lower heat recuperation in the cooler, a high amount excess heat from the cooler at high temperature level is available that can be used for power generation. This heat exchanger network however seems only reasonable at relatively high electricity prices.
The 2nd generation shows a higher CO2 enrichment potential of about 90%dry CO2, depending on fuel mix, with the benefit of a more efficient CPU compared to the 1st generation, on the other hand the heat consumption will be elevated, so that finally the additional power demand is similar.
Nevertheless the 2nd generation oxyfuel plants perform slightly better than the 1st generation oxyfuel plants in terms of increased levelized cost of clinker and CO2 avoided. The evaluations were made considering Nth of a kind (NOAK) project based on the current knowledge of the technologies and have a high degree of uncertainty and will require a case by case evaluation.

The **Life Cycle Assessment** indicated 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, allows achieving negative emissions in the cement clinker production process. Taking the key data from AC2OCem about 110% carbon removal is achievable in Switzerland. The availability of biomass resources is likely to be limited and their sustainable supply needs to be secured.
The implementation of oxy-CCS causes reduced direct emissions of some air pollutants such as NOx SOx, CO and particulates at the local level, because they are either produced in lower amounts thanks to an O2-rich combustion process and/or co-captured alongside CO2.
The higher electricity required for CCS systems can still be associated with emissions of air pollutants. This case shows the importance to develop electricity decarbonization in parallel with abatement of other pollutants to secure win-win transitions.

Contribution to the facilitation of the emergence of CCUS

The AC2OCem 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 CO2 reduction in the time ahead. The results and findings from this project significantly advance the technology for 1st and 2nd generation oxyfuel and helps to de-risk the investment in first of it's kind demonstrators. 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.

The AC2OCem 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 AC2OCem project has confirmed that the oxyfuel technology is one of the most promising technological solutions for the cement industry to capture CO2 from its cement operation.

Translating the results to the Swiss Cement Plants is possible. Applying oxyfuel to the cement plants in Switzerland would lead to a CO2 reduction of almost 2.5 Mio t CO2/year. (based on Emissionshandelsregister 2022). With the objected biogenic share of biomass (acc. Cemsuisse 60% thermal substitution in 2050) a net carbon removal by the Swiss cement sector is possible. Taking the key data from AC2OCem (i.p. 90% capture rate) and assume 1/3 of the emissions arising from the thermal input about 110% removal is achievable.

However, there are certain conditions for successful carbon capture and oxyfuel deployment in particular:

- Space availability
  Space availability can be a challenge for oxyfuel revamping, this is valid however for all Carbon Capture options, for some end of pipe solutions potentially more space is required (not investigated in this study). The investigations within AC2OCem with the two real cases has shown that there are significant efforts needed in dismantling or moving existing infrastructure or buildings. Important is to consider the additional space required for the erection.

- CO2 offtakers and sink
  Emitters will require CO2 offtakers, be it for CO2 permanent sequestration or for CO2 conversion, as well as partners for logistics and the infrastructure. Timelines for a national and international infrastructure need to be aligned accordingly.

- Access to green electrical power at reasonable cost
  As seen in AC2OCem power is the main contributor to the operation cost of a Carbon Capture system based on oxyfuel. Therefore beside waste heat recovery access to reasonable cost green electricity is key.

- Technology developments
  AC2OCem confirmed that Oxyfuel is one of the most promising technology to decarbonize the cement industry. Nevertheless it has to be underlined that the technology is new and first of its kind installations will be expected to bring up new learnings for the generations to follow. It cannot be expected that such a technology is fully operational from day 1 onwards.
  Other technologies, alternative CCUS concepts to oxyfuel are also developing and its not possible to predict the stake oxyfuel will be taking in future. Holcim is convinced that there is not a one size fits all solution, that the capture technology will have to be adapted to the specific conditions. Depending on the site conditions retrofitablity efforts and the risks related to integrated systems are not favorable compared to an alternative end of pipe technology.
- Governmental support in terms of permitting, funding, regulatory frame (CBAM, Carbon Contracts for Difference, CCU in ETS,…), CO2 logistics, low carbon public procurement, storage liabilities etc. is needed to deploy CCUS projects. The uncertainties on the regulatory side, on the CO2 price etc. is not supportive.

Strengthen the competitiveness and growth of European companies

The participation of three partners from the cement industry and three technology providers in AC2OCem indicated the strong interest and necessity of the project to support and facilitate future large-scale oxyfuel demonstration in the cement industry. Two workpackages of the project were led by industrial partners, workpackage 3 was led by Thyssenkrupp Polysius GmbH, and workpackage 4 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.

Without CCS no carbon neutrality can 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, there are systems that are implemented on European level to mitigate this effect for instance the Carbon Border Adjustment Mechanism (CBAM). Some 50’000 jobs were directly attributed to the European cement industry. Related to cement and concrete about 1.1 million 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. AC2OCem project contributed to the improvement of cost efficiency of one of the most promising capture technologies to support future competitiveness of European cement production.

Economy wide, companies participating in AC2OCem 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. AC2OCem knowledge sharing activities support the industry in their communication with society.

Implementation / Chances for commercializing the technology further

Consortia members commented the commercialization of the technology as follows:

Holcim as a future host of oxyfuel technology is gaining relevant information from the pilot-scale oxyfuel burner and calciner tests of AC2OCem that are directly transferred to concrete projects and will be useful in the design and operational considerations of an oxyfuel cement plant. Two oxyfuel projects in the Group, the Holcim C2B project in Germany and the Go4Zero project in Belgium, have been selected by EU to be funded by the European Innovation Fund. In this way, Holcim will use the AC2OCem results beyond the project within the demonstration activities at TRL 8.

Also **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 CI4C project in Mergelstetten based on Oxyfuel 2nd generation 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 AC2OCem 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 CO2 transport and storage activities but is also promoting the best CO2 capture technologies for its clients such as cement producers. AC2OCem 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.

Thyssenkrupp Polysius: 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.

6 National and international cooperation

The AC2OCem 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:

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

Holcim ensured that the work within AC2OCem is representative for the cement industry and involved sister companies including Holcim Switzerland according the needs.

7 Communication & Publications

A detailed list of all dissemination actions is listed on the final report, that can be found on the ACT homepage (link), some highlights are described in chapter 4.1 or this report.

Dedicated workpackages deliverables reports are published on the AC2OCem webpage (link), some are still to be published.

Beside the dissemination actions Holcim shares the key documents of AC2OCem with all main internal stakeholders related to the topic.

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