Schweizerische Eidgenossenschaft
Confédération suisse
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Bundesamt für Energie BFE

Bundesamt für Umwelt BAFU

Final Report 22.06.2022

Decarbonizing Cement

Technology assessment and policy relevant evidence for the decarbonization of the Swiss cement industry

Source: © cemsuisse

Date: 22.06.2022

Location: Bern

Funding Agencies:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Swiss Federal Office of the Environment FOEN
Climate Policy Section
CH-3003 Bern
www.bafu.admin.ch

Co-Financing:
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SFOE Contract Number: SI/502204-01

Summary

Switzerland has committed to halving its greenhouse gas emissions by 2030 compared to 1990 levels and reaching net-zero by 2050 in an attempt to help limit global warming to 1.5°C above pre-industrial levels [7]. With the cement industry responsible for approximately 5% of total Swiss emissions and almost 25% of all industry emissions in Switzerland, there is clear consensus about the need for sector decarbonization [1][2]. This project is driven by the need for a comprehensive and detailed techno-economic analysis of all cement decarbonization technologies modeled and adapted for the Swiss context, creating a coherent baseline for various policy options to drive the transition towards net-zero cement production. This study aims to synthesize techno-economic insights of the technologies in order to get an overview of the state of development and costs, as well as a comparability of the options in Switzerland (also with regard to a possible realization of negative emissions). Secondly, the technical, economical, commercial, organizational and regulatory barriers are investigated, and policy options are initially developed and discussed to potentially overcome these obstacles.

In part I, after an initial literature review and a preliminary consolidation of the available decarbonization technologies, a workshop with the respective project stakeholders from industry and administration yields a list of prioritized CO2 mitigation technologies for further investigation, including alternative fuels, energy efficiency, clinker substitution, alternative clinkers and carbon capture. The assessment explores the different technologies along multiple criteria in the Swiss context, namely CO2 reduction potential, cost, technical readiness level (TRL), etc. Both CO2 abatement potential and costs are calculated per technology allowing for a comparison of the different options. The potential for negative emissions in the cement industry is also explored. With this data, we draft multiple decarbonization pathways by combining different mitigation options and assessing their cumulative impact in reaching net-zero for the Swiss cement industry. For each pathway, we also calculate the cost-effectiveness of each technological scenario.

The results show that the decarbonization technologies and approaches assessed in Part I of this study are at different stages of commercialization and development. Energy efficiency, clinker substitution and alternative fuels are already common practice in the European cement industry while alternative clinkers and carbon capture are novel solutions. The latter are thus associated with higher investment costs and risks than the established decarbonization measures; yet, their potential climate impact is comparably higher. Overall, we conclude that net-zero emissions are achievable by 2050 for the Swiss cement industry but hinge on the deployment of carbon capture. Depending on the CO2 mitigation pathway, even negative emissions are possible.

On an absolute cost basis, the least cost pathway to net-zero is through a diversified portfolio of solutions, i.e., a combination of energy efficiency, clinker substitution, alternative fuels and carbon capture and storage (CCS). Based on our assumptions and analysis, this pathway yields an overall CO2 abatement cost of 113 CHF/ton$_{CO2}$, leading to modelled annual decarbonization cost of around 300 million CHF for the Swiss cement industry. A sensitivity analysis shows that abatement costs increase with lower shares of biomass in the fuel mix (due to lower carbon dioxide removal [CDR] credit revenues), while costs decrease with reductions in clinker-cement ratio. Since Swiss cement plants must participate in the Swiss Emissions Trading System (ETS), a market-based CO2-pricing instrument, the abatement costs can be compared to the CO2 price in the ETS - which is around 86 CHF/tonCO2 at the time of writing this report - to assess the cost effectiveness of decarbonisation measures.

An individual consideration for the mitigation options reveals the following: Increasing clinker substitution, in principle, is always possible and even lowers the overall cost of decarbonization. Alternative fuels, especially the ramp up of biomass, can contribute to the decarbonization of the fuel mix which amounts to 30% of the total emissions. Biomass would allow for net negative emissions in combination with CCS and remains cost effective vis-á-vis today's ETS price even if the prices of biomass increase over the next years. With regards to negative emissions, our findings show that the Swiss cement industry could generate a substantial quantity of CDR, even at the biomass volumes used today at a competitive price compared to other permanent CDR solutions. This could allow for additional

revenue generation through the sale of CDR credits. For CCS, numerous technology options exist, with some being commercially validated and readily available. While CCS leads to higher CO2 abatement costs than other mitigation options, its abatement potential is also significantly higher. Our analysis shows that reaching net-zero in the Swiss cement industry is not feasible without CCS deployment. Alternative clinkers are expensive today and offer negligible CO2 abatement potential.

Part II of the report focuses on the deployment barriers of these decarbonization technologies as well as a range of policy options to potentially address them. As a first step, we develop an overview over barriers through literature research and stakeholder interviews, covering a broad range from technical, economical, commercial, organizational to regulatory barriers. Next, potential policy options are collected from literature and interviews with domain experts from academia, think tanks, NGOs and regulatory and political bodies, also drawing on examples from other countries. When then hold a stakeholder workshop to validate and synthesize the findings.

The barrier analysis yields the following implementation challenges with different degrees of complexity for the individual technologies:

- Clinker substitution, which involves the substitution of clinker with other materials such as fly ash, with a relatively low abatement cost compared to solutions like CCS, faces technical and market demand barriers as highly blended cements lead to longer setting times and on-site delays with economic implications for the construction project. The local and long-term availability and future price of supplementary cementitious materials (SCMs) are further obstacles to the large-scale rollout of such cements.
- For alternative fuels such as biomass and green hydrogen, their future long-term availability in sufficient volumes is a relevant concern for cement manufacturers and poses a barrier to significant fuel mix changes.
- As a crucial technology to reach net-zero in the cement industry, CCS is associated with several deployment hurdles. Depending on the selected capture technology, CCS increases industry energy demand significantly; adsorption-based MEA capture, for instance, would increase electric energy and thermal demand by almost a factor two if rolled out to all Swiss cement plants. Other less mature capture technologies have different energy demand profiles. A sufficient supply of renewable/CO2 neutral energy is therefore relevant as well as the availability of a national and international CO2 transport and storage infrastructure. In addition, the notable increase in the cost of producing clinker from 75CHF/$t_{clinker}$ to 191 CHF/$t_{clinker}$ and the perceived lack of long-term investment security pose challenges.
- Alternative clinkers today are three times more expensive than conventional clinker, lack relevant standards and most are in early-stage development, limiting their potential for mitigation on the timescale until 2050.

EU and Swiss policy could help in overcoming these barriers. While there are few cement-specific policies in place globally already, a number of existing and discussed policy options from other contexts and industries could be considered. Some technology-specific barriers appear to call for tailored regulatory solutions. Clinker substitution barriers, for instance, could be addressed by a shift from the prescriptive Swiss concrete code to a performance-based approach, allowing for the overall reduction in clinker and cement production.

For technologies involving significant investments and high costs per ton such as CCS, the current CO2 price and uncertainty over infrastructure and fuel and energy availability are insufficient to justify the expenditures. To overcome these hurdles, a range of policy instruments are being developed for the medium term, covering subsidies, incentives and pricing mechanisms. A significant body of work has been created in the European Union, with the development of complementary mechanisms into a framework, combining Carbon Contracts for Difference (CCfD) to cover the additional costs of CO2 abatement, the phase out of free allocations and the Carbon Border Adjustment Mechanism (CBAM) to create a level playing field with imports and avoid carbon leakage. These policies could potentially be complemented with mechanisms that create initial demand, such as low carbon public procurement. Prospectively, in the longer term, assuming a likely increase in carbon prices and more stringent international emissions targets, CCS may move towards commercial viability and trade exposed sectors could potentially require less protection. In this way, it may be an option to let the costs and risks gradually transition to the private sector. In addition, CO2 standards imposed on locally produced products and imports in the long-term could ensure net-zero compatibility across all sectors while mitigating the impact on competitiveness. Overall, the design of these options and coordination with other climate policies requires further research.

In parallel to the ongoing policy evaluation and design efforts, industry players have the opportunity to expand technical and cost knowledge and gain experience required for successful installation of CCS through pilot projects as can be seen throughout Europe and beyond. These pilots are often industry-lead but are supported through direct state funding in different forms of public-private partnerships. Similar approaches are being adopted in Switzerland for the cement and other heavy industries, such as the pilot and demonstration project DemoUpCARMA.

Within the months of writing this report, there have been significant shifts in climate policies and positions globally and particularly in Europe. We observe numerous industry-lead initiatives and investments into R&D for CO2 utilization, piloting and demonstrating CCS on cement plants, large CO2 infrastructure projects and more that are already addressing some of the barriers highlighted in this report, especially on technical risks and infrastructure availability.

Zusammenfassung

Die Schweiz hat sich verpflichtet, ihre Treibhausgasemissionen bis 2030 gegenüber dem Stand von 1990 zu halbieren und bis 2050 auf Null zu reduzieren, um die globale Erwärmung auf 1,5°C über dem vorindustriellen Niveau zu begrenzen [7]. Da die Zementindustrie für etwa 5 % der gesamten Schweizer Emissionen und fast 25 % aller Industrieemissionen in der Schweiz verantwortlich ist, besteht ein klarer Konsens über die Notwendigkeit einer Dekarbonisierung des Sektors [1][2]. Das Projekt wurde durch die Notwendigkeit einer umfassenden und detaillierten techno-ökonomischen Analyse aller Technologien für die Dekarbonisierung der Zementindustrie vorangetrieben, die für den schweizerischen Kontext modelliert und angepasst wurden, um eine kohärente Grundlage für verschiedene politische Optionen zu schaffen, die den Übergang zu einer Netto-Null-Produktion von Zement fördern. Diese Studie zielt darauf ab, die technisch-ökonomischen Erkenntnisse der Technologien zusammenzufassen, um einen Überblick über den Entwicklungsstand und die Kosten sowie eine Vergleichbarkeit der Optionen in der Schweiz (auch im Hinblick auf eine mögliche Realisierung negativer Emissionen) zu erhalten. In einem zweiten Schritt werden die technischen, ökonomischen, kommerziellen, organisatorischen und regulatorischen Barrieren untersucht, und es werden zunächst politische Optionen zur möglichen Überwindung dieser Hindernisse erörtert und diskutiert.

In Teil I wird nach einer ersten Literaturrecherche und einer vorläufigen Konsolidierung der verfügbaren Dekarbonisierungs-Technologien ein Workshop mit Vertretern der verschiedenen Projektbeteiligten durchgeführt, welcher zu einer Priorisierung der relevanten Technologien für weitere Untersuchungen führt. Es wird eine detaillierte Analyse dieser CO2-Minderungsoptionen durchgeführt, darunter alternative Brennstoffe, Energieeffizienz, Klinkersubstitution, alternative Klinker und Kohlenstoffabscheidung. Bei der Bewertung werden die verschiedenen Technologien anhand mehrerer Kriterien im Schweizer Kontext untersucht, nämlich CO2-Reduktionspotenzial, Kosten, technischer Reifegrad (TRL), usw. Sowohl das CO2-Vermeidungspotenzial als auch die Kosten werden für jede Technologie berechnet, um einen Vergleich der verschiedenen Optionen zu ermöglichen. Das Potenzial für negative Emissionen in der Zementindustrie wird ebenfalls untersucht. Mit diesen Daten entwerfen wir mehrere Dekarbonisierungspfade, indem wir verschiedene Reduzierungsoptionen kombinieren und

ihre kumulativen Auswirkungen auf das Erreichen von Netto-Null für die Schweizer Zementindustrie bewerten. Für jeden Weg berechnen wir auch die Kosteneffizienz jedes technologischen Szenarios.

Die Ergebnisse zeigen, dass sich die in Teil I dieser Studie bewerteten Dekarbonisierungs-Technologien und -ansätze in unterschiedlichen Stadien der Kommerzialisierung und Entwicklung befinden. Energieeffizienz, Klinkersubstitution und alternative Brennstoffe sind in der europäischen Zementindustrie bereits gängige Praxis, während alternative Klinker und Kohlenstoffabscheidung neuartige Lösungen sind. Letztere sind daher mit höheren Investitionskosten und Risiken verbunden als die etablierten Dekarbonisierungsmassnahmen; ihre potenziellen Klimaauswirkungen sind jedoch vergleichsweise höher. Insgesamt kommen wir zu dem Schluss, dass Netto-Null-Emissionen für die Schweizer Zementindustrie bis 2050 erreichbar sind, aber vom Einsatz der Kohlenstoffabscheidung abhängen. Je nach CO2-Minderungspfad sind sogar negative Emissionen möglich.

Mit Blick auf die absoluten Kosten ist der kostengünstigste Weg zu Netto-Null-Emissionen ein diversifiziertes Lösungsportfolio, d.h. eine Kombination aus Energieeffizienz, Klinkersubstitution, alternativen Brennstoffen und Kohlenstoffabscheidung und -speicherung (CCS). Basierend auf unseren Annahmen und Analysen führt dieser Weg zu CO2-Vermeidungskosten von insgesamt 113 CHF/Tonne$_{CO2}$, was zu modellierten jährlichen Dekarbonisierungskosten von rund 300 Millionen CHF für die Schweizer Zementindustrie führt. Eine Sensitivitätsanalyse zeigt, dass die Vermeidungskosten mit einem geringeren Anteil von Biomasse im Brennstoffmix steigen (aufgrund geringerer Einnahmen aus Gutschriften zur Kohlendioxid-Entfernung [CDR]), während die Kosten mit einem geringeren Klinker-Zement-Verhältnis sinken. Da die Schweizer Zementwerke am Schweizer Emissionshandelssystem (ETS), einem marktbasierten CO2-Preisinstrument, teilnehmen müssen, können die Vermeidungskosten mit dem CO2-Preis im ETS verglichen werden, um die Kosteneffizienz von Dekarbonisierungsmaßnahmen zu bewerten; dieser liegt zum Zeitpunkt der Erstellung dieses Berichts bei rund 86 CHF/tCO2.

Eine Einzelbetrachtung der Minderungsoptionen zeigt Folgendes: Eine Erhöhung der Klinkersubstitution ist prinzipiell immer möglich und senkt sogar die Gesamtkosten der Dekarbonisierung. Alternative Brennstoffe, insbesondere der Ausbau der Biomasse, können zur Dekarbonisierung des Brennstoffmixes beitragen, der 30 % der Gesamtemissionen ausmacht. Biomasse würde in Kombination mit CCS negative Nettoemissionen ermöglichen und bleibt im Vergleich zum heutigen ETS-Preis kosteneffizient, selbst wenn die Biomassepreise in den nächsten Jahren steigen. Was die negativen Emissionen betrifft, so zeigen unsere Ergebnisse, dass die Schweizer Zementindustrie selbst bei den heute verwendeten Biomassemengen eine beträchtliche Menge an CDR zu einem wettbewerbsfähigen Preis im Vergleich zu anderen dauerhaften CDR-Lösungen erzeugen könnte. Dies könnte zusätzliche Einnahmen durch den Verkauf von CDR-Gutschriften ermöglichen. Für CCS gibt es zahlreiche technologische Optionen, von denen einige kommerziell validiert und am Markt verfügbar sind. CCS verursacht zwar höhere CO2-Vermeidungskosten als andere Minderungsoptionen, hat aber auch ein deutlich höheres Vermeidungspotenzial. Unsere Analyse zeigt, dass das Erreichen einer Netto-Null-Emission in der Schweizer Zementindustrie ohne den Einsatz von CCS nicht machbar ist. Alternative Klinker sind heute teuer und bieten ein vernachlässigbares CO2-Vermeidungspotenzial.

Teil II des Berichts befasst sich mit den Hindernissen für die Einführung dieser Dekarbonisierungstechnologien sowie mit einer Reihe von Policy-Optionen, mit denen diese Hindernisse möglicherweise beseitigt werden könnten. In einem ersten Schritt erarbeiten wir durch Literaturrecherche und Befragung von Stakeholdern einen Überblick über die Hindernisse, wobei wir ein breites Spektrum von technischen, wirtschaftlichen, kommerziellen, organisatorischen und regulatorischen Hindernissen abdecken. Anschliessend werden aus der Literatur und aus Interviews mit Experten aus der Wissenschaft, Think Tanks, Nichtregierungsorganisationen, Regulierungsbehörden und politischen Gremien potenzielle Policy-Optionen zusammengetragen, wobei auch Beispiele aus anderen Ländern herangezogen werden. Anschliessend wird ein Stakeholder-Workshop durchgeführt, um die Ergebnisse zu validieren und zusammenzufassen.

Die Analyse der Hindernisse zeigt folgende Herausforderungen auf, welche für die einzelnen Technologien unterschiedlich komplex sind:

- Die Klinkersubstitution, bei der Klinker durch andere Materialien wie z. B. Flugasche ersetzt wird und die im Vergleich zu Lösungen wie CCS relativ niedrige Emissionsminderungskosten aufweist, stösst auf technische Hindernisse und Nachfragebeschränkungen aus dem Markt, da hochgemischte Zemente zu längeren Abbindezeiten und Verzögerungen auf der Baustelle führen, was sich wirtschaftlich auf das Bauprojekt auswirkt. Die lokale und langfristige Verfügbarkeit und der künftige Preis von SCMs (Supplementary Cementitious Materials) sind weitere Hindernisse für die breite Einführung solcher Zemente.
- Bei alternativen Brennstoffen wie Biomasse und grünem Wasserstoff ist ihre künftige langfristige Verfügbarkeit in ausreichenden Mengen ein wichtiges Anliegen der Zementhersteller und stellt ein Hindernis für wesentliche Änderungen im Brennstoffmix dar.
- CCS ist eine entscheidende Technologie, um in der Zementindustrie Netto-Null-Emissionen zu erreichen, und ist mit mehreren Einführungshürden verbunden. Je nach gewählter Abscheidetechnologie erhöht CCS den Energiebedarf der Industrie beträchtlich; beispielsweise erhöht die MEA-Technologie zur CO2-Abspaltung den Bedarf an elektrischer und thermischer Energie fast um den Faktor zwei, wenn sie in allen Schweizer Zementwerke installiert wird. Andere, weniger weit entwickelte Abscheidungstechnologien haben andere Energiebedarfsprofile. Ein ausreichendes Angebot an erneuerbarer/CO2-neutraler Energie ist daher ebenso wichtig wie die Verfügbarkeit einer nationalen und internationalen CO2-Transport- und Speicherinfrastruktur. Darüber hinaus stellen die deutlich gestiegenen Kosten für die Klinkerproduktion und die fehlende langfristige Investitionssicherheit eine Herausforderung dar.
- Alternative Klinker sind heute dreimal so teuer wie herkömmlicher Klinker, es fehlen einschlägige Normen und die meisten befinden sich in einem frühen Entwicklungsstadium, was ihr Minderungspotenzial bis 2050 einschränkt.

Insgesamt könnte die Politik der EU und der Schweiz potentiell zur Überwindung dieser Hindernisse beitragen. Zwar gibt es derzeit weltweit nur wenige zementspezifische Politikmassnahmen, doch könnten eine Reihe bestehender und diskutierter Policy-Optionen aus anderen Kontexten und Branchen in Betracht gezogen werden. Einige technologiespezifische Hindernisse scheinen massgeschneiderte regulatorische Lösungen zu erfordern. Hindernisse bei der Substitution von Klinker könnten beispielsweise durch eine Umstellung von der präskriptiven Schweizer Betonverordnung auf einen leistungsorientierten Ansatz angegangen werden, der eine allgemeine Verringerung der Klinker- und Zementproduktion ermöglichen könnte.

Bei Technologien, die mit erheblichen Investitionen und hohen CO2-Minderungskosten verbunden sind, wie z.B. CCS, reichen der derzeitige CO2-Preis und die Ungewissheit über die Infrastruktur und die Verfügbarkeit von Brennstoffen und Energie nicht aus, um Investitionsaktivität zu rechtfertigen. Um diese Hürden zu überwinden, bestehen eine Reihe von politischen Instrumenten, die mittelfristig von Subventionen über Anreize bis hin zu Preismechanismen reichen. In der Europäischen Union wurde hier bereits ein Rahmen erarbeitet, in dem potentiell komplementäre Policy-Optionen zusammengefügt wurden: Er beinhaltet Carbon Contracts for Difference (CCfD) zur Deckung der zusätzlichen Kosten der CO2-Vermeidung, die schrittweise Abschaffung kostenloser Zertifikatezuteilungen und den Carbon Border Adjustment Mechanism (CBAM) zur Schaffung gleicher Wettbewerbsbedingungen für Importe und zur Vermeidung von Carbon Leakage. Diese Politikmassnahmen könnten unter Umständen durch Mechanismen ergänzt werden, die eine anfängliche Marktnachfrage schaffen, wie z. B. ein kohlenstoffarmes öffentliches Beschaffungswesen. Längerfristig könnte CCS unter der Annahme eines wahrscheinlichen Anstiegs der Kohlenstoffpreise und strengerer internationaler Emissionsziele kommerziell rentabel werden. Zusätzlich ist es denkbar, dass die dem Handel ausgesetzten Sektoren möglicherweise weniger Schutz benötigen könnten. So könnte es eine Option sein, die Kosten und Risiken allmählich auf den privaten Sektor zu übertragen. Darüber hinaus könnten CO2-Normen für lokal hergestellte Produkte und Importe langfristig die Netto-Null-Kompatibilität in allen Sektoren sicherstellen und gleichzeitig die Auswirkungen auf die Wettbewerbsfähigkeit abmildern. Insgesamt bedarf die Ausgestaltung dieser Optionen und die Koordinierung mit anderen klimapolitischen Massnahmen weiterer Forschung.

Parallel zu den laufenden Policy-Prozessen hat die Industrie die Möglichkeit, ihr technisches und kostenbezogenes Wissen zu erweitern und die für eine erfolgreiche Installation von CCS erforderlichen Erfahrungen durch Pilotprojekte zu sammeln, wie dies in ganz Europa und darüber hinaus bereits zu beobachten ist. Diese Pilotprojekte werden häufig von der Industrie geleitet, aber auch durch direkte staatliche Finanzierung in verschiedenen Formen von Public-Private Partnerships unterstützt. Ähnliche Ansätze werden in der Schweiz für die Zementindustrie und andere Schwerindustrien, beispielsweise durch das Pilot- und Demonstrationsprojekt DemoUpCARMA bereits verfolgt.

In den Monaten, in denen dieser Bericht verfasst wurde, haben sich die klimapolitischen Strategien und Positionen weltweit und insbesondere in Europa verändert. Wir beobachten zahlreiche Brancheninitiativen und Investitionen in Forschung und Entwicklung für die CO2-Nutzung, die Erprobung und Demonstration von CCS in Zementwerken, grosse CO2-Infrastrukturprojekte etc., die bereits einige der in diesem Bericht hervorgehobenen Hindernisse angehen, insbesondere in Bezug auf technische Risiken und die Verfügbarkeit von Infrastruktur.

Résumé

La Suisse s'est engagée à réduire de moitié ses émissions de gaz à effet de serre d'ici 2030 par rapport aux niveaux de 1990 et à atteindre un niveau net zéro d'ici 2050 afin de contribuer à limiter le réchauffement climatique à 1,5°C au-dessus des niveaux préindustriels [7]. L'industrie du ciment étant responsable d'environ 5 % des émissions totales de la Suisse et de près de 25 % de toutes les émissions de l'industrie en Suisse, il existe un consensus clair sur la nécessité de décarboniser le secteur [1][2]. Ce projet est motivé par le besoin d'une analyse technico-économique complète et détaillée de toutes les technologies de décarbonisation du ciment modélisées et adaptées au contexte suisse, créant ainsi une base de référence cohérente pour les différentes options politiques visant à conduire la transition vers une production de ciment nette zéro. Cette étude vise à synthétiser les connaissances technico-économiques des technologies afin d'obtenir une vue d'ensemble de l'état de développement et des coûts, ainsi qu'une comparabilité des options en Suisse (également en ce qui concerne la réalisation possible d'émissions négatives). Ensuite, les barrières techniques, économiques, commerciales, organisationnelles et réglementaires sont étudiées, et des options politiques sont initialement développées et discutées pour potentiellement surmonter ces obstacles.

Dans la première partie, après une première revue de la littérature et une consolidation préliminaire des technologies de décarbonisation disponibles, un atelier avec les parties prenantes respectives de l'industrie et de l'administration permet d'établir une liste de technologies d'atténuation du CO2 prioritaires pour une étude plus approfondie. Une analyse détaillée des options d'atténuation du CO2 est réalisée, notamment les carburants de substitution, l'efficacité énergétique, la substitution du clinker, les clinkers de substitution et la capture du carbone. L'évaluation explore les différentes technologies selon plusieurs critères dans le contexte suisse, à savoir le potentiel de réduction du CO2, le coût, le niveau de préparation technique (TRL), etc. Le potentiel de réduction du CO2 et les coûts sont calculés par technologie, ce qui permet de comparer les différentes options. Le potentiel d'émissions négatives dans l'industrie du ciment est également étudié. Grâce à ces données, nous élaborons plusieurs voies de décarbonisation en combinant différentes options d'atténuation et en évaluant leur impact cumulatif pour atteindre le niveau net zéro pour l'industrie suisse du ciment. Pour chaque voie, nous calculons également le rapport coût-efficacité de chaque scénario technologique.

Les résultats montrent que les technologies et les approches de décarbonisation évaluées dans la partie I de cette étude se trouvent à différents stades de commercialisation et de développement. L'efficacité énergétique, la substitution du clinker et les combustibles de substitution sont déjà des pratiques courantes dans l'industrie européenne du ciment, tandis que les clinkers de substitution et la capture du

carbone sont des solutions nouvelles. Ces dernières sont donc associées à des coûts d'investissement et à des risques plus élevés que les mesures de décarbonisation établies ; pourtant, leur impact potentiel sur le climat est comparativement plus élevé. Dans l'ensemble, nous concluons que les émissions nettes nulles sont réalisables d'ici 2050 pour l'industrie suisse du ciment, mais qu'elles dépendent du déploiement du captage du carbone. En fonction de la voie d'atténuation du CO2, des émissions négatives sont même possibles.

En termes de coût absolu, la voie la moins coûteuse pour atteindre le niveau zéro net passe par un portefeuille diversifié de solutions, c'est-à-dire une combinaison d'efficacité énergétique, de substitution du clinker, de combustibles de substitution et de captage et stockage du carbone (CSC). Sur la base de nos hypothèses et de notre analyse, cette voie permet d'obtenir un coût global de réduction du CO2 de 113 CHF/tonneCO2, ce qui se traduit par un coût annuel de décarbonisation modélisé d'environ 300 millions de CHF pour l'industrie suisse du ciment. Une analyse de sensibilité montre que les coûts de réduction augmentent avec la diminution de la part de la biomasse dans le mélange de combustibles (en raison de la baisse des revenus des crédits de suppression du dioxyde de carbone [CDR]), tandis que les coûts diminuent avec la réduction du ratio clinker-ciment. Étant donné que les cimenteries suisses doivent participer au système suisse d'échange de quotas d'émission (ETS), un instrument de tarification du CO2 basé sur le marché, les coûts de réduction peuvent être comparés au prix du CO2 dans l'ETS - qui est d'environ 86 CHF/tonneCO2 au moment de la rédaction de ce rapport - pour évaluer la rentabilité des mesures de décarbonisation.

Un examen individuel des options d'atténuation révèle ce qui suit: L'augmentation de la substitution du clinker, en principe, est toujours possible et fait même baisser le coût global de la décarbonisation. Les combustibles de substitution, en particulier l'augmentation de la biomasse, peuvent contribuer à la décarbonisation du mélange de combustibles qui représente 30 % des émissions totales. La biomasse permettrait des émissions nettes négatives en combinaison avec le CSC et reste rentable par rapport au prix actuel du SCEQE, même si les prix de la biomasse augmentent au cours des prochaines années. Dans ce contexte, la bonne gouvernance et les incitations financières sont importantes pour garantir l'utilisation d'une biomasse durable. En ce qui concerne les émissions négatives, nos résultats montrent que l'industrie suisse du ciment pourrait générer une quantité substantielle de CDR, même avec les volumes de biomasse utilisés aujourd'hui, à un prix compétitif par rapport aux autres solutions de CDR permanent. Cela pourrait permettre de générer des revenus supplémentaires par la vente de crédits RDC. Pour le CSC, il existe de nombreuses options technologiques, dont certaines sont validées commercialement et facilement disponibles. Si le CSC entraîne des coûts de réduction des émissions de CO2 plus élevés que les autres solutions d'atténuation, son potentiel de réduction est également nettement supérieur. Notre analyse montre qu'il n'est pas possible d'atteindre le niveau net zéro dans l'industrie suisse du ciment sans recourir au CSC. Les clinkers alternatifs sont aujourd'hui coûteux et offrent un potentiel de réduction du CO2 négligeable.

La deuxième partie du rapport se concentre sur les obstacles au déploiement de ces technologies de décarbonisation ainsi que sur une série d'options politiques permettant de les surmonter. Dans un premier temps, la recherche documentaire et les entretiens avec les parties prenantes nous permettent d'avoir une vue d'ensemble des obstacles, qu'ils soient techniques, économiques, commerciaux, organisationnels ou réglementaires. Ensuite, les options politiques potentielles sont collectées à partir de la littérature et d'entretiens avec des experts du domaine issus du monde universitaire, de groupes de réflexion, d'ONG et d'organismes réglementaires et politiques, en s'appuyant également sur des exemples d'autres pays. Nous organisons ensuite un atelier avec les parties prenantes pour valider et synthétiser les résultats.

L'analyse des obstacles a permis de dégager les défis de mise en œuvre suivants, avec différents degrés de complexité pour les différentes technologies:

- La substitution du clinker, qui consiste à remplacer le clinker par d'autres matériaux tels que les cendres volantes, avec un coût de réduction relativement faible par rapport à des solutions comme le CSC, se heurte à des obstacles techniques et à la demande du marché, car les ciments fortement mélangés entraînent des temps de prise plus longs et des retards sur le chantier, avec des implications économiques pour le projet de construction. La disponibilité locale et à long terme et le prix futur des matériaux cimentaires supplémentaires (MCS) sont d'autres obstacles au déploiement à grande échelle de ces ciments.

- En ce qui concerne les combustibles de substitution tels que la biomasse et l'hydrogène vert, leur disponibilité future à long terme dans des volumes suffisants est une préoccupation importante pour les fabricants de ciment et constitue un obstacle à des changements significatifs du mélange de combustibles.
- Le captage et le stockage du carbone, technologie essentielle pour atteindre le niveau zéro dans l'industrie du ciment, se heurtent à plusieurs obstacles. Selon la technologie de captage choisie, le CSC augmente considérablement la demande d'énergie de l'industrie; le captage de l'AME par adsorption, par exemple, multiplierait presque par deux la demande d'énergie électrique et thermique s'il était appliqué à toutes les cimenteries suisses, selon la technologie de captage. D'autres technologies de captage moins matures présentent des profils de demande énergétique différents. Une offre suffisante d'énergie renouvelable/neutre en CO2 est donc importante, de même que la disponibilité d'une infrastructure nationale et internationale de transport et de stockage du CO2. En outre, l'augmentation notable du coût de production du clinker, qui est passé de 75 CHF/tclinker à 191 CHF/tclinker, et le manque perçu de sécurité d'investissement à long terme constituent des défis.
- Les clinkers alternatifs sont aujourd'hui trois fois plus chers que le clinker conventionnel, ils ne sont pas conformes aux normes en vigueur et la plupart d'entre eux n'en sont qu'aux premiers stades de développement, ce qui limite leur potentiel d'atténuation à l'horizon 2050.

Les politiques de l'UE et de la Suisse pourraient aider à surmonter ces obstacles. Bien que peu de politiques spécifiques au ciment soient déjà en place dans le monde, un certain nombre d'options politiques existantes et discutées dans d'autres contextes et industries pourraient être envisagées. Certains obstacles spécifiques à la technologie semblent nécessiter des solutions réglementaires adaptées. Les obstacles liés à la substitution du clinker, par exemple, pourraient être levés en abandonnant le code suisse du béton, qui est prescriptif, au profit d'une approche fondée sur les performances, ce qui permettrait de réduire globalement la production de clinker et de ciment.

Pour les technologies impliquant des investissements importants et des coûts élevés par tonne, comme le CSC, le prix actuel du CO2 et l'incertitude quant aux infrastructures et à la disponibilité des combustibles et de l'énergie ne suffisent pas à justifier les dépenses. Pour surmonter ces obstacles, une série d'instruments politiques sont en cours d'élaboration pour le moyen terme, couvrant les subventions, les incitations et les mécanismes de tarification. Un travail important a été réalisé dans l'Union européenne, avec le développement de mécanismes complémentaires dans un cadre, combinant les contrats sur le carbone pour la différence (CCfD) pour couvrir les coûts supplémentaires de la réduction du CO2, la suppression progressive des allocations gratuites et le mécanisme d'ajustement aux frontières du carbone (CBAM) pour créer des conditions de concurrence équitables avec les importations et éviter les fuites de carbone. Ces politiques pourraient éventuellement être complétées par des mécanismes qui créent une demande initiale, comme les marchés publics à faible teneur en carbone. À plus long terme, dans l'hypothèse d'une augmentation probable des prix du carbone et d'objectifs internationaux plus stricts en matière d'émissions, le CSC pourrait devenir commercialement viable et les secteurs exposés aux échanges pourraient nécessiter une protection moindre. Ainsi, il pourrait être envisageable de laisser les coûts et les risques passer progressivement au secteur privé. En outre, les normes de CO2 imposées aux produits fabriqués localement et aux importations à long terme pourraient garantir une compatibilité nette zéro dans tous les secteurs tout en atténuant l'impact sur la compétitivité. Dans l'ensemble, la conception de ces options et la coordination avec d'autres politiques climatiques nécessitent des recherches supplémentaires.

Parallèlement à l'évaluation des politiques et aux efforts de conception en cours, les acteurs du secteur ont la possibilité d'approfondir leurs connaissances techniques et financières et d'acquérir l'expérience nécessaire pour réussir l'installation du CSC grâce à des projets pilotes, comme on peut le constater dans toute l'Europe et au-delà. Ces projets pilotes sont souvent menés par l'industrie, mais sont soutenus par un financement public direct dans le cadre de différentes formes de partenariats public-privé. Des approches similaires sont adoptées en Suisse pour le ciment et d'autres industries lourdes, comme le projet pilote et de démonstration DemoUpCARMA.

Au cours des mois qui ont suivi la rédaction de ce rapport, les politiques et les positions en matière de climat ont évolué de manière significative au niveau mondial, et plus particulièrement en Europe. Nous observons de nombreuses initiatives et investissements de l'industrie dans la R&D pour l'utilisation du CO2, le pilotage et la démonstration du CSC dans les cimenteries, les grands projets d'infrastructure de CO2 et plus encore qui s'attaquent déjà à certains des obstacles mis en évidence dans ce rapport, en particulier les risques techniques et la disponibilité des infrastructures.

Take-home messages

- This report suggests that there is a pathway for the Swiss cement industry to achieve net-zero emissions by 2050. Based on current assumptions, our analysis shows that this goal will require the deployment of carbon capture and storage (CCS). Depending on the CO2 mitigation pathway, even negative emissions are possible, through the combustion of biogenic materials as fuel and CCS.
- Based on our assumptions and analysis, the least cost pathway to net-zero is through a diversified portfolio of solutions, i.e., a combination of energy efficiency, clinker substitution, alternative fuels and CCS with an overall CO2 abatement cost of 113 CHF/ton$_{CO2}$, leading to modelled annual decarbonization cost of around 300 million CHF for the Swiss cement industry. This pathway notably increases the industry energy demand by almost a factor two.
- The decarbonization technologies are at different stages of commercialization and development and face various deployment barriers, the most notable being their high costs, the long-term access to alternative materials, sufficient renewable energy and alternative fuels such as biomass as well as the availability of CO2 transport and storage infrastructure.
- EU and Swiss policy could help in overcoming these barriers. While there are few cement-specific policies in place globally already, a number of existing and discussed policy options from other contexts and industries such as the ETS, Carbon Contracts for Difference (CCfD), public reverse auctions or Carbon Border Adjustments Mechanism (CBAM) could be considered. Their design and coordination with other climate policies requires further research, however.
- While policy research and design is ongoing, in order to parallelize and thus accelerate, the cement producers could engage in plant-level analyses and pilot decarbonization projects in line of numerous other similar activities in the European and global cement industry.

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ACC	Accelerated Carbon Curing
ASU	Air separation unit
BAT	Best Available Techniques
BECCS	Bioenergy with Carbon Capture and Storage
BYF	Belite-Ye'elimite-Ferrite clinker
CaL	Calcium Looping
CAP	Chilled Ammonia Process
CAPEX	Capital expenditures
CBAM	Carbon border adjustment mechanism
CCR	Carbon Capture Ratio
CCS	Carbon Capture and Storage
CCSC	Carbonatable calcium silicate clinkers
CDR	Carbon dioxide removal
CEM	Cement
CEMCAP	CO2 capture from cement production
CH	Switzerland
CHF	Swiss franc
CO2	Carbon Dioxide
COC	Cost of clinker
CPU	CO2 purification unit
CSA	Calcium Sulfoaluminate clinker
DSR	Direct Separation Reactor
EOR	Enhanced Oil Recovery
EPD	Environmental Product Declarations
EPFL	École polytechnique fédérale de Lausanne
ETS	Emission Trading System
EU	European Union
EUR	Euro
FOEN	Swiss Federal Office for the Environment
FTA	Free Trade Agreement
GBFS	Granulated blast furnace slag
GBP	British Pound Sterling
GHG	Greenhouse Gas

GJ	Gigajoule
H2	Hydrogen
HMC	Hydrated Magnesium Carbonate
IPCC	Intergovernmental Panel on Climate Change
IDDRI	Institute for Sustainable Development and International Relations
LC3	Limestone Calcined Clay Cement
LEILAC	Low Emissions Intensity Lime and Cement
LRF	Linear Reduction Factor
MAL	Membrane-Assisted CO_2 Liquefaction
MEA	Monoethanolamine
MJ	Megajoule
MRV	Monitoring, reporting and verification
MW	Megawatt
MWh	Megawatt hour
NETs	Negative emissions technologies
OPC	Ordinary Portland Cement
OPEX	Operating expenses
OxyF	Oxyfuel
PRTR	Pollutant Release and Transfer Register
PVC	Polyvinyl chloride
RBPC	Reactive Belite-rich Portland Cement
RIS	Resource Information System
SCM	Supplementary cementitious material
SFOE	Swiss Federal office of Energy
SOX	Sulfur oxides
TES	Tree Energy Solutions
TFEU	Treaty on the Functioning of the European Union
TRL	Technical Readiness Level
USD	United States dollar
WTO	World Trade Organization
W/C	Water-cement ratio

1 Introduction

1.1 Background

The Swiss Federal Council has announced a net-zero greenhouse gas emissions target by 2050 and has adopted the corresponding “Long-Term Climate Strategy for Switzerland” in January 2021 [1]. In order to achieve this goal, industry emissions have to be reduced substantially. With the cement industry responsible for approximately 5% of total Swiss emissions and almost 25% of all industry emissions in Switzerland[1] [2][3], there is clear consensus about the need for decarbonization in this sector. Switzerland’s government, the Federal Council, has recently published a report in response to a postulate of a then Member of the National Council, that captures the need for measures that not only address technology and supply side issues, but also for the development of measures that affect demand as well as market diffusion of technologies that are conducive to complete decarbonization and even negative emissions [4].

The importance of finding a way to net-zero for the cement industry is also acknowledged on an international level, with multilateral agencies such as the International Energy Agency highlighting the role of the cement industry in achieving net-zero emissions and even its potential as a source of negative emissions [5]. Despite this importance, planning for an at-scale deployment of solutions to achieve this sector decarbonization is still at very early stage in Switzerland. While knowledge about these technologies exists, both internally within cement production companies and published by external bodies (cembureau, Verein Deutscher Zementwerke, UK Concrete, International Energy Agency, Energy Transition Commission, United Nations Environment Program), it now requires a synthesis of these insights and economic assessments, and comparisons between the technologies to achieve the next level of clarity on the path towards investment decisions to retrofit existing assets. In addition, uncertainties exist regarding appropriate policy frameworks that enable the implementation of efficient decarbonization pathways. These are the challenges that this report will address by first, synthesizing existing insights about cement decarbonization technologies and their application to the Swiss context and second, investigating the current and potential regulatory frameworks that enable the implementation of such technologies.

1.2 Project Motivation

Switzerland has committed to halving its greenhouse gas emissions by 2030 and reaching net-zero by 2050 compared to 1990 levels. This commitment is a means to limiting global warming to 1.5°C compared with the pre-industrial era [7].

Cement is the main CO2-intensive component of concrete, globally the most heavily used construction material [6]. Cement production is a major source of CO2 emissions due to fuel combustion and chemical process emissions, accounting for 5% of the 2019 Swiss national CO2 emissions. Looking at the industrial sector, cement is responsible for 22% of the CO2 emissions and consumes 8% of the final energy [2][3]. Consequently, the cement industry is a key lever in decarbonizing the Swiss economy.

Multiple international and European reports focus on the breadth of technological approaches to decarbonize the cement industry such as [6]–[9], while other studies highlight one or the other technologies such as [10]–[13]. These studies analyze the developments of the global cement sector, however, lack country-specific technology and policy-relevant insights and options.

The most relevant paper found for Switzerland at this point is Zuberi et al. [14]. It explores the energy efficiency improvements and the associated CO2 abatement potential of the Swiss cement industry including the necessary investment cost. The study does however not consider an in-depth analysis of the different technology options such as alternative fuels, alternative clinkers etc. in detail and does not

[1] Including emissions from waste incineration.

include a comparison of the different carbon capture technologies with their respective energy demand, costs and technical readiness levels. Also, the costs of carbon capture in the study exclude the cost of CO2 transport and storage which today represent a significant fraction of the overall costs. The study aims to be a basis for effective policies yet does not examine and put forth concrete policy implications. A more recent study by Obrist et al. [15] uses a bottom-up techno-economic optimization to present energy technology developments in the cement industry and potential policy strategies such as CO2 tax. The paper focuses on modeling different decarbonization pathways under various policy scenarios. The technologies considered are carbon capture (oxyfuel, MEA, chilled ammonia) and kiln retrofits, and does not consider other technology options (novel cements, alternative fuels etc.).

This project is thus driven by the need for a comprehensive and detailed techno-economic analysis of all cement decarbonization technologies modeled and adapted for the Swiss context, creating a coherent baseline for modelling various policy options to drive the transition towards net-zero cement production in Switzerland, while maintaining the regional competitiveness.

1.3 Project Goals

The cement industry is considered to be one of the most challenging sectors to decarbonize in the transition to a low-carbon economy mainly due to chemical process emissions which are especially challenging to eliminate [16]. The complex emission structure (process and fuel emissions) requires the consideration of all potential decarbonization technologies. Industry stakeholders and policymakers have started to investigate these technologies and their implications on CO2 abatement, yet there are significant differences in terms of development status, costs and regulatory framework.

In a first step, the project aims to synthesize techno-economic insights of the technologies in order to get an overview of the state of development and costs, as well as a comparability of the options in Switzerland (also with regard to a possible realization of negative emissions). Secondly, the technical, economical, commercial, organizational and regulatory barriers are investigated, and policy scenarios are modeled to overcome these obstacles resulting in a regulatory framework and policy options.

Goal 1: **Synthesis of techno-economic insights of all relevant decarbonization technologies from the Swiss cement industry**

- What are the available and in the pipeline decarbonization technologies? What is their CO2 abatement potential, cost and technical readiness level specifically in Switzerland?
- What are the current and projected costs for the implementation of these technologies? Are costs expected to change with economies of scale?
- How can the technologies be combined to maximize CO2 mitigation potential and what is the overall mitigation cost per approach?
- Can the technologies realize negative emissions and to what extent?

Goal 2: An overview of barriers (technical, economical, commercial, organizational and regulatory) and policy options to overcome those barriers

- What are the barriers to deployment of individual technologies in Switzerland?
- How have these barriers been dealt with abroad?
- What options exist for policy designs to overcome these barriers?

The study has principally two audiences: First, Switzerland's cement industry for whom this report provides an overview of key features of an national decarbonization pathways for the cement sector, particularly an overview of the technologies and their respective techno-economic assessments and associated regulatory barriers; federal and possibly cantonal administrative units are the second audience who have a role in the development of a legal and regulatory framework conducive to decarbonization of and even the provision of negative emissions by the cement sector.

2 Understanding Cement and Emission Sources

Concrete is a mixture of cement, aggregates, water and other suitable material, where cement acts as a binder to hold the aggregates together. Cement is a generic term that may be used to describe many inorganic and organic materials that act as a binder, by far the most commonly used and most versatile cement is Portland cement, a hydraulic cement [17]. Mixing hydraulic cement and water triggers a chemical reaction, allowing the concrete to harden and set. Cement is a fine and homogeneous powder composed of clinker, gypsum and additives commonly known as supplementary cementitious materials (SCMs) or fillers (e.g., blast furnace slag, coal fly ash, natural pozzolanas, limestone, etc.).

Figure 1 shows the Portland cement production process. Highlighted in grey are the preheater/ precalciner and the kiln where the clinker forms and emissions are highest.

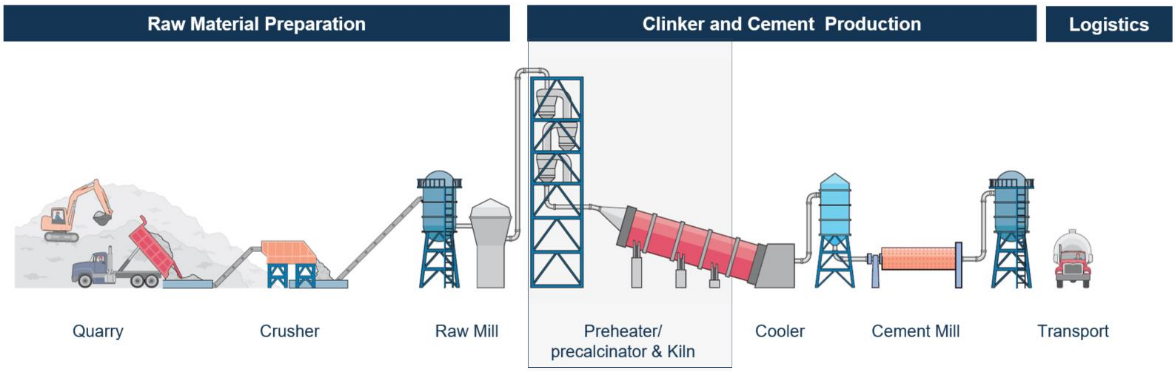


Figure 1: Cement production process [18]

Clinker is produced from raw materials including limestone and clay, which are crushed, homogenized and fed into the pre-heater and kiln to be heated up to 1,450°C. This is the temperature required for the raw materials to undergo chemical changes to form clinker. The main clinker compounds are Alite, Belite, Aluminate and Ferrite, which are formed at varying temperatures in the process. Proportions vary depending on raw meal composition and firing temperature and contribute to defining the hydration and strength development properties of the cement product (relevant for the discussion of alternative clinkers).

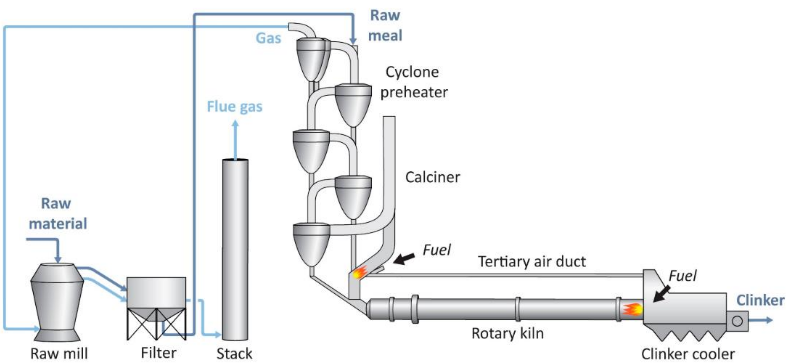


Figure 2: Clinker burning line including the pre-calciner/pre-heater and kiln [10]

The clinker burning line illustrated in Figure 2 shows the steps and the main equipment required to convert raw material to clinker. The raw material, mainly limestone and clay, are introduced into the raw mill to prepare the raw meal for the clinker production process. The raw material is dried by the flue gas from the preheater, after which the flue gas and the raw meal are separated by a filter and the raw meal is sent to the preheater. In the preheater, the flue gases from the calciner and the rotary kiln are mixed with the meal for heat transfer before they are separated again for the meal to then enter the cyclones which are stacked above each other as displayed in the figure. The preheated meal enters the calciner where calcination occurs triggering an endothermic reaction where calcium carbonate from the limestone decomposes into lime and carbon dioxide (CaCO3 -> CaO + CO2). 94-98% of the calcination is complete by the final stage of the preheater i.e. the calciner at temperatures between 800 - 900°C [19]. The raw meal then enters the kiln where the remaining unreacted calcium carbonate is processed and the formation of clinker occurs. Around 60% of the cements plant`s total fuel input is consumed by the calciner, whereas the remaining 40% is consumed by the main burner that heats the rotary kiln [10]. At the final stage of the process, the hot clinker enters the cooler where it is cooled by ambient air.

Clinker production is the main source of emissions in cement manufacturing. There are two main sources of emissions:

1. **Process Emissions:** Emissions from the calcination process which involves the thermal decomposition of Calcium Carbonate (e.g., limestone, marble etc.) into Calcium Oxide (lime) and Carbon Dioxide.
2. **Fuel Emissions:** Fuels used to heat up the raw material to drive the necessary chemical reactions in the pre-heater and kiln up to 1,450°C. The remaining chemical reactions resulting in the formation of Alite, Belite, Aluminate and Ferrite (components of clinker) occur at temperatures between 800 - 1,450°C. These compounds form through the reaction of free Lime from the calcination process with Silica, Alumina, and Ferrite from sand, clay and other raw materials introduced as meal with the limestone (see Figure 3).

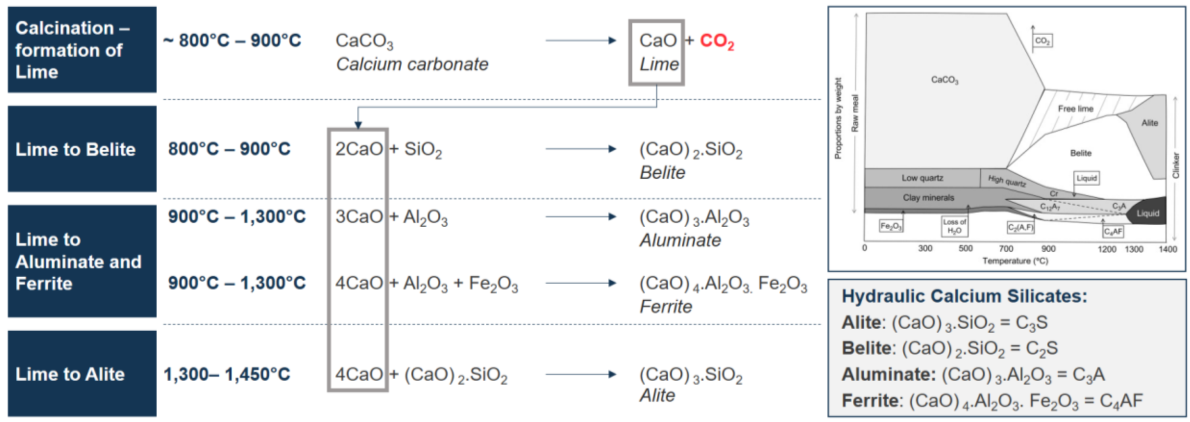


Figure 3: Principal reactions in clinker formation

It is important to point out the chemical processes involved to understand the CO2 mitigation options. For example, using zero-carbon fuels will not eliminate the CO2 emitted from the calcination process (released in equation 1 Figure 3). In Switzerland, cement process emissions represent 70% of the total scope 1 emissions [3], which can mainly be eliminated through carbon capture. Therefore, a transition to zero-carbon fuels can only reduce emissions by 30%.

3 The Swiss Cement Industry

In Switzerland there are six cement plants, cumulatively producing 4.2 million tons of cement and 3.2 million tons clinker in 2019 [20][3]. According to cemsuisse, the Swiss cement association, the demand for cement in Switzerland is approximately 4.7 million tons and is expected to increase in the medium term with increasing construction activity due to infrastructure expansion and the high demand for housing [20]. Other sources predict the demand for cement in Europe to remain stable, due to the relatively slow economic and population growth in comparison with other emerging economies [9].

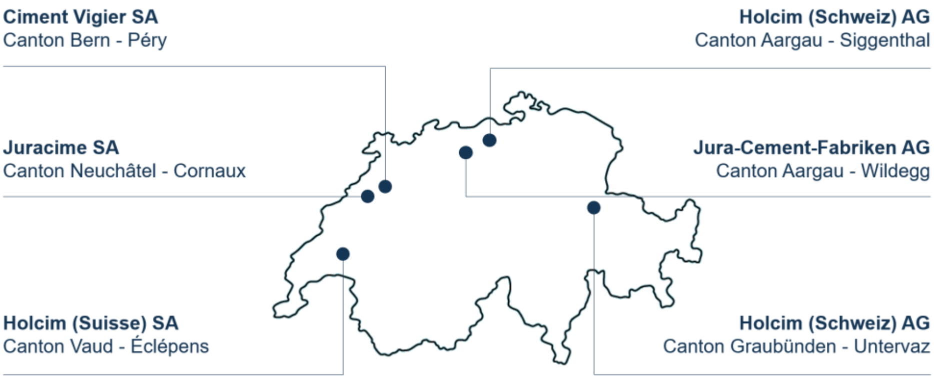


Figure 4: Location of the six cement plants in Switzerland

In 2019, the cement industry was responsible for 2.457 million tons CO2, equivalent to 5% of the annual Swiss national emissions. These include scope 1 emissions attributed to geogenic emissions resulting from the calcination process, in addition to the non-biogenic emissions due to the onsite combustion of primary and secondary/waste fuels. During that year, biogenic emissions, considered climate neutral and resulting from the combustion of biomass, amounted to 0.258 million tons CO2-biogenic.

Cement producers in Switzerland are part of the Swiss emission trading scheme (ETS) which has been linked to the EU ETS since January 2020 and are thus required by law to report on their scope 1 emissions [21]. Cement producers have actively worked on reducing emissions over the years and achieved a total scope 1 emission reduction of 38% compared to the 1990 baseline (see Figure 5) [3][20]. The emission reductions were primarily achieved through energy efficiency measures, a shift from primary fossil fuels to waste fuels, increasing the share of biomass in the fuel mix, and a shift towards lower-clinker cements (discussed later in the report). The Swiss emission intensity of clinker production is 762 $kg_{CO2}/ton_{clinker}$, 10% lower than the global average of 850 $kg_{CO2}/ton_{clinker}$ [22].

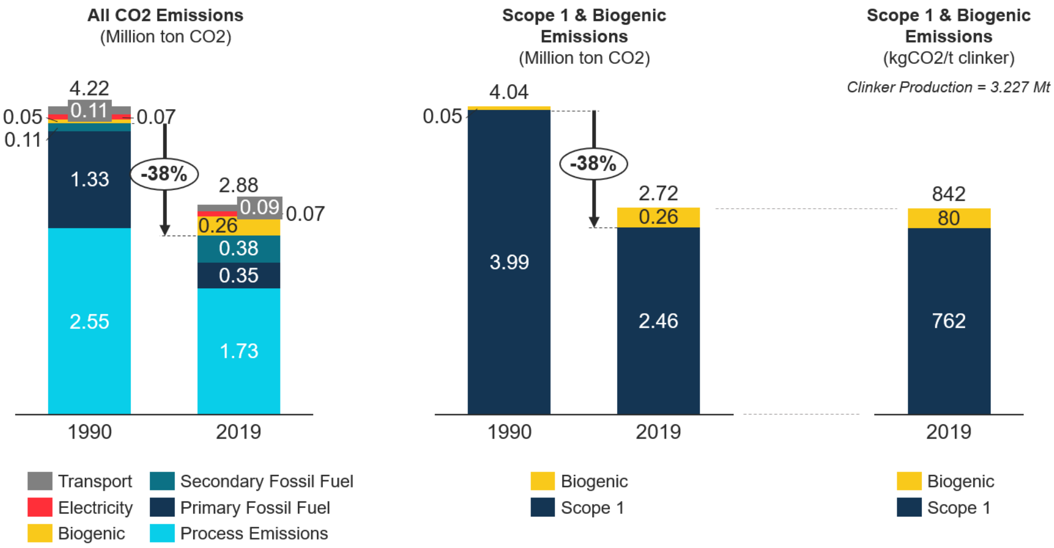


Figure 5: Development of CO2 emissions from the Swiss cement industry[2]

Although not considered in the ETS, it is imperative to quantify indirect emissions (transport and electricity) and climate neutral emissions (biogenic emissions from the onsite combustion of biomass). Introducing decarbonization technologies such as CCS will require a significant amount of additional electricity supply, increasing indirect emissions which impact the national GHG inventory. An adequate baseline for biogenic emissions is key as it will play a future role in combination with CCS for achieving CDR/negative emissions.

As mentioned previously, one of the main strategies in reducing cement production emissions in Switzerland over the years has been the shift in fuel mix from primary fossil fuels to secondary waste-derived fuels and biomass with lower or zero fossil fuel emission factors. In 2019, the Swiss cement industry consumed 11.478 PJ of thermal energy and 1.365 PJ of electric energy (refer to Appendix A for details on energy consumption). Figure 6 shows that the specific consumption (on a per clinker basis) of primary fossil fuels has dropped by 33% between 2010 and 2019, whereas the share of secondary fossil fuels and biomass have both increased by 43%.

[2] Primary fossil fuels are e.g., lignite, gas oil, natural gas etc. Secondary fossil fuels are waste derived fuels with a fossil fuel content (e.g., waste oil, plastic waste, waste tires and rubber). Emission and fuel consumption details can be found in the Appendix A.

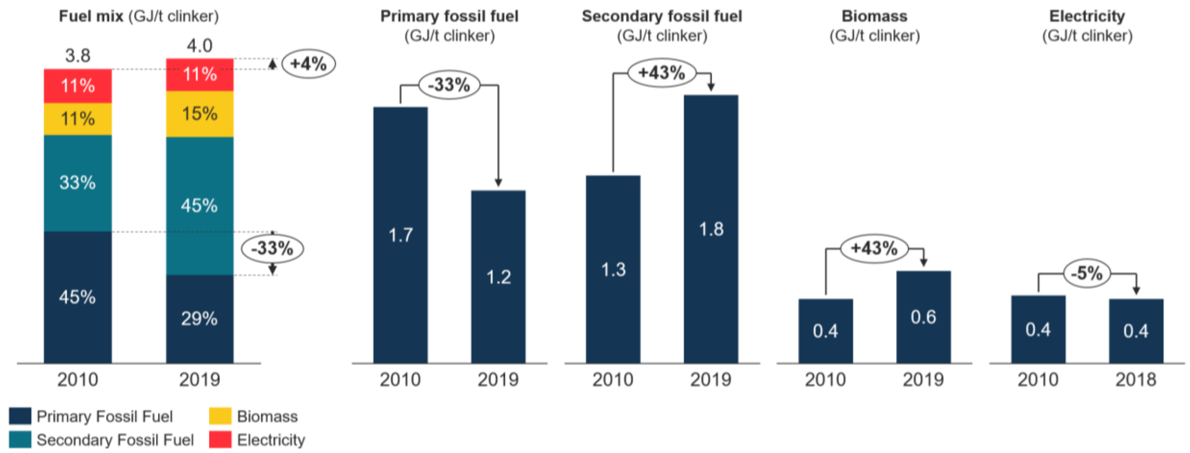


Figure 6: Development of the fuel mix of the Swiss cement plants

Swiss cement plants on average have a clinker specific final energy use equivalent to the upper bound (4 GJ/ton$_{clinker}$) of the global Best Available Techniques (BAT) defined by the European Commission [23] [24] (see Figure 7). The lower bound of 3.3 GJ/ton$_{clinker}$ reveals that further energy efficiency improvements can reduce the energy input required to produce one ton of clinker. In emerging markets, new efficient cement plants are being installed based on BAT which improves the global average efficiency. The BAT is achieved under ideal conditions which are challenging to achieve in reality and especially in existing plants. It is highly dependent on multiple factors including kiln capacity, moisture of raw material, moisture of fuels, types of cement production and more. In absolute numbers, the annual thermal and electric energy consumption has decreased from 14 to 12.8 PJ between 2010 and 2019, whereas clinker production dropped from 3.6 to 3.2 million ton$_{clinker}$ during that same period. Because the clinker production decreased at a higher rate than energy consumption, the specific energy consumption in 2019 is higher than that of 2010, meaning that slightly more energy is consumed per unit output.

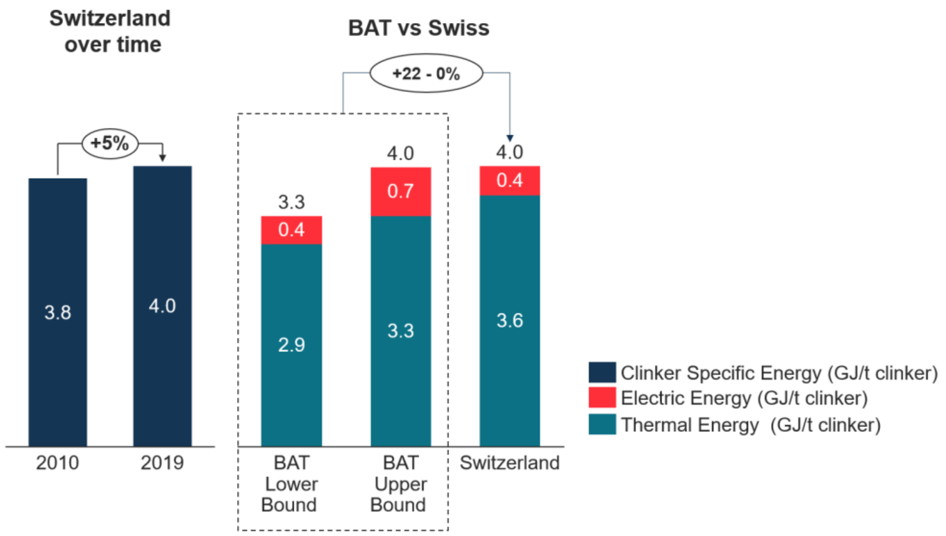


Figure 7: Specific final energy use of clinker production

PART I – Synthesis of techno-economic insights

In Part I of this study, we explore the different decarbonization technologies available to cement producers today to reach net-zero. In this techno-economic synthesis we introduce the different technologies and calculate their CO2 abatement potential and cost for the cement industry in Switzerland. Using these findings, we draft multiple pathways to net-zero and calculate the overall cost of achieving this on an industry level.

4 Methodology

4.1 Scope and technology prioritization

The aim of the first phase of this study is to perform a synthesis of techno-economic insights of the different cement decarbonization options within the Swiss context. After an initial literature review and a preliminary consolidation of the available technologies, a workshop with representatives of the different project stakeholders was organized to prioritize the relevant technologies. The project stakeholders are as listed in Table 1:

Table 1: List of project stakeholders

Stakeholder	Category
Holcim (Schweiz) AG	Cement producer
Jura-Cement-Fabriken AG	Cement producer
Ciments Vigier SA	Cement producer
Cemsuisse	Association of the Swiss cement industry
Swiss Federal Office for the Environment (FOEN)	Public administration
Swiss Federal office of Energy (SFOE)	Public administration
Sustainability in Business Lab at ETHZ	Academia

The workshop resulted in a longlist of technology options that are investigated across multiple criteria in this study. Table 2 shows the list of technologies and whether the solution mitigates fuel emissions, process emissions or both. The assessment criteria are listed in Table 3 and have been applied to the different technologies to different levels of detail depending on the priority of the technology identified by the stakeholder group and data availability.

It is important to note that this study focuses on the cement industry and does not account for demand-side measures from other stakeholders in the value chain such as concrete producers, contractors, building owners etc. Due to this, and the prognosis that cement demand will remain stable in Europe until 2050 [25][26], this report **maintains a fixed cement production until 2050** (4.2 million tons of cement). Reducing the demand for cement is nevertheless one of the most effective means to minimize emissions stemming from the cement industry and should be a key focus of the construction industry in the upcoming years. Cement reduction is achieved through multiple means: new approached to design, building materials other than concrete, substitution of cement with additives, less overspecification etc. Cement reduction remains out of the scope of this study but should be considered in future work considering a complete value chain approach.

Table 2: Longlist of technologies

Emission Source	Approach	Technology/Solution
Energy-related emissions	Energy efficiency	Change or retrofit of kiln
	New and alternative fuels	Natural gas
		Waste
		Biomass
		Zero carbon/green hydrogen
Energy- and process-related emissions	Lower clinker-to-cement ratio	Blending with supplementary cementitious materials (SCMs) including fly ash, ground granulated blast-furnace slag, clay etc.
	Alternative clinkers	Reactive Belite-rich Portland Cement (RBPC)
		Belite-Ye'elimite-Ferrite clinker (BYF)
		Calcium Sulfoaluminate clinker (CSA)
		Carbonatable calcium silicate clinkers (CCSC)
		Hydrated Magnesium Carbonate (HMC)
	Carbon capture	Post-combustion capture (e.g., MEA, CAP, MAL)
		Oxyfuel combustion technologies
		Calcium looping (tail-end and integrated)
		LEILAC
	Enhanced carbon uptake	Mineral carbonation / accelerated CO2 curing
		Natural re-carbonation of concrete

Table 3: Technology assessment criteria

Assessment Criteria
Potential CO2 mitigation
Cost
Changes to existing equipment
Infrastructure integration and boundary conditions
Technical readiness
Feasibility in Switzerland

4.2 Data collection and emissions baseline

As a first step in the data collection process, we extract emission data from Switzerland's GHG Inventory [3] which provides emission and activity data on different industries operating in Switzerland. The data includes a breakdown of the industry fuel consumption and respective emission factors, in addition to the emission factor of the cement calcination process and the annual clinker and cement production. This data was used to calculate the total cement industry emissions, namely **scope 1 and biogenic emissions**. See Appendix A for data details. These values are used to create an initial emission baseline that is used throughout the project.

The initial emission baseline is then compared to the CO2 data of the public Swiss Pollutant Release and Transfer Register (Swiss PRTR) [27] which provides data on different pollutants emitted by facilities across Switzerland. The CO2 emissions from the six cement production plants in Switzerland were extracted for multiple years and compared to the values in step 1 to ensure data robustness. The two data sets are consistent and thus the emission baseline is considered sound.

The fuel consumption and emissions baseline is used to calculate different factors such as the clinker/cement emission intensity and as a basis for modelling different alternative fuel consumption scenarios (Section 5.2). The clinker emission intensity ($kg_{CO2}/ton_{clinker}$) is used as a reference point for all decarbonization options presented in this study and is determined by the following equation:

$$Emission\ Intensity_{clinker} = \frac{Total\ CO2\ Emissions}{Annual\ clinker\ production}$$

Although the emission baseline includes all emission data (including transport and electricity consumption for example), for the assessment of the technologies listed in Table 2 we focus on scope 1 and biogenic emissions[3]. Scope 1 emissions are direct emissions and relevant for accounting purposes and biogenic emissions are climate neutral and relevant for the quantification of negative emissions in the case of carbon capture. Figure 5 shows the total and specific (per $ton_{clinker}$) scope 1 and biogenic emissions of the Swiss cement industry. We use the 2019 emissions as a baseline in our assessment, with scope 1 emissions equivalent to 2.457 million tons CO2 or 762 $kg_{CO2}/ton_{clinker}$ and biogenic emissions equivalent to 0.259 million tons CO2-biogenic or 80 $kg_{CO2\text{-}biogenic}/ton_{clinker}$ with an annual clinker production of 3.227 million tons clinker.

[3] Only in the assessment of carbon capture do we briefly consider the scope 2 indirect emissions attributed to the extra electricity demand of the capture technology.

4.1 CO2 marginal abatement cost (MAC) curve

Marginal abatement cost (MAC) curves have been used as a tool in assessing the economics of varying CO2 mitigation options. This approach supports policymakers make decisions to achieve their emission targets at the least cost. It is a useful and effective approach in comparing technologies based on the cost and potential of CO2 abatement [28]. The cost of abatement represents the monetary value per unit of realized or estimated CO2 saved per technology or decarbonization measure (CHF/ton$_{CO2}$). It is displayed on the y-axis of the chart. The x-axis presents the CO2 abatement potential per measure (kg$_{CO2}$/ton$_{clinker}$) (see Figure 8). The technologies depicted in the chart need to yield actual reduction of CO2. The baseline for comparison is the actual emission at the time of estimation [29], which in this study is the emission intensity of clinker in 2019 equivalent to 762 kg$_{CO2}$/ton$_{clinker}$.

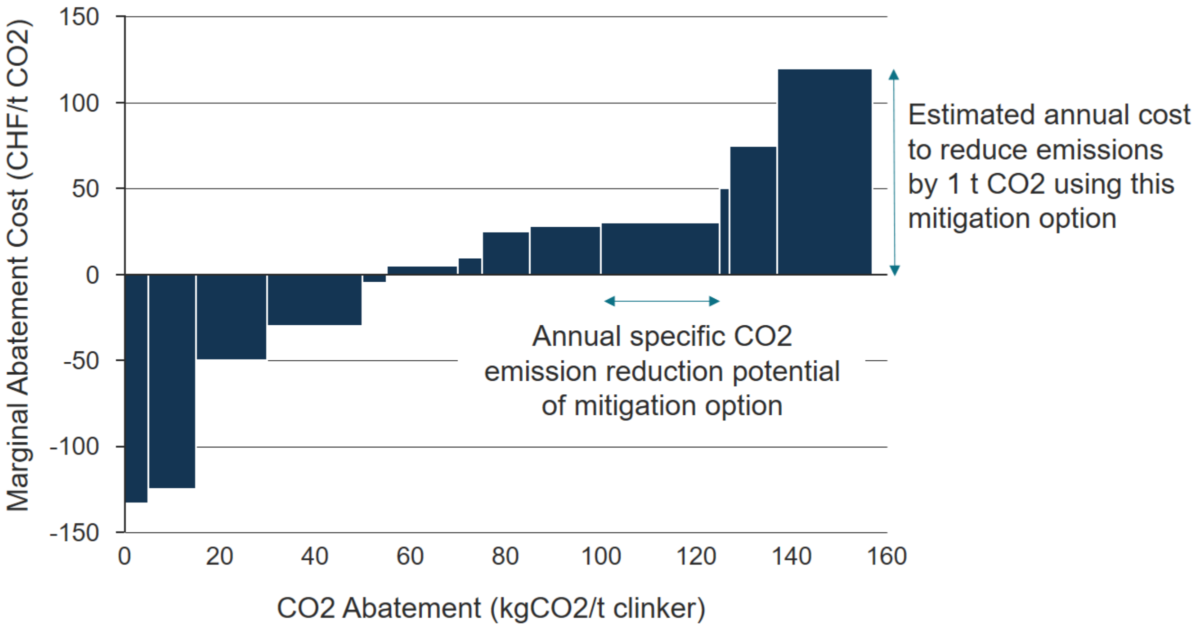


Figure 8: Sample of marginal abatement cost (MAC) curve

To calculate the MAC, the difference between the annual cost of the mitigation option and baseline technology is divided by the potential CO2 savings with the implementation of the new technology. The formula is as follows:

$$MAC_{clinker} = \frac{\Delta\, Annual\ cost_{\ Migitgation\ option-Baseline}}{\Delta\, CO2\ emissions_{\ Migitgation\ option-Baseline}}$$

The graph MAC curve is constructed using the resulting calculations, where each bar in the graph represents one CO2 mitigation option and these are sorted by increasing cost per ton CO2. To include the full range of technologies in one MAC, technology specific methodologies were used in this study to derive the annual cost and CO2 saving potential per mitigation option, depending on the technology and data availability. The calculation methodology of each will be discussed in the respective technology chapters.

5 Approaches to lower cement emissions

The cement industry in Switzerland has devoted a substantial effort over the years to CO2 mitigation solutions. There exist multiple decarbonization levers with varying risks, costs and impacts, some of which exploited more than others in Switzerland. This section aims to discuss the mitigation options in detail and assess them in the Swiss context according to the criteria listed in Table 3.

5.1 Energy Efficiency

5.1.1 Background

The 2019 specific final energy consumption of the Swiss cement industry is 4.0 $GJ/ton_{clinker}$ compared to the lower bound of the Best Available Techniques (BAT) of 3.3 $GJ/ton_{clinker}$. This implies that there is room for energy efficiency improvements. Electrical and thermal energy saving result from the upgrade of on-site equipment used in the preparation of raw material (e.g., replacing mills and raw material grinders), for the production of clinker (e.g., upgrading and retrofitting kilns) and cement grinding (e.g., replacing mills).

5.1.2 Methodology

The main data source for this section of the study are Zuberi et al [14] and Obrist et al [15], which have modelled the impacts of energy efficiency measured on the Swiss cement industry.

Based on the data provided by Zuberi et.al on electricity and fuel savings from equipment upgrades, we focus on the retrofit and upgrades to kilns as they yield thermal energy savings which are relevant to this study because they are reflected in on-site direct scope 1 emission reductions. Upgrades to raw material preparation and cement grinding do not impact thermal energy consumption but only electricity consumption which is linked to indirect emissions (out of the scope of this study) [14]. The data given by Zuberi et al. shows the CO2 abatement potential of energy efficiency measures and estimates the remaining utilization potential of these best practice technologies for the Swiss cement industry (i.e. the remaining diffusion) (see Table 4). Multiplying the CO2 abatement and the remaining diffusion potential results in the overall remaining CO2 abatement potential of energy efficiency measures for the Swiss cement industry[4].

Table 4: Impact of energy efficiency measures on CO2 abatement for the Swiss cement industry [14]

	Fuel Savings	**CO2 Abatement**	**Remaining Diffusion**
Clinker production energy efficiency measures	$MJ/ton_{clinker}$	$kg_{CO2}/ton_{clinker}$	%
Changing from lepol kilns to kilns with cyclone preheaters and precalciners	900	64	6%
Upgrade preheater kiln to preheater/precalciner kiln	430	31	42%

These values are then validated with the findings of Obrist et al, which shows that with more efficient precalciners and kilns the absolute energy savings are equivalent to 0.27 $GJ/ton_{clinker}$. This equates to 7% of the 2019 specific final energy consumption, then multiplied by the 30% fuel-related emissions to find the impact on the overall emissions.

[4] Refer directly to [14] and [15] for additional details regarding the values and methodology considered in the respective studies.

The abatement cost of energy efficiency is calculated by subtracting the lifetime fuel savings (operational cost savings) due to fuel efficiency from the additional investment cost ($CHF/ton_{clinker}$) of upgraded kilns with cyclone preheater and precalciner. We use the thermal energy consumption as shown in Table 5 of the old and upgraded technologies respectively to calculate the fuel costs of each over a lifetime of 40 years, with a fuel cost provided by industry experts[5]. We assume a fixed fuel price over the lifetime of the technology. The CO2 abatement cost is then calculated by dividing the cost by the overall CO2 abatement potential.

$$Abatement\ Cost_{Energy\ Efficiency} = \frac{\Delta\ Investment\ cost - Lifetime\ fuel\ savings}{\Delta\ CO2\ emissions\ _{Energy\ efficiency-Baseline}}$$

Table 5: Thermal energy consumption and investment cost of clinker production technologies [15]

	Thermal Energy Consumption	**Investment Cost**
Clinker production technology	$GJ/ton_{clinker}$	$CHF/ton_{clinker}$
Upgraded kiln with cyclone preheater and precalciner	2.164	214
Kiln with cyclone preheater and precalciner	2.44	179
Difference (Δ)	0.276	35

5.1.3 Results

With the information presented in Table 4 from Zuberi et.al, multiplying the CO2 abatement and the remaining diffusion, produces an overall CO2 abatement of approximately 16 $kg_{CO2}/ton_{clinker}$. To verify, the data from Obrist et al yielded an overall CO2 reduction of **2%** equivalent to **16 $kg_{CO2}/ton_{clinker}$** using the baseline of 762 $kg_{CO2}/ton_{clinker}$.

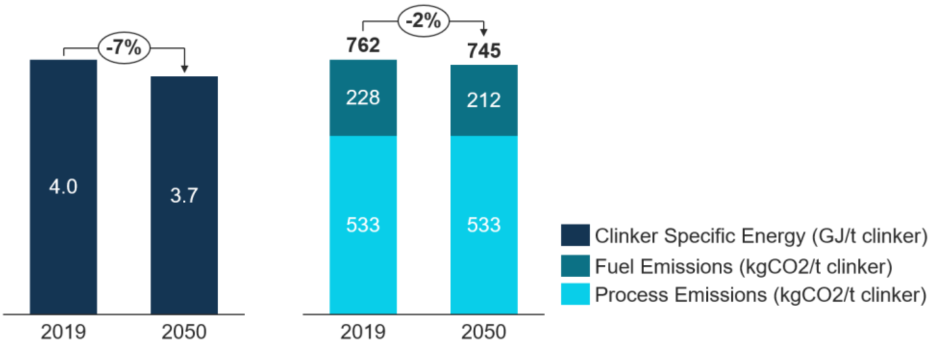


Figure 9: Overall CO2 reductions due to energy efficiency

The abatement cost of energy efficiency considering the additional investment cost for an upgraded kiln with cyclone preheater and precalciner and the fuel savings over 40 years lifetime is **-4 CHF/ton_{CO2}**. This

[5] The average cost of fuel currently used in Swiss cement plants is estimated at 3.14 CHF/GJ based on fuel price inputs from expert interviews.

implies that upgrading equipment is economically attractive as the energy savings pay off the additional investment cost making the cost of CO2 abatement practically zero.

5.2 Alternative Fuels

5.2.1 Background

Transitioning from the combustion of fossil fuels to alternative fuels such as waste and biomass is one of the main strategies Swiss cement producers have used over the years to decarbonize their operations. The most dominant fuel used in the past was coal which has been now replaced with larger shares of waste material such as waste tires and plastics, as well as biomass such as wood waste. Depending on the type of alternative fuels, the availability and quality varies between regions.

In Switzerland, cement plants are prohibited from incinerating municipal waste and problematic special wastes (e.g., chlorinated solvents or paint residues with a high heavy metal content). Permitted, however, is the use of bulk wastes with a low pollution potential and high calorific value (sewage sludge, used oil, used tires etc.) [30]. High fuel substitution rates are technically possible, however some factors must be accounted for, e.g., the low calorific value of most organic materials – requiring further treatment and impact on clinker chemistry from using certain fuels such as PVC or sewage sludge [25].

Biomass is an interesting option for the cement industry as its combustion results in biogenic emissions which are considered climate neutral. Also, the use of bioenergy with carbon capture and storage (BECCS) leads to negative emissions which offers a competitive opportunity for carbon dioxide removal (CDR) offsetting [31]. Today, the share of primary fossil fuels used by the Swiss cement industry is 33%, secondary fossil fuels is 50% and biomass lies at 17%[6].

5.2.2 Methodology

As mentioned previously, significant effort was spent collecting the relevant data to construct a fuel and emissions baseline. This data was consolidated in an excel model allowing for the testing of various fuel consumption scenarios and the resulting impact on the total industry emissions. A breakdown of the fuel emission factors, 2019 fuel consumption and resulting fuel emissions can be found in Appendix A.

We model four future fuel scenarios each at two price points representing the current fuel price and potential future fuel prices. Details regarding the scenarios can be found in Table 6. We extract the emission factors from Switzerland`s National Inventory Report [3] for the listed fuels (natural gas and biomass) and we assume an emission factor of 0 ton_{CO2}/TJ for green hydrogen[7][8]. With the respective emission factors and prices per fuel, we are able to calculate the CO2 mitigation potential and the abatement costs per fuel scenario. We compare the CO2 mitigation potential to the current clinker emission intensity of 762 $kg_{CO2}/ton_{clinker}$. In the biomass scenarios, we also compare the additional biogenic emissions to the current biogenic emissions of 80 $kg_{CO2\text{-}biogenic}/ton_{clinker}$.

For the biomass scenarios (scenarios 3 and 4), we primarily aim to test a more moderate scenario (25% biomass) and the biomass target set by cemsuisse for 2050 (60% biomass). As opposed to other studies, we consider simplified fuel mixes towards both ends of the continuum of possible fuel ratios – i.e. 25% and 60% biomass – rather than complex fuel scenarios in an attempt to present the effects of the individual fuel replacement options. We consider that the initial 17% biomass remains at a cost of 1.47 CHF/GJ and the

[6] As opposed to Figure 6, here we do not consider electricity consumption.

[7] Since the hydrogen emission factor is not listed in the Swiss GHG Inventory [3], and we cannot determine the exact source of green hydrogen procured in the future, we assume an emission factor of 0 ton_{CO2}/TJ for green hydrogen.

[8] While other zero carbon/green alternative fuels such as synthetic liquid hydrocarbons or methane could play role in the future energy mix [33], these options are not considered in this study; in principle, green hydrogen could be seen as a proxy for these zero carbon alternatives from an emissions perspective.

increased price applies to the added biomass capacity. Additionally, we do not change the amount of clinker production or any other variables, meaning that the total energy consumed remains stable in all scenarios.

The availability and prices of biomass are based on the «Biomassenpotenziale der Schweiz für die energetische Nutzung - Ergebnisse des Schweizerischen Energiekompetenzzentrums SCCER BIOSWEET» report [32] which shows the sustainable potential of biomass in Switzerland for primary energy use and their respective prices. Today, the cement industry uses waste wood which according to our interviews with stakeholders, costs around 1.47 CHF/GJ. In the future, and with the rising demand for biomass in other industries, the price of biomass is expected to rise, and the availability of cheaper biomass sources will be limited. Therefore, we assume a future scenario where cement kilns burn biomass at a price of 9 CHF/GJ, around the price of forest hard wood according to the mentioned study. The SCCER Biosweet report also shows that domestically sourced sustainable biomass has the potential to provide almost 100 PJ primary energy per year (see Figure 10) [32]. These values are also adopted in the Swiss "Energieperspektiven 2050+ Exkurs Biomasse" published in 2021 [33]. Today, the cement industry consumes approximately 11.5 PJ of final energy, which in relation to the 100 PJ theoretical sustainable biomass potential does not seem significant. However, considering that the total final energy consumption of the entire Swiss industry was 145 PJ in 2020 [34], we expect high future competition for biomass resources and potentially the need for biomass imports. Additionally, the technical suitability and fitness for use in of the different biomass sources in cement plants needs to be technically addressed.

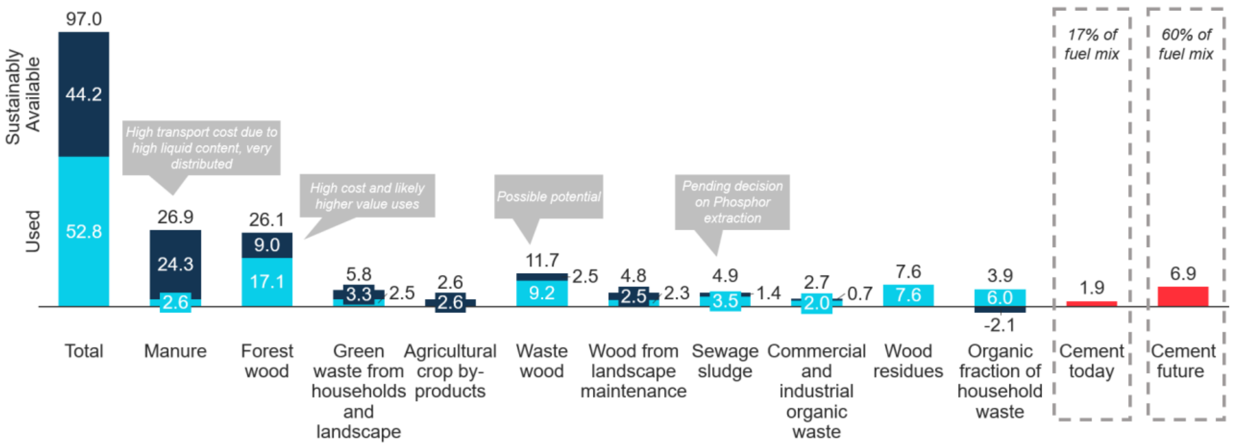


Figure 10: Domestic annual biomass primary energy (PJ/year) potential in Switzerland [32] with the current and potential future demand (PJ/year) for biomass by the Swiss cement industry[9]

[9] The values represent the sustainable biomass potential, i.e. taking into account ecological and technical limitations of biomass usage. Negative values for organic household waste because food waste best be collected and used for anaerobic digestion instead of combustion.

Table 6: Scenarios for modelling the impact of alternative fuels[10]

Fuel Scenario		Description	Fuel Prices	
			Current	Potential Future
1	**Green hydrogen**	Replacing all primary fossil fuels (33% of the fuel mix) with green hydrogen	Green hydrogen = 5 CHF/kg = 42 CHF/GJ[11] [35]	Green hydrogen = 2 CHF/kg = 17 CHF/GJ[10] [35]
2	**Natural gas**	Replacing all primary fossil fuels (33% of the fuel mix) with natural gas	Natural gas = 7.5CHF/GJ[12]	Natural gas = 15 CHF/GJ[13]
3	**Biomass 25%**	Increasing the share of biomass from 17% to 25% by replacing primary fossil fuels	Waste wood = 1.47 CHF/GJ[11]	Forest hard wood = 9 CHF/GJ [32]
4	**Biomass 60%**[14]	Increasing the share of biomass from 17% to 60% by replacing primary fossil fuels	Waste wood = 1.47 CHF/GJ[11]	Forest hard wood = 9 CHF/GJ [32]

5.2.3 Results

To summarize, the results of our model show that substituting primary fossil fuels with biomass could be an affordable and effective decarbonization lever even at high future biomass prices (9 CHF/GJ).

With an assumed current green hydrogen price of ~5 CHF/kg$_{H2}$, replacing all primary fossil fuels with H2 results in an abatement cost of 406 CHF/ton$_{CO2}$. A future price of 2 CHF/kg$_{H2}$ brings the cost to 137 CHF/ton$_{CO2}$. With an emission factor of zero, replacing the 33% primary fossil fuels with green hydrogen reduces the overall clinker emissions by 108 kg$_{CO2}$/ton$_{clinker}$ or 14% compared to the 762 kg$_{CO2}$/ton$_{clinker}$ bassline.

In the natural gas scenario and with a gas price of 7.5 CHF/GJ, replacing all primary fossil fuels with natural gas results in an abatement cost of 89 CHF/ton$_{CO2}$ and reduces emissions by 42 kg$_{CO2}$/ton$_{clinker}$ or 6% This is primarily due to the difference in CO2 intensity between the most used primary energy sources lignite/coal and natural gas. A potential future price of 15 CHF/GJ drives the abatement cost up to 293 CHF/ton$_{CO2}$.

Increasing biomass share to 25% and 60% by replacing primary fuels saves money (~30 CHF/ton$_{CO2}$) with the current price of 1.47 CHF/GJ biomass. This is true because the current cost of primary fossil fuels, primarily coal, is estimated to be 4.2 CHF/GJ as provided by an expert interview with a cement producer. If the price of biomass increases to 9 CHF/GJ, the abatement cost increases to 60 CHF/ton$_{CO2}$, still lower than the lower bound of both the green hydrogen and natural gas scenarios. The impact of this action is a 3% and 17% drop in total emissions respectively. To be considered in the biomass scenarios are the higher share of biogenic emissions which in combination with CCS allows for more CDR credits and additional

[10] Emission factors for natural gas and biomass can be found in Appendix A. Green hydrogen is assumed to have an emission factor of 0 ton$_{CO2}$/TJ.

[11] Calculated using the gravimetric energy density of hydrogen 120 MJ/kg$_{H2}$

[12] These fuel prices are provided via an expert interview with a Swiss cement producer

[13] Since natural gas is a commodity with volatile prices, we assume a scenario with the price of the price doubling in the future

[14] This is the scenario adopted by cemsuisse in their Roadmap 2050 report [41]

revenue. In scenario 3, with 25% share of biomass, biogenic emissions increase by 34% whereas in scenario 4 with 60% biomass, biogenic emissions increase by 175% compared to the 80 $kg_{CO2\text{-}biogenic}/ton_{clinker}$ baseline.

The abatement costs can be compared to the ETS CO2 price which is around ~86 CHF/ton_{CO2} at the time of writing this report [36]. This comparison gives companies an idea of whether it is more cost effective to implement the mitigation measure or purchase ETS credits, keeping in mind that the ETS CO2 price is expected to rise in the coming years. At an exchange rate of 1.07 CHF/EUR, the substitution of primary fossil fuels with biomass is economically attractive even at higher prices. At the moment, the cement industry in Switzerland - and the EU - receive free allowances to protect them from carbon leakage under the ETS. This implies that today, even if the CO2 abatement cost is less that than the CO2 price, cement companies may not have a financial incentive to implement the mitigation option since the company currently does not necessarily pay the price of their CO2 emissions[15]. But with the discussions in the EU to phase out free allocations starting 2026, the comparison with the ETS CO2 price becomes highly relevant. This will be discussed in further detail in Part 2 of the report.

Since fuel-related emissions from Swiss cement are equivalent to 30% of the total scope 1 emissions, even a full decarbonization of the fuel mix will yield a maximum CO2 abatement of 30%. Thus, alternative fuels need to be combined with other mitigation technologies to get to net-zero by 2050. The combination of biomass and CCS can push beyond this 30% reduction with negative emissions as will be seen in the Chapter 7.

Table 7: Results of the alternative fuel modelling[16]

Fuel Scenario		**CO2 Abatement**		**CO2 Abatement Cost**		**Additional Biogenic Emissions**	
		$kg_{CO2}/ton_{clinker}$	% reduction	CHF/ton_{CO2}		$kg_{CO2\text{-}biogenic}/ton_{clinker}$	% addition
				Current Fuel Prices	**Potential Future Fuel Prices**		
1	**Green hydrogen**	108	14%	406	137	0	0%
2	**Natural gas**	42	6%	89	293	0	0%
3	**Biomass 25%**	25	3%	-29	60	27	34%
4	**Biomass 60%**[17]	130	17%	-29	60	141	175%

5.3 Clinker Substitution

5.3.1 Background

Clinker substitution involves the reduction of the amount of clinker in the cement mixture i.e., minimizing the clinker-to-cement ratio. Ordinary Portland Cement (OPC) also known as CEM I contains 95% clinker.

[15] The companies pay for the emissions that exceed a certain benchmark.
[16] The current baseline cement emission intensity is 762 $kg_{CO2}/ton_{clinker}$ and 80 $kg_{CO2\text{-}biogenic}/ton_{clinker}$
[17] cemsuisse considers 60% biomass in 2050 in their Roadmap 2050 report.

Substituting clinker reduces the emissions associated with the production of clinker. Supplementary cementitious materials (SCMs) react chemically with water or with water and hydrated cement paste to form additional strength-bearing phases, densifying the microstructure of the concrete [37]. SCMs can be natural materials such as natural pozzolans or limestone (filler), waste, industry by-products such as granulated blast furnace slag (GBFS) and fly ash. The European cement standard EN197-1 lists the 27 types of cements ranging from a clinker-to-cement ratio of 5% to 95% [38].

Today, more than 80% of SCMs used to reduce the clinker in cement are limestone, fly ash or GBFS. Limestone, globally abundant, can only be substituted up to 10-15% due to its limited reactivity [39]. Unreactive limestone content can be increased if combined with other reactive SCMs. The availability of fly ash and GBFS, by-products of coal power plants and steel production respectively, are expected to decrease in Europe as coal plants are decommissioned and steel is increasingly recycled. This phenomenon will impact the availability, quality and price of these SCMs, making it difficult for cement producers to rely on this approach.

There also exist demand side barriers to the use of SCMs. Many SCMs have been proven to improve long-term strength and performance of concrete, however low early stage strength of high-blended cements is a concern [8]. This is especially challenging in the building industry with its low profit margins, as additional curing time has a significant impact on the project budget. Researchers are actively working on improving early-stage strength of blended cements. Novel products such as highly blended cements are perceived by the customer as too risky, costly and difficult to use [6]. Therefore, market side barriers exist to their full-scale deployment.

Table 8: List of SCMs [6]

SCM[18]	**Definition**
Gypsum *(calcium sulphate)*	A soft sulphate material required to control how cement hardens. Gypsum is added to clinker, 3–5 % of the mix, to form OPC.
Limestone	Limestone can be blended with clinker to reduce the final clinker content of cement. Usually regarded as a filler, it is also reactive.
Calcined shale / clay	A fine-grained sedimentary rock formed of clay minerals, can be used as an SCM when calcined.
Granulated blast furnace slag (GBFS)	By-products of iron- and steel- making, quenched in water or steam to produce a sand-like granular product. Mixed into cement.
Fly ash	A coal combustion product composed of fine particles carried out of the boiler by flue gases in power plants.
Industrial sludge	A semi-solid slurry produced from wastewater from industrial processes.

[18] Other SCMs exist such as volcanic rocks, silica fume, rice hull/husk ash, forms of agricultural and industrial waste etc.

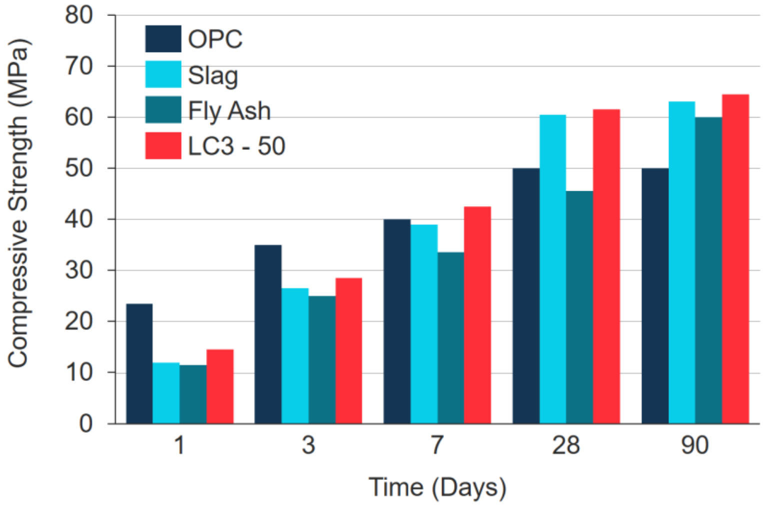


Figure 11: Strength development of blended cements in comparison to OPC [40]

An interesting and yet unexploited blended cement in Switzerland is limestone calcined clay cement LC3 which has been developed and heavily researched at EPFL in Switzerland. LC3 is a mixture of clinker, calcined clays, limestone and gypsum. Clay calcination does not produce process emissions and calcination occurs at ~800°C compared to limestone at ~1,450°C, requiring 20% less thermal energy. Calcination of the clay allows for higher substitution rates, up to 50%. However, LC3 requires kaolinite-rich clays which are not globally readily available and for which there is no public information regarding availability in Switzerland. Cement companies in Switzerland are independently testing the possibility of producing LC3 and brining it on the market in the upcoming years.

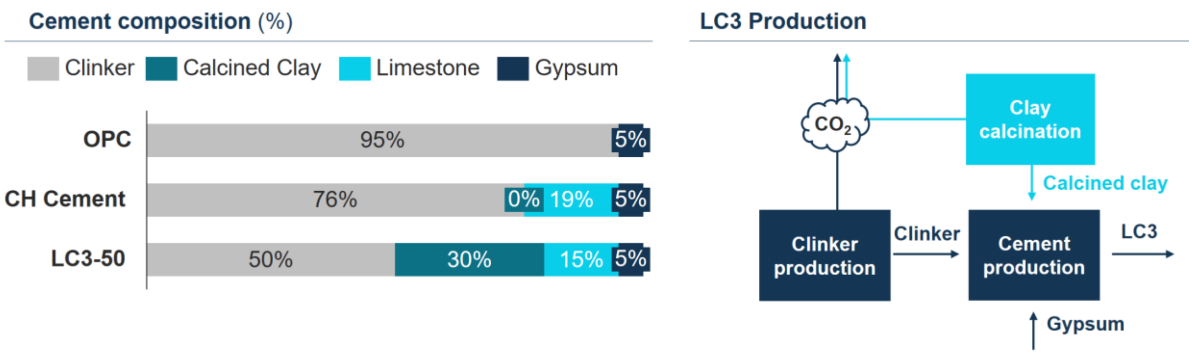


Figure 12: Composition and production of LC3

5.3.2 Methodology

A literature review of the existing SCMs, their global and local availability, and prices was performed to understand the future potential of blended cements in decarbonizing Swiss cement. It is imperative to quantify the availability of SCMs and estimate the distance to Swiss cement plants as transport has an economic tradeoff on profitability. The prices of the most relevant SCM are retrieved from exchanges with cement producers in Switzerland, as they have the values for the materials delivered to Switzerland.

An expert interview performed with Prof. Karen Scrivener who is leading the Construction Material Lab at EPFL, provided useful insight into blended cements and LC3 specifically. Discussions with cement producers also yielded insights into their ongoing efforts in detecting kaolinite-rich clays near their production sites.

The calculation of the abatement cost is in line with previous sections. Since blended cements involve the substitution of clinker, the cost of SCMs is compared to the current cost of clinker which is approximately 75 CHF/t clinker[19] to calculate the operational cost. We use fly ash delivered in Switzerland as a proxy for SCMs, with a price of 110 CHF/ton[20]. We assume a substitution rate of 1:1 for the purpose of this study[21] and disregard any emissions attributed to SCMs as this is beyond the scope of this study and since fly ash and GBFS are waste materials from other industries[22]. We assume no major changes to the equipment on site and thus no additional capital costs[23].

Overall low clinker-cement ratios of around 50% - 55% as suggested by some literature sources, are difficult to achieve for economic and logistical reasons in Switzerland. Thus, a clinker-cement ratio of 65% is considered possible in the Swiss case compared to today`s ratio of ~76% given the relaxation of regulations and market demand stimulation [14]. This assumption is in line with the 62% clinker-cement ratio for 2050 considered by cemsuisse in the Roadmap 2050 report [41].

5.3.3 Results

In Switzerland, the use of SCMs is well established as it has been one of the main strategies to decarbonize the sector. Today, the share of CEM I [42] is only around 7% of the total cement production whereas CEM II [37][38] has more than 90% market share. The composition of the most commonly used cements can be found in Appendix B. Swiss cement producers claim to have reached the substitution limits permitted by concrete standard, thus further clinker substitution is limited unless the norm is modified. Use of EN 197-1 cements is limited in certain exposure classes within the national annexes to concrete standard EN 206-1, which in Switzerland is the SIA 262/1. These limitations will be discussed in further detail in Part 2 of the report.

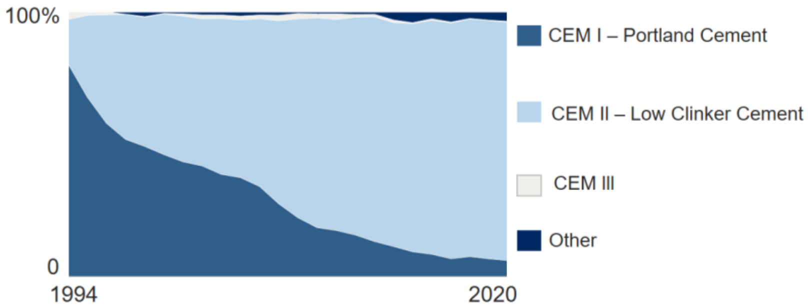


Figure 13: Cement delivered according to type in Switzerland

In Switzerland, there are no sources of GBFS, fly ash or natural pozzolans. The industry has relied on limestone as a filler material and on small fractions of burnt oil shale which is imported from across the

[19] This value results from our CCS model which will be discussed later in this report. The value was confirmed with Swiss cement producer.
[20] We do not consider LC3 in our calculations because to date there is no public information regarding the availability or price of kaolin-rich clay in Switzerland.
[21] According to a cement expert: "The replacement ratio depends on the performance. Slag and fly ash typically react slower than clinker. In order to reach the same compressive strength after 28 days you need twice as much slag/fly ash as clinker (the concrete norm specifies respective k values for slag of 0.5 and fly ash of 0.4). After a longer curing period slag and fly ash can achieve similar compressive strength as clinker i.e. a substitution ratio of about 1t:1t holds in the long run."
[22] To avoid double accounting
[23] Additional equipment may include extra grinding and storage capacity according to expert interviews.

border in Germany. Due to the lack of locally available SCMs, this material needs to be imported. We were able to retrieve actual prices of some SCMs delivered in Switzerland (e.g., slag and GBFS) as well as data on their availability (see Table 9). The prices range from 100 – 130 EUR/ton, almost double the cost of clinker (75 CHF/ton$_{clinker}$). The replacement of clinker with SCMs eliminates all clinker-related emissions. With this in mind, the abatement costs, with an SCM price of 110 CHF/ton, is equivalent to **46 CHF/ton$_{CO2}$**. Also, the reduction from a 76% to 65% clinker-cement ratio generates a CO2 abatement of **14%** equivalent in absolute value to **107 kg$_{CO2}$/ton$_{clinker}$.**

Table 9: Price, availability and potential replacement rates of different SCMs

SCM	**Price**[24] [6][8]	**Availability**[14] [9][6]	**Theoretical Substitution Rate** [38]
Limestone	~6-9 CHF/ton in Switzerland	Widely available and used heavily by cement industry i.e., supply established. However, non-reactive filler material so limited replacement in cement.	1–20%
Clay	13 (common clay); 150 (kaolin); 600-700 USD/ ton (metakaolin)	Clays available in Switzerland, kaolin content is generally unknown. Some existing raw material pits have been tested but do not contain sufficient quantities or are of medium quality. Greenfield pits face multiple hurdles. Brick manufacturers not able to supply quantities required by cement industry.	Calcinated clay 30% + 15% limestone
Granulated blast furnace slag (GBFS)	110-130 EUR/ton delivered in Switzerland	Global annual availability 330 million tons of which ~290 million tons in use. ~90% of used slag already used in cement/ concrete. Availability likely to decrease due to increased availability of scrap steel and the use of alternative steelmaking methods. Steel industry lobbying to allocate a fraction of their emissions to slag (burden sharing/ accounting), making slag an unattractive SCM for cement.	90%
Fly ash	100-120 EUR/ton delivered in Switzerland	Global annual availability 600-900 million tons of which 300 million tons in use (1/3 of total). Reserve available volume varies in quality and mostly has low performance. Seasonal availability varies. With coal consumption dropping in Europe, future fly ash availability decreases.	35%
Natural pozzolans	35–90 USD/ton	Available globally but localized. Not available in Switzerland.	55%

The application of LC3 in Switzerland has not been established yet. A large deposit of kaolinite-rich clay is available in the south of Germany in the Munich area, however due to the local nature of cement production, the transport distances are considered too large. Individual cement producers are testing clay deposits

[24] The prices for material delivered in Switzerland and their availability are provided by industry stakeholders

around their production site for kaolinite content, yet there have been no significant discoveries so far. Cement producers also mention that in case a suitable clay deposit is found, establishing a new mining pit is tedious due to the environmental regulations and public pressure. Calcined clay and limestone are allowed in European standard EN 197-1 to a 65% clinker content (CEM II/B-Q) [38]. The 2021 extension of this standard with the optimal LC3 formula with 50% clinker is in revision this year and should enter the standard under CEM II/C-Q [45]. In case this is passed on an EU level, it would need to be transposed into the Swiss norm. More on this in Part 2 of the report.

5.4 Alternative clinkers

5.4.1 Background

Cement-Carbon Cycle

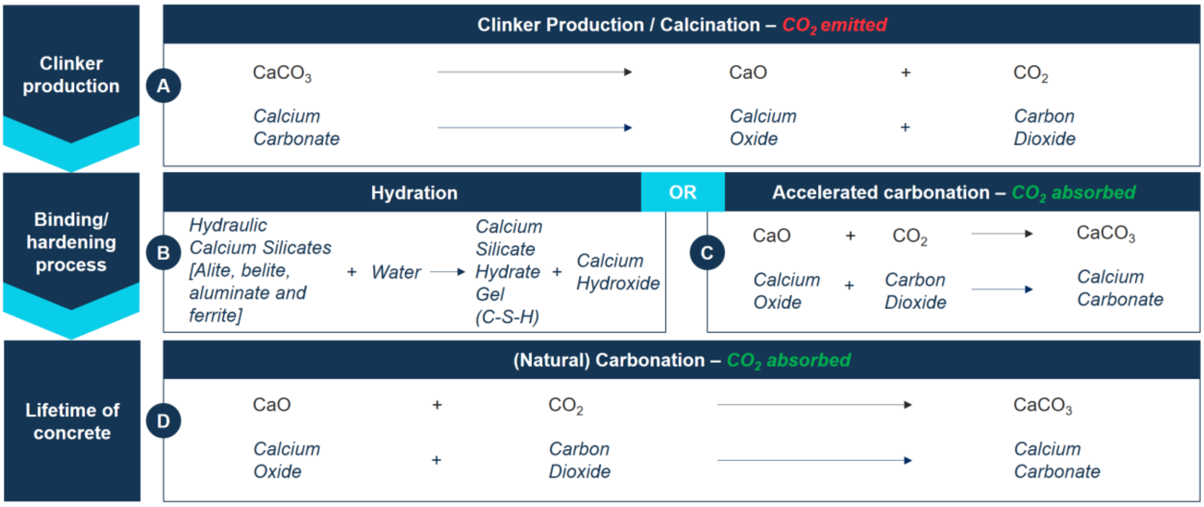


Figure 14: Cement-Carbon Cycle

The cement carbon cycle shows the different phases of the reactions between cementitious materials and CO2 (see Figure 14):

A - Clinker production/ Calcination

During clinker production, CO2 is emitted as limestone (calcium carbonate) decomposes into lime (calcium oxide) and CO2. Lime continues to react in the kiln to produce clinker which is a combination of hydraulic calcium silicates (alite, belite, aluminate and ferrite). The corresponding chemical reactions can be seen in Figure 3 in the report introduction. The composition of the raw meal into the production process dictates the formation of and ratio of hydraulic calcium silicates. Alternative binders as will be discussed in this chapter have different ratios of these silicates.

B – Hydration

Binder systems[25] harden either through hydration or carbonation curing. Hydraulic binders harden in the presence of water. Most conventional concrete is produced using hydraulic binder based on OPC. The hydration reaction and hardening of concrete occurs over days or even weeks until the concrete reached

[25] Cements acts as a binding agent in concrete. We refer to cements as binder systems.

adequate strength. Yet after one day, mechanical properties are already good enough to allow for the removal the frame formwork onsite.

C – Accelerated carbonation

Some binders harden through carbonation curing. The material is exposed to high concentrations of CO2 which reacts with calcium oxide to form calcium carbonate. CO2 is thus encapsulated, in a reversed reaction to the calcination process in "A". Theoretically, all process emissions emitted in clinker production can be reabsorbed through carbonation [46]. This has yet to be achieved in reality. Different start-ups are working on accelerated carbon curing (ACC) as will be discussed later in this study. Carbonation inhibits the ability of concrete matrix to protect steel reinforcement and thus ACC is not used for structural applications [47]. Most common use of ACC today is for non-steel-reinforced precast concrete elements as they are cured in specialized chambers (discussed in section 6.1)[26].

D – (Natural) Carbonation

Since traditional hydraulic binders such as OPC are based on calcium compounds, they too react with CO2 over their lifetime to produce calcium carbonate. Therefore, concrete elements act as a carbon sink. This process is very slow and takes decades (see text box below for more information).

Natural Carbonation

Calcium oxide in cement materials is thermodynamically unstable over time and reacts with and reabsorbs atmospheric CO2 through a physiochemical process called carbonation (CaO + CO2 <-> CaCO3), reversing the calcination process occurring during the production of clinker. The relevant equations can be seen in Figure 14 of the cement carbon cycle, where equation "D" is for natural carbonation process and equation "A" displays calcination. CO2 diffuses into the pores of cement-based materials such as concrete or mortar starting at the surface and gradually moving inwards. Natural carbonation can theoretically absorb 100% of cement process emissions, however this would require decades for completion. This has adverse effects on the structure performance as the porosity increases slightly and the amorphous phases with the calcite are not in binding phases.

Carbonation occurs at different speeds. It occurs at a faster rate in non-reinforced concretes and porous and thin applications such as mortar and concrete blocks. More porous material has a higher air exposure and can therefore take up more CO2. Demolished reinforced concrete left exposed to the air has an accelerated CO2 uptake due to the larger surface area exposed to the air.

A study by Xi et al. [48] attempts to quantify the global CO2 uptake by cement carbonation. It assesses the total quantity of cement uptake between 1930 and 2013. The results show that the CO2 sequestration rate increases annually and the total carbonation during that period amounts to almost 43% of cement process emissions. Applying this to Switzerland where cement process emissions are equivalent to 70% of scope 1 emissions, yields a theoretical natural CO2 uptake equivalent to up to 30% of total cement emissions over 80 years.

Nevertheless, the IPCC Guidelines for National GHG Inventories do not consider carbon absorbed by natural carbonation of cement-based products. Therefore, cement companies cannot rely on natural carbonation as a decarbonization lever [49]. The natural CO2 uptake also depends on a variety of factors including surface exposure, climate conditions, structure lifetime and more, it is also out of the control of cement producers.

[26] Precast concrete elements represent 5% of the Swiss cement supply [53]

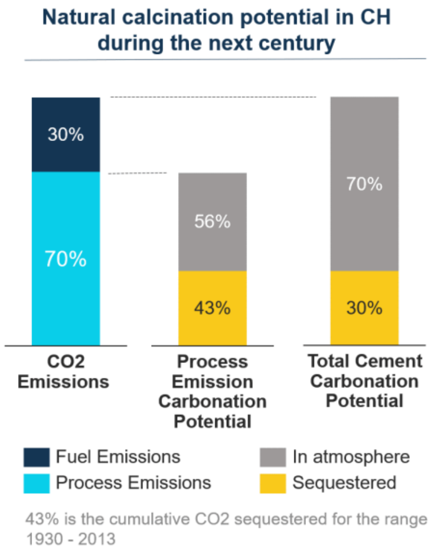


Figure 15: Natural carbonation potential in Switzerland during the next century

Alternative clinkers

Alternative clinkers, also known as alternative binder systems, are manufactured materials that are able to harden through hydration or/and carbon curing CO2 and act as binders for concrete potentially replacing OPC clinker for specific applications. Over the years, there has been a growing interest in academia and industry in developing such binder systems as a means to reduce cement emissions. The main barriers relating to alternative clinkers are the availability of raw material and the low mechanical properties and uncertainties regarding durability of these binders.

Table 10: List of relevant alternative clinkers

Alternative Clinker	Binding/Hardening Process	Description
Reactive Belite-rich Portland cement (RBPC)	Hydraulic curing	Clinker based on belite rather than alite, produced with the same process as OPC but with lower limestone content and lower clinkering temperature thus reducing emissions. These clinkers rely on hydration curing.
Calcium sulfoaluminate (CSA)	Hydraulic curing	Clinker based on belite with ye'elimite or calcium sulphoaluminate, produced with the same process as OPC but with lower limestone content and more aluminum, lower clinkering temperature thus reducing emissions. These clinkers rely on hydration curing.
Belite-Ye'elimite-Ferrite (BYF)	Hydraulic curing	Clinkers based on belite, ye'elimite and ferrite, produced with the same process as OPC but with lower clinkering temperature and energy requirements for grinding. BYF clinkers are a subset of CSA clinkers. These clinkers rely on hydration curing.

Carbonatable calcium silicate clinkers (CCSC)	Accelerated carbonation curing	Clinkers based on low-lime calcium silicates (e.g., wollastonite), produced with the same process as OPC. These clinkers rely on carbonation curing and thus can only be applied on precast concrete elements.
Hydrated Magnesium Carbonate (HMC)	Hydraulic curing Accelerated carbonation curing	Clinkers based on magnesium oxide, generally by calcinating natural magnesite, a process that is highly carbon-intensive. Theoretical CO2-negative potential (absorb more CO2 than is released) [50]. These clinkers rely on hydration and carbonation curing. Very early stage, unclear whether application is limited to pre-cast.

OPC has a high alite content which was driven by the market need for rapid hardening concrete. Higher alite content entails higher CO2 emissions. Belite-rich RBPC has lower early-stage hydration making it suitable for mass and heavy strength concrete such as damns. It is included in most cement norms but is limited by market demand. CSA has been commercialized and in use in China where it has been on the market since the 60s while in Europe it only recently (20 years) sparked interest due to its potential CO2 savings. In the recent years more research has been done in Europe on CSA, yet there is no compositional framework (standards) outside of China to date and is currently being drafting in the EU. The remaining alternative clinkers listed in Table 10 are still in research and development or pilot phase.

5.4.2 Methodology

We aim to calculate the CO2 saving potential of each of the alternative clinkers listed in Table 10 when applied to the Swiss cement industry. In order to do so, we calculate the fuel and process emissions of the various alternative binders compared to OPC and apply these savings to the Swiss clinker emission baseline.

We extract data on the clinker phase enthalpy of formation and process emissions of the different binder systems from Gartner et al [47]. The enthalpy of formation is used to calculate the fuel savings as it is approximately proportional to fuel consumption in the case of efficient dry-process kiln. From the same study we obtain the composition of different binder systems including OPC. The manufacturing enthalpy, process emissions and clinker composition can be found in Appendix C - Table 25 .

For every binder system, including OPC, we calculate the process emissions by multiplying the composition by the respective process emissions of the clinker phases. The same method is used for fuel consumption. The difference in process emissions and fuel consumption between OPC and the alternative binder system represents the potential abatement. These savings are applied to Swiss cement emissions which are 225 $kg_{CO2}/ton_{clinker}$ and 537 $kg_{CO2}/ton_{clinker}$, for fuel and process emissions respectively (total of 762 $kg_{CO2}/ton_{clinker}$).

Due to the early-stage development and patents of alternative binder systems, we had to rely on the information available for CSA, the most advanced and commercial alternative clinker, in order to calculate the abatement cost.

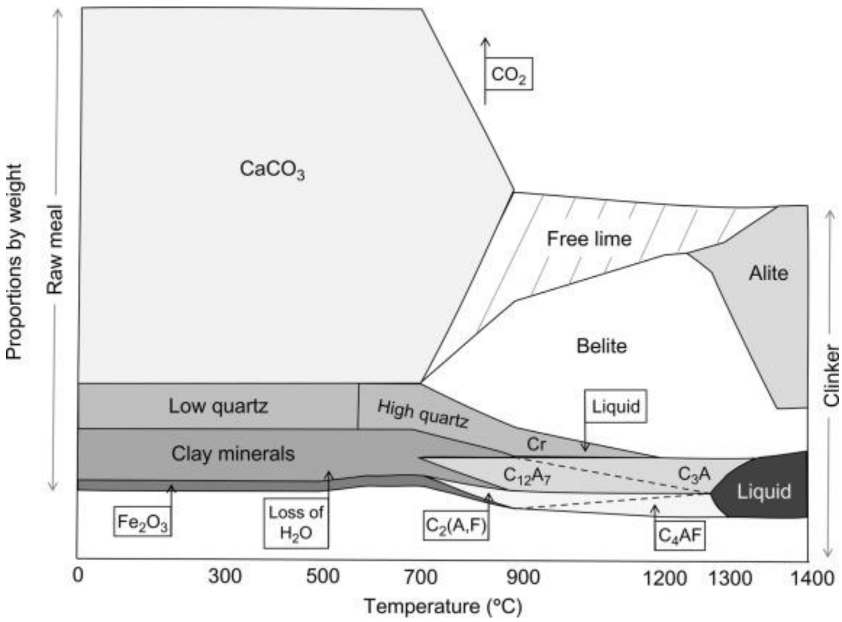


Figure 16: Formation of calcium silicates in the clinker production process [19]

5.4.3 Results

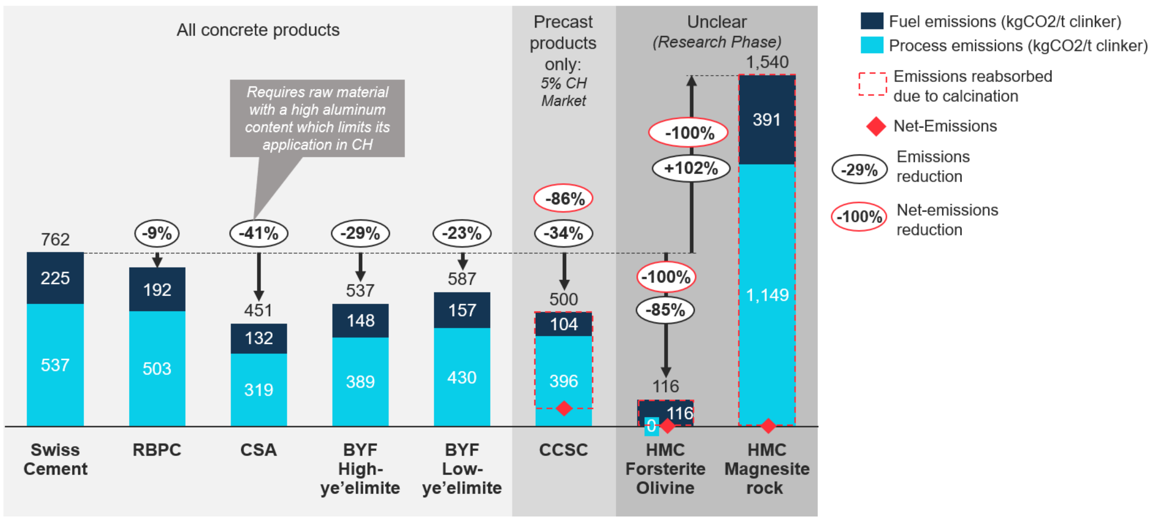


Figure 17: Theoretical CO2 reduction potential of alternative clinkers for the Swiss cement industry

RBPC[27]

RBPC uses the same raw material as OPC but with different proportions of raw material affecting the alite/belite ratio. Belite is the most abundant phase which results in lower process and fuel emissions as can be seen in Table 25. Our calculations show that RBPC can reduce clinker emissions by 9% in Switzerland. The ideal clinkering temperature is 1,350°C compared to the 1,450°C required by OPC (see Figure 16 for an illustration of the formation of clinker phases). RBPC can be produced using the same equipment as OPC but required additional grinding post-manufacturing. Some of the main characteristics of RBPC compared to OPC include: (i) lower water demand, (ii) early strength gain with higher long-term strength, (iii) similar setting times, (iv) lower heat of hydration and (v) improved sulfur and chloride resistance. It is used in China for large pour applications such as dams and meets the cement standard. The cost of production is estimated to be similar to OPC as it required no additional equipment and uses the same raw material. To be kept in mind is that the partial shift in capacity from OPC to RBPC in one plant will result in an interruption in the stable production process of cement, leading to inefficiencies. Also, this shift will require changes in operational processes, training and equipment.

CSA and BYF

Both CSA and BYF can be manufactured in existing cement plants. BYF is an intermediate between CSA and OPC, with CSA having a higher ye'elimite content thus requiring expensive aluminum-rich materials such as bauxite. An initial search on the Swiss Resource Information System (RIS) [51] reveals that bauxite/aluminum-rich rocks are found in 3 locations in Switzerland (Spillgerten, Amselgrat, Dréveneuse). The price of CSA is three times as expensive as OPC in Europe according to one expert (~300 CHF/ton). CSA is used in special applications which require rapid strength development and shrinkage compensation. BYF development was driven by the need to reduce the cost of CSA by using less costly material and providing a product more versatile and suitable to the conventional concrete market. BYF requires less-concentrated sources of aluminum usually found in bauxites, clay and fly ash. The extra raw material requires transportation to the cement plant and is usually more expensive than limestone making BYF pricier than OPC. BYF differs from OPC in that it sets rapidly requiring some chemical additives and user training. In Switzerland, 41% and 23-29% of cement emissions can be saved by transitioning to CSA and BYF respectively. Today, however, BYF is not yet commercially produced.

CCSC

Binders based on calcium silicates can harden through hydration or carbonation. Research has focused on accelerating the carbonation process in controlled environments while ensuring a uniform hardening profile. Wollastonite is a calcium silicate mineral that can be found in certain locations across the globe but is not common and can be used in the production of CCSC [52]. Such binders are too unreactive to harden by hydration and therefore require rapid carbonation [8]. Accelerated carbonation or ACC occurs in air-tight curing chambers under certain atmospheric conditions (temperature, humidity and ventilation) where the concrete elements are exposed to high concentrations of CO2. Thus, CO2 is stored in these concrete elements. This method can therefore only be applied to pre-cast concrete products with smaller cross-sections (e.g., blocks, tiles and pavers). Conventional curing chambers can be converted to CO2 curing chambers requiring a certain investment [7]. The binder can be developed in conventional OPC manufacturing plants and is in early-stage commercialization.

A Swiss RIS search confirms wollastonite in one location in Switzerland (Claro, Ticino). Yet, an interviewed geology expert[28] believes that there may be other sources of this calcium silicate mineral in Switzerland that have not been entered into the RIS database as not all mineral phases are mentioned. Therefore, the availability needs to be confirmed in geological studies. As for the CO2 impact, the production of CCSC applied in Switzerland saves 34% of cement emissions. Yet, in theory, all process emissions can be re-

[27] Appendix C contains additional information on alternative clinkers

[28] Expert from Netzwerk Mineralische Rohstoffe Schweiz (NEROS) and ETHZ Georesources Switzerland Group

absorbed through ACC and yield a net-emission reduction of 86% compared to the 762 $kg_{CO2}/ton_{clinker}$. Pre-cast products only make up 5% of the total cement supply in Switzerland, limiting the extensive use and impact of this binder in the market [53]. Looking back at the numbers from 2008 to today, these products have historically also been between 5-6 % of the market. Also, as mentioned previously, ACC can only be applied to non-steel-reinforced concrete elements and requires the supply of CO2 that can theoretically be sourced on- or off-site.

HMC

Magnesium oxide (MgO)-based cements that harden through carbonation similar to CCSC have also been proposed as an alternative to OPC. From an emissions perspective this is valid depending on the source of raw materials. MgO is often manufactured from magnesite rock which releases an exorbitant amount of process emissions as can be seen in Figure 17 (even larger than those of OPC). Basic magnesium silicate rocks such as olivines are another source of MgO which is globally available but not as well distributed as limestone. However, the unresolved challenge is the industrial manufacturing of MgO from these rocks. We calculate the environmental performance of both options in the Swiss context: HMC from magnesite rock produces double as much CO2 as OPC, whereas forsterite olivine sourced MgO-cement emits 85% less CO2. It is believed that these binders can however absorb more CO2 through carbonation than emitted through production, making them CO2-negative. This has yet to be proven and requires years of research. Additionally, the material properties of HMC based on today`s research are very low according to one expert.

Hardening through carbonation implies that HMC cements is also limited to pre-cast concrete products as in the case of CCSC [47]. Yet there is not enough public information to confirm this and the technology is very early stage. The durability of MgO-based cements is also an open question in addition to the production process which will most likely require a different process compared to OPC.

To sum up the listed alternative clinkers, although many of them have the potential to reduce CO2 such as BYF and CSA, there are still multiple hurdles to overcome including local raw material availability, price, TRL, standardization and most importantly market acceptance and diffusion. Given these constrains, we assume a market penetration of around 12% by 2050 (refer to Appendix C for additional details regarding alternative clinkers).

To calculate the abatement cost of alternative clinkers, we rely on the price of CSA as an indicator. The given price of CSA in Europe is roughly 300 EUR/ton_{CSA} according to an interviewed cement producer. Our calculations show that the cost of cement in Switzerland to be around 100 CHF/ton_{cement}. The capital costs are assumed negligible as the same facility and equipment can be used to produce OPC and CSA. With a CO2 reduction potential of 41%, this results in an abatement cost of 487 CHF/ton_{CO2}. If the price of CSA drops by 50%, the CO2 abatement cost reduces to 158 CHF/ton_{CO2}. As for the abatement potential, with a market share of 12%, 38 $kg_{CO2}/ton_{clinker}$ can be saved corresponding to 5% of today`s Swiss cement emissions.

5.5 Carbon Capture and Storage (CCS)

5.5.1 Background

CCS has been found in multiple studies to be the technology that as the largest potential to decarbonize the cement industry [54]. Solutions that are available today have already been exploited to a certain extent. Although there is remaining CO2 saving potential as we saw in the previous sections, none of the technologies will result in a deep decarbonization of the industry. CCS prevents CO2 from entering the atmosphere. It requires the separation of CO2 from the cement plant flue gas, where this CO2 is later transported and stored or used in other applications. Although not deployed yet at commercial scale in the cement industry, the power and industrial sectors have experience with CCS installations of a cumulative annual capture of 40 million tons CO2 [54].

Various CCS technologies exist that can be introduced in a cement production process. They are either classified as post-combustion or integrated technologies, meaning that the CO2 is either captured at the flue gas or during the cement production process in an integrated fashion. The capture technologies assessed in this report include:

1. **Monoethanolamine (MEA) Absorption:** A post-combustion technology, where CO2 is absorbed from the flue gas with MEA solvent. Flue gas is cooled and SOX emissions removed by scrubbing. MEA solvent comes in contact with the flue gas and absorbs the CO2. The solvent splits from the CO2 and is regenerated in the desorber unit. CO2 is compressed/ liquefied to reach transportation specification. Heat and power are required for MEA regeneration, fans, pumps, and compression [7][10].
2. **Chilled Ammonia Process (CAP):** Operates similarly to the MEA technology, but requires additional power to chill the ammonia.
3. **Membrane-Assisted CO_2 Liquefaction (MAL**): Also a post-combustion technology where CO2 is absorbed using polymeric membranes resulting in a moderate CO2 quality and thus requiring liquification. This approach only requires electric power.
4. **Oxyfuel:** As opposed to the previously mentioned solutions, this technology requires the modification of the cement kiln as atmospheric conditions need to be different. Kiln fuels are burned in the presence of pure oxygen (oxyfuel conditions) rather than air to produce a flue gas with high CO2 concentrations. The gas atmosphere of the pre-heater, calciner, rotary kiln and the clinker cooler is changed to sustain oxyfuel conditions. An air separation unit requires additional power [10].
5. **Calcium looping (CaL):** This approach is based on the carbonation reaction and can be installed in two formats:
    a. **Tail-end configuration:** A post-combustion solution where **f**lue gas is sent to a separate carbonator and the CO2 is removed via the reaction with CaO (carbonation). Sorbent regeneration occurs in the distinct CaL calciner where coal is burnt under oxyfuel conditions. The resulting CaO-rich purge is used as raw meal.
    b. **Integrated:** Same concept applied ask in the tail-end configuration, but the CaL calciner is combined with the existing cement plant kiln calciner. The calciner must be retrofit to operate under oxyfuel conditions. This configuration is more efficient but requires significant changes to the cement plant and operational down-time.
6. **Low Emissions Intensity Lime and Cement (LEILAC):** Applicable only to new cement plants, LEILAC is the newest CCS technology developed in an EU Horizon 2020 project. CO2 capture occurs without contact with air or flue gases, abolishing the need for separation and the associated energy penalty. A Direct Separation Reactor (DSR) substitutes the conventional calciner and the raw meal is heated by both conductive and radiative heat transfer from the reactor wall causing it to calcine [7]. Since the DSR replaces the calciner, LEILAC is usually considered as a capture technology for new plants but can be installed in existing plants in case of deep retrofits. It captures only process emissions but can be coupled with other post-combustion capture for fuel emissions.

LEILAC

The LEILAC technology is demonstrated at a Heidelberg Cement plant in Belgium with a capacity of 25,000 ton_{CO2}/year equivalent to 5% of the plant`s total emissions. Although this is a promising technology, it still requires additional research and development to bring it to the scale required by the cement industry. There is no public performance and cost data, hence it was excluded from the CCS modelling performed as part of this project. Nevertheless, below are some of the key advantages and disadvantages of LEILAC:

Advantages:

- Enables the capture of 95% process emissions at no additional energy cost and no extra capital cost (apart from CO2 compression) and thus is expected to be cheaper than other capture technologies
- No additional chemicals, no additional processes (e.g., no need for costly gas separation technologies)
- New-build cement plant will incur little or no financial penalty for installing the technology from the start
- Installation not reliant on CO2 infrastructure as is takes the place of a conventional calciner and a CO2 compressor can be installed at a later stage

Disadvantages:

- Captures only process emissions requiring the independent decarbonization of fuel mix and because fuel emissions are not captured, CDR is not possible and the potential remains unused. It is claimed that LEILAC can be coupled with other post-combustion technologies that can capture fuel emissions
- Applicable to new-built cement plants

Open issues:

- Pilot is for 5% CO2 capacity and thus the technology needs to be scaled by 20 times
- Further development is required for increasing the temperature to ~950°C for applicability in the cement industry

5.5.2 Methodology

For the purpose of this project, we perform a deep dive into the topic of CCS and its applicability for the Swiss cement plants. We perform an in depth analysis of the different technologies and construct a techno-economic model allowing us to compare the performance of the different capture technologies based on CO2 impact and cost. The model and analysis is based on data from the Horizon 2020 project "CO2 capture from cement production" (CEMCAP) [55][56], Voldsund et al [10] and Gardarsdottir [11]. Voldsund et al presents a consistent technical comparison for capture technologies in the cement industry while Gardarsdottir et al presents the corresponding cost performance[29].

In our assessment, the technologies are analyzed along key dimensions including:

1. **Energy demand:** Quantified the additional fuel and electric power requirements of the different capture technologies.
2. **Emissions:** Quantified the direct and indirect CO2 emissions from CCS additional fuel demand and adapted to Swiss cement and fuel emission intensities.

[29] For a detailed description of the assumptions and methods refer to the mentioned studies directly.

3. **Cost:** Quantified the costs and adapted the findings to Switzerland. An added value of this study is the inclusion of CO2 transport and storage costs which are not included in other studies[30]. This gives a more realistic picture of the cost of implementing CCS.
4. **Retrofittability:** Aggregated existing qualitative retrofittability assessment from CEMCAP project into one score.

A best available techniques (BAT) reference plant is used as a basis for Voldsund et al analysis [23]. A mentioned previously in this report, Swiss cement plants lie on the upper bound of the BAT. The reference plant uses a dry kiln process, with a 5-stage cyclone preheater, a rotary kiln and grate cooler. All Swiss plants use a dry process except the plant in Cornaux, which uses a semi-dry process [24]. The capacity of the plant in their study is 3 kilo $ton_{clinker}$/day, equivalent to 0.95 million $ton_{clinker}$/year, whereas the largest Swiss cement plant produces 0.69 million $ton_{clinker}$/year. We account for this difference by normalizing the results to the clinker production through linear scaling (e.g., $MJ/ton_{clinker}$ and $CHF/ton_{clinker}$).

We extract the following information as a basis for our calculations:

1. **Technical CO2 performance:**
   - Power and heat requirements of the reference cement plant (MW)
   - Power and heat requirements of the capture technologies (MW)
   - Carbon Capture Ratio (CCR) of each capture technology (%)
2. **Economic cost performance:**
   - Capital cost of the capture technologies (million EUR)
   - Cost of solvents, membranes and other technology specific elements (EUR/ton)
   - Economic parameters such as lifetime (years), discount factor (%) etc.
   - Labor requirements (employees) and overhead costs (%/total cost)

The remaining parameters relevant for our calculations of the application of CCS to Swiss cement plants are extracted from multiple sources. An overview of the parameters and assumptions is listed in Appendix D. The average emissions from a Swiss cement plant are:

Table 11: Swiss cement emissions

Total Swiss cement stack emissions	$kg_{CO2}/ton_{clinker}$	**842**
Scope 1 emissions	$kg_{CO2}/ton_{clinker}$	762
Biogenic emissions	$kg_{CO2}/ton_{clinker}$	80

We define the system boundaries in our model as seen in Figure 18. Emissions from clinker production and the additional emissions due to CCS operation are considered for the technical assessment. We mainly focus on direct emissions of on-site fuel combustion and clinker production; however, we quantify indirect emissions due to increased electricity consumption to observe the impact of these technologies on the national GHG balance. For the cost analysis, we consider the cost of raw material, fuel, clinker production and CO2 capture, transport and storage.

[30] The CO2 transport and storage costs are extracted from a study on the feasibility and cost of a full CO2 transport pipeline in Switzerland [58].

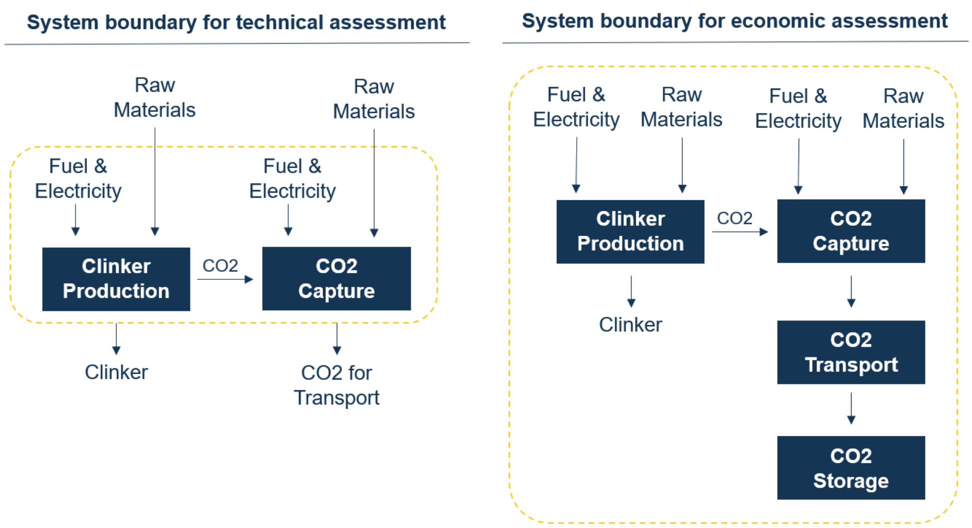


Figure 18: System boundaries for our analysis

Technical CO2 Performance

The capture technologies require a significant amount of energy. The electric power, coal and natural gas requirements extracted from Voldsund et al are presented in Table 12. We use these to calculate the energy requirements and consequently the CO2 impact of the different capture technologies. Absorption capture technologies – MEA and CAL – require a significant amount of steam for solvent regeneration. The steam can be produced on-site using a gas boiler or imported depending on the surrounding availability. Membrane technologies – MAL – requires only electricity supply to operate (e.g., for CO2 liquification). Oxyfuel also mainly requires electricity to power the air separation unit (ASU) and CO2 purification unit (CPU). An organic Rankine cycle can be installed to cover some of these additional power needs using waste heat. The CaL technologies require extra fuel for the additional calciner and power for the CPU and ASU. A steam cycle recovers waste heat and produces power to cover the demand [10]. Other fuels can be used to cover the energy requirements listed in Table 12 (e.g., biogas rather than natural gas for MEA and CAP). Yet for the purpose of this study, we use the same fuel assumptions as in Voldsund et al.

Table 12: Power and fuel requirements of reference plant and CCS technologies

	Reference Plant	MEA	CAP	MAL	OxyF	CaL Tail-end	CaL Integrated
Reference Plant Thermal Power	105						
Net Electric Power (MW)	15.9	14	8	34	19	-9	5
Consumption	15.9	14	8	34	22	31	26
Generation	0	0	0	0	2.9	40	21
Coal (MW)		0	0	0	0	126	72
Gas (MW)		92.7	56.1	0	0	0	0

Given the power and fuel requirements per technology, we calculate the energy demand per ton of clinker produced:

$$Energy\ (thermal\ or\ electric)\ demand\ \left[\frac{MJ}{ton\ clinker}\right] = \frac{Power\ requirement\ [MW]}{Clinker\ production\ \left[\frac{ton\ clinker}{hour}\right]} \times 3{,}600\left[\frac{MJ}{MWh}\right]$$

Consequently, using the Swiss fuel and electricity emission factors listed in Appendix D, we calculate the associated CO2 emissions as follows:

$$CO2\ emissions\ \left[\frac{kgCO2}{ton\ clinker}\right] = \sum Emission\ factor\ \left[\frac{kgCO2}{MJ}\right] \times Energy\ demand\ \left[\frac{MJ}{ton\ clinker}\right]$$

We calculate the emissions resulting from the reference plant and those resulting from the on-site combustion of fuels required for CCS. With the given Carbon Capture Ratio (CCR) in Table 13, we calculate the total amount of CO2 captured per technology:

$$CO2\ captured\ \left[\frac{kgCO2}{ton\ clinker}\right] = CCR\ [\%]\ \times CO2\ generated\ \left[\frac{kgCO2}{ton\ clinker}\right]$$

Table 13: Carbon Capture Ratio (CCR)

	MEA	CAP	MAL	Oxy-fuel	CaL Tail-end	CaL Integrated
Carbon Capture Ratio (CCR)	90%	90%	90%	90%	94%	95%

The remaining emissions from the cement plant stack is equivalent to the difference between the total CO2 generated from the reference plant plus the CCS technology and the CO2 captured:

$$Residual\ emissions\ \left[\frac{kgCO2}{ton\ clinker}\right] = CO2\ generated_{Total}\ \left[\frac{kgCO2}{ton\ clinker}\right] - CO2\ captured\ \left[\frac{kgCO2}{ton\ clinker}\right]$$

The CO2 avoided from the stack is quantified as it is useful to compare the effectiveness of CCS as a mitigation technology to the other approaches discussed previously in the report. It is calculated by subtracting the CO2 captured per technology from the CO2 generated by the reference plant (excluding the extra emissions from the respective capture technology):

$$Avoided\ CO2\left[\frac{kgCO2}{ton\ clinker}\right] = CO2\ generated_{Ref\ plant}\ \left[\frac{kgCO2}{ton\ clinker}\right] - Residual\ emissions\ \left[\frac{kgCO2}{ton\ clinker}\right]$$

To account for the indirect emissions from electricity consumption, we calculate the equivalent avoided CO2 by subtracting these emissions from the avoided CO2:

$$Equivalent\ avoided\ CO2 \left[\frac{kgCO2}{ton\ clinker}\right] = Avoided\ CO2 \left[\frac{kgCO2}{ton\ clinker}\right] - Indirect\ emissions \left[\frac{kgCO2}{ton\ clinker}\right]$$

Figure 19 visually displays the different metrics and their relation to one another. From a CO2 accounting perspective and relevant for the decarbonization efforts of the cement industry is the “avoided CO2”. We calculate the “equivalent avoided CO2” to assess the impact of indirect electricity emissions and get a sense of its impact on the national annual Swiss GHG budget.

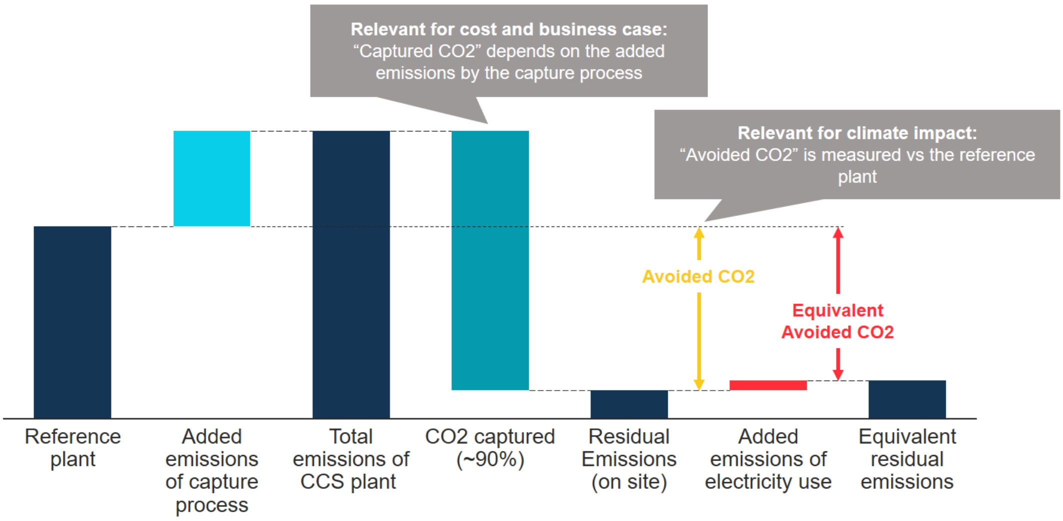


Figure 19: Metrics of the technical emission model

Cost performance

An evaluation of the costs of the different CO2 capture technologies is essential in combination with the CO2 impact in determining which of solutions is most effective in the Swiss context. The costs and CO2 abatement are used at a later stage to calculate the abatement cost of CCS allowing us to compare to the remaining technologies discussed in this report.

In order to calculate the cost of operating the reference cement plant with CCS, we consider the following cost buckets: investment cost per technology (CAPEX), energy costs, raw material and other variable costs linked to clinker production and CCS operation, labor and overheat costs and lastly CO2 transport and storage (OPEX). The investment costs of the capture technologies are considered for “Nth of a kind” i.e. for commercial plants built after large-scale demonstration and commercial adoption. The costs are extracted from Gardarsdottir et al. which estimates the capital costs of the different capture technologies based on equipment and component lists per technology [11], with data regarding the non-standard components based on information from the CEMCAP industry partners and literature. Therefore, the least developed technologies such as Oxyfuel and CaL having the most theoretical costs whereas already commercial technologies such as MEA having the most realistic. What is unclear is how the capture technologies with low TRLs will drop in price with economies of scale. Plaza et al. provides a detailed analysis on the current state of the art carbon capture technologies in the cement industry globally [54]. The assumptions and input into the cost model considered in our study are available in Appendix D.

An added value of this report is the inclusion of CO2 transport and storage costs which are usually disregarded in similar studies despite their substantial impact on the final cost. In a recent BFE-study, engineering company SAIPEM [57], a global energy and infrastructure provider, with support from sus.lab roughly designed a Swiss CO2 pipeline collection network and estimated its overall costs at scale [58]. The cost of transporting CO2 from emitters in Switzerland to Rotterdam and then to the offshore storage location in the North Sea are provided in Figure 20. Additionally, the image shows the cost of permanent offshore storage. The cost estimates of transporting CO2 in Switzerland are higher than those numbers given for the EU context. The reason for this is that the cost indicated for transport in Switzerland considers the investment cost of the entire network including the main backbone pipeline and the connection pipelines to all 31 large emitters in Switzerland whereas the EU cost estimate is calculated based on one dedicated end-to-end pipeline. In other words, the Swiss values are an average complete network cost per ton of CO2 and can thus be considered rather conservative. Alternative infrastructure financing and operating models can drive down these costs in the future.

Based on this, in the cost model, we assume a CO2 transport cost of 45 CHF/ton$_{CO2}$ and an offshore storage cost of 23 CHF/ton$_{CO2}$[31] [32].

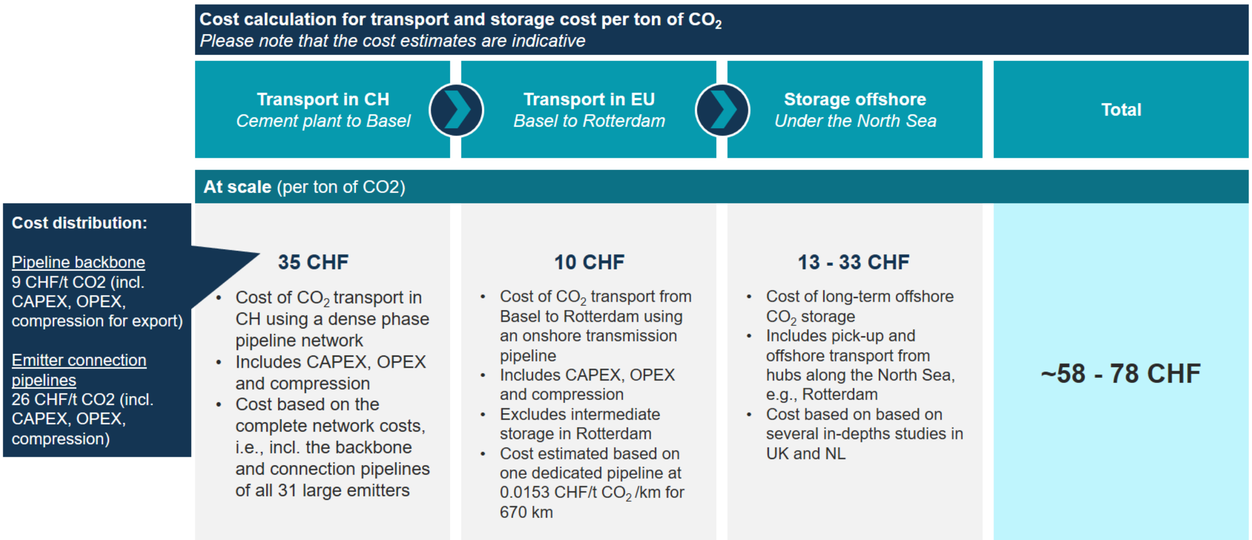


Figure 20: Cost calculation for transport and storage of CO2 from Switzerland to offshore North Sea storage [49][50][58]

The cost performance of each of the capture technologies is assessed along two metrics. The first is the cost of clinker (COC) which accounts for all annual costs including annualized investment cost. Important to note is that the COC includes all additional costs attributed to the operation of the capture technology (e.g., fuels, solvents etc.). The second metric is the cost of avoided CO2 which is essentially the CO2 abatement cost of the capture technologies. The cost of avoided CO2 is calculated using the COC attributed to the capture technology (i.e. the extra cost of capturing emissions) divided by the quantity of emissions avoided at the stack.

[31] For early movers, data from a recent Waste-to-energy project at KVA Linth suggests transport and storage costs of 111 to 139 CHF/ton$_{CO2}$.

[32] Not considered in this study is the overlap in costs and energy requirements for CO2 compression with [58]. Accounting for these will drive down the costs and improve the CO2 performance further.

$$Cost\ of\ clinker\ (COC)\ \left[\frac{CHF}{ton\ clinker}\right] =$$

$$Annual\ CAPEX + Fixed\ OPEX + Variable\ OPEX + Energy\ costs + CO2\ transport\ and\ storage$$

$$Cost\ of\ avoided\ CO2\ \left[\frac{CHF}{tonCO2}\right] = CCS\ CO2\ abatement\ cost\ = \frac{CCS\ Cost\ of\ clinker\ [\frac{CHF}{ton\ clinker}]}{Avoided\ CO2\ [\frac{ton\ CO2}{ton\ clinker}]}$$

Retrofittability

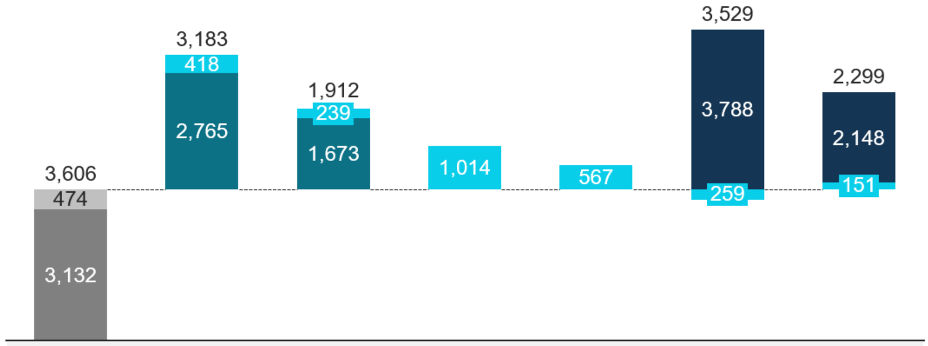
The possibility of retrofitting an existing cement plant and installing each of the considered CCS technologies is assessed qualitatively by consolidating the research done by Voldsund et al and Plaza et al [10][54]. The assessment criteria includes: (i) impact on cement production; (ii) equipment and on-site space requirements; (iii) additional utilities and services; (iv) Additional chemicals and systems; and (v) available experience and technical readiness level (TRL).

5.5.3 Results

Energy Demand

All CO2 capture technologies require a significant amount of energy, in some cases up to double the requirement of the reference plant[33]. The absorption technologies – MEA and CAP – require a noteworthy amount of steam for the solvent regeneration. MAL and Oxyfuel technologies only require additional electric power of which the associated emissions are considered scope 2 indirect emissions. The CaL technologies also consume a significant amount of fuel, modelled as coal in our study; however, other fuels can be used as long as the temperatures required for the calcination process can be reached.

[33] The results take into account the waste heat available from the reference cement plant. Displayed in Figure 21 are the net energy requirements.

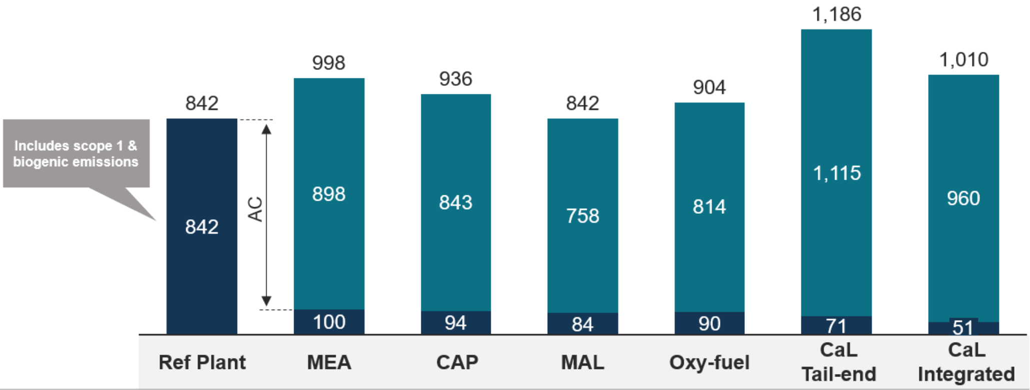


	Ref Plant	MEA	CAP	MAL	OxyF	CaL Tail-end	CaL Integrated
Ref Plant Base Power	105						
Net Electric Power (MW)	15.9	14	8	34	19	-9	5
Consumption	15.9	14	8	34	22	31	26
Generation	0	0	0	0	2.9	40	21
Coal (MW)		0	0	0	0	126	72
Gas (MW)		92.7	56.1	0	0	0	0

Figure 21: Thermal and electric energy requirements of the reference plant and the individual CO2 capture technologies

CO2 Mitigation Potential

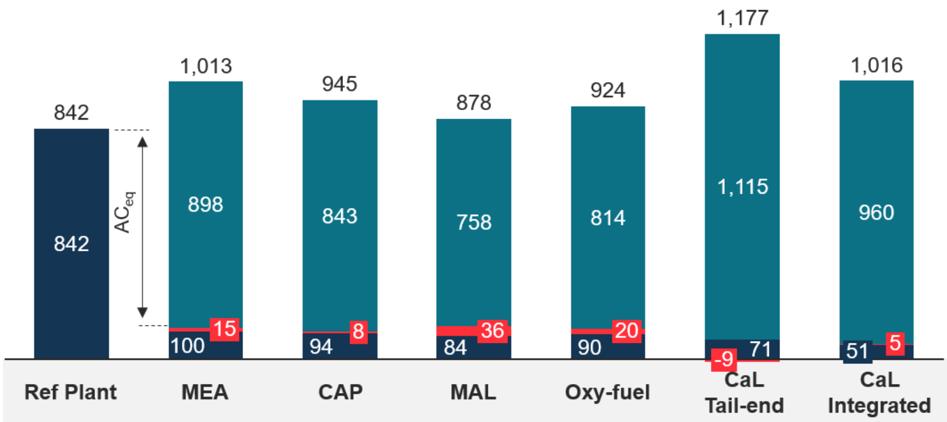
The 2019 CO2 intensity of clinker production in Switzerland amounted to 842 kg$_{CO2}$/ton$_{clinker}$ including scope 1 and biogenic emissions. We assume this to be the stack emissions of the reference plant. As shown in Figure 22, the highest emissions are attributed to the CaL technologies due to their increased consumption of coal with high emission factor (92.7 kg$_{CO2}$/GJ). With the given CO2 captured per technology, it is evident that the integrated CaL has the highest avoided CO2 (94%) and thus the lowest emitted CO2 emissions post capture (51 kg$_{CO2}$/ton$_{clinker}$) and is thus the most effective technology in terms of decarbonization. Overall, all technologies result in a CO2 avoided ranging from 88 – 94%.



		Ref Plant	MEA	CAP	MAL	Oxy-fuel	CaL Tail-end	CaL Integrated
Carbon Capture Ratio (CCR)	%		90%	90%	90%	90%	94%	95%
CO2 Captured	kg CO2/t clinker		898	843	758	814	1,115	960
Avoided CO2 (AC)	kg CO2/t clinker		742	748	758	752	771	791
	%		88%	89%	90%	89%	92%	94%

Figure 22: Captured and emitted CO2 of the reference cement plant without and with the installation of capture technologies

Accounting for the emissions due to increased electric power requirement, we calculate the equivalent avoided CO2 for which the results are displayed in Figure 23. With the electricity emission factor in Switzerland (128 $kg_{CO2\text{-}eq}$/MWh) [61], the CO2 impact of additional power requirements, even in the case of MAL and Oxyfuel that have a high power demand, is limited in relation to the total emissions of clinker production and CO2 capture. We do not consider these scope 2 emissions further in this report.



		Ref Plant	MEA	CAP	MAL	Oxy-fuel	CaL Tail-end	CaL Integrated
Equivalent Avoided CO2 (AC_{eq})	kg CO2/t clinker		727	740	722	732	780	786
	%		86%	88%	86%	87%	93%	93%

Figure 23: Captured and directly and indirectly emitted CO2 of the reference cement plant without and with the installation of CO2 capture technologies

Cost Performance

The total cost of operating the reference cement plant with carbon capture increases the COC by 124-161% depending on the installed technology. Figure 24 shows the breakdown of the different cost factors. Oxyfuel has the lowest COC among all CCS options. MEA, the most advanced technology, has the lowest CAPEX but has a high OPEX and fuel cost. In all scenarios, the cost of additional net fuel and electricity exceeds the cost of the fuel consumed by the reference plant for clinker production. Interesting to observe is the notable cost of transporting and storing the captured CO2 which needs to be accounted for in planning. In order to understand the magnitude of the increased COC, we calculate its impact on the total cost of a building. The effect is negligible as the impact amounts to less than 1% increase in the total building cost[34].

The cost of CO2 avoided (CO2 abatement cost) lies between 123-157 CHF/ton$_{CO2}$, with Oxyfuel having the lowest cost of avoided CO2 (see Figure 25)[35]. The costs of pilot projects installed today are likely to be higher depending on the technology and it's TRL. We consider the cost of CO2 avoided to be the CO2 abatement cost of CCS technologies as it is equivalent to the cost of mitigating one unit of CO2. The current ETS CO2 price of ~86 CHF/ton$_{CO2}$ is not sufficient to cover the cost of CCS. The policy segment of this study will explore policy options to support the financing of CCS for cement industry in Switzerland.

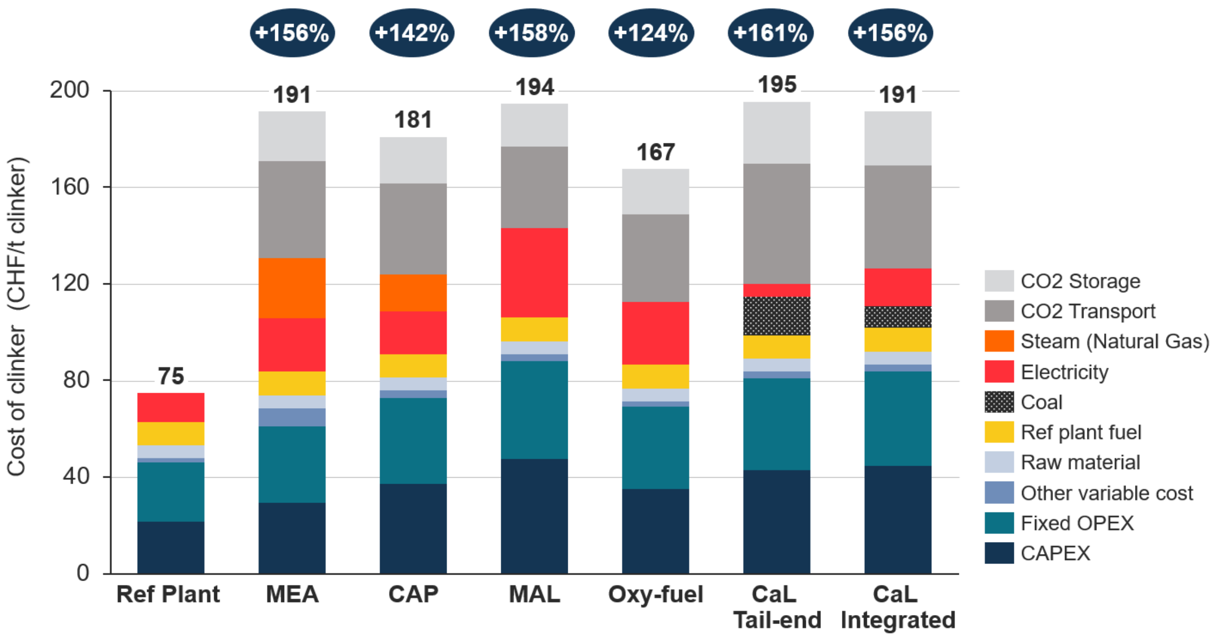


Figure 24: Cost of clinker for the different CO2 capture technologies

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[34] Assumptions for the calculation: 0.7 m^3 of concrete per m^2 of building space; clinker-cement ratio ~80%; 290 kg$_{cement}$ per 1 m^3 concrete; MEA technology with 159% increase in COC

[35] The cost of CO2 avoided is equivalent to the CO2 abatement cost per capture technology

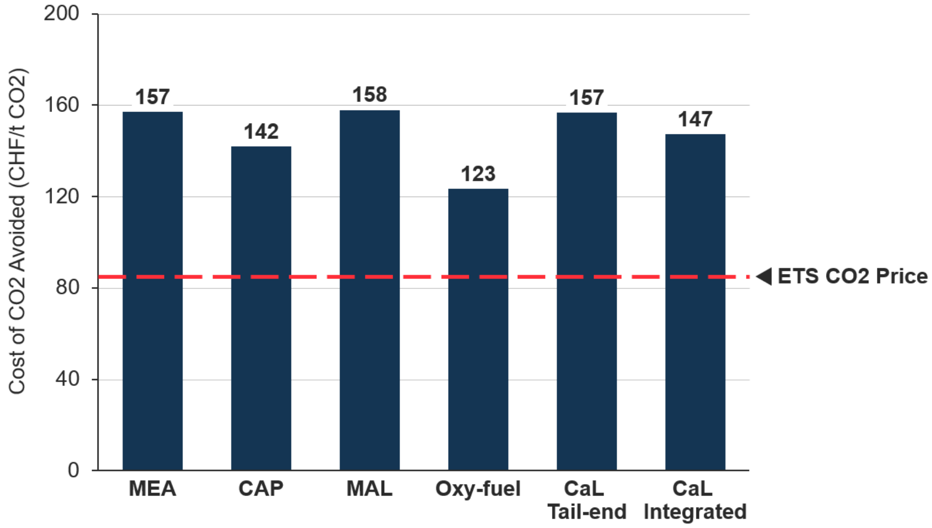

Figure 25: Cost of CO2 avoided for the different CO2 capture technologies

Retrofittability

In order to mitigate the emissions from Swiss cement production, it is crucial that CCS technologies can be retrofitted to existing cement plants. While direct capture technologies (LEILAC) are promising technologies, they can only be installed in new plants. With the remaining lifetime of existing facilities, it is unlikely that new cement plants with integrated CCS will be constructed in the near future [15]. Post-combustion technologies are therefore the preferred option as they can be added to existing plants and does not affect the production process.

Here are the main conclusions per CCS technology based on the retrofittability criteria:

- MEA: Post-combustion independent units that do not impact clinkerization process nor clinker quality. Short downtime for installation for flue gas rerouting, which can be also done during annual maintenance. Equipment can flexibly be place anywhere on site. As shown in Figure 21, MEA demands large amounts of steam and electricity potential requiring local grid upgrades. This technology also requires a supply of MEA solvent. This is the most advances technology and has reached commercialization in the coal industry [54]. It is currently at a TRL level of 8. In the cement industry, the largest pilot is in China capturing 50,000 tons$_{CO2}$ per year. Norway's Longship project aims to build the first full scale CCS facility at the Norcem Brevik cement plant with an annual capture capacity of 0.4 million tonsCO2 [62][36].
- CAP: Similar to MEA, CAP is independent of the clinker production process and can be installed flexibly with minimal downtime. Utility requirements are also significant. As for chemical supply, CAP requires aqueous solutions of amines or ammonium which is a hazardous substance. Thus new handling procedures need to be introduced. Regulatory constrains also need to be accounted for. The research and pilots performed throughout the CEMCAP project advanced the TRL level to 6. Today, CAP is ready to be demonstrated for a capacity of 100,000 ton$_{CO2}$ per year [54].
- MAL: A post-combustion technology, with similar installation conditions like MEA and CAP. It only requires additional power, for which the local grid needs to be evaluated. Refrigerant systems are needed which is easy to handle. This technology is still in the lab testing and small pilot project phase and has a low TRL level of 4

[36] For reference, the six cement plants cumulatively emit 2.72 million ton$_{CO2}$ (Scope 1 and biogenic).

- OxyFuel: Technology integration is high as the kiln needs to be retrofitted to oxyfuel combustion conditions. It is unclear whether this will impact the clinker quality due to the changes in material conversion and operation specifications. Lengthily operational downtime needed to retrofit the plant. It also requires space near the kiln which may be unavailable. The technology requires additional power and oxygen which requires attention for handling but this knowledge can be imported from other industries. The CEMCAP project tested multiple aspects of the technology including an oxyfuel burner prototype which brought the TRL level up to 6.
- CaL – Tail-end: A post-combustion technology which needs minor integration as the sorbent purge is used as raw meal into the clinker production process. Can be flexibly placed on-site. The major change in utility requirements is the need for large amounts of coal (or another fuel if right temperatures can be reached) and oxygen. The technology has been testing at a cement plant in Taiwan capturing 1 tonCO2/hour and the project shall be expanded till 2025 to capture 0.45 million ton_{CO2} per year [54]. The CEMCAP project has also tested the technology and considers it to be ready for larger scale demonstration. The TRL level is 7.
- CaL – Integrated: Calciner and preheater are modified and the impact on clinker production is undefined. Significant downtime required due to the high level of integration. Fuel and chemical requirements similar to the tail-end configuration. There is currently no operational experience with this technology. It is being further developed in the EU project CLEAN clinKER (CLEANKER) project [63]. The current TRL level is 6.

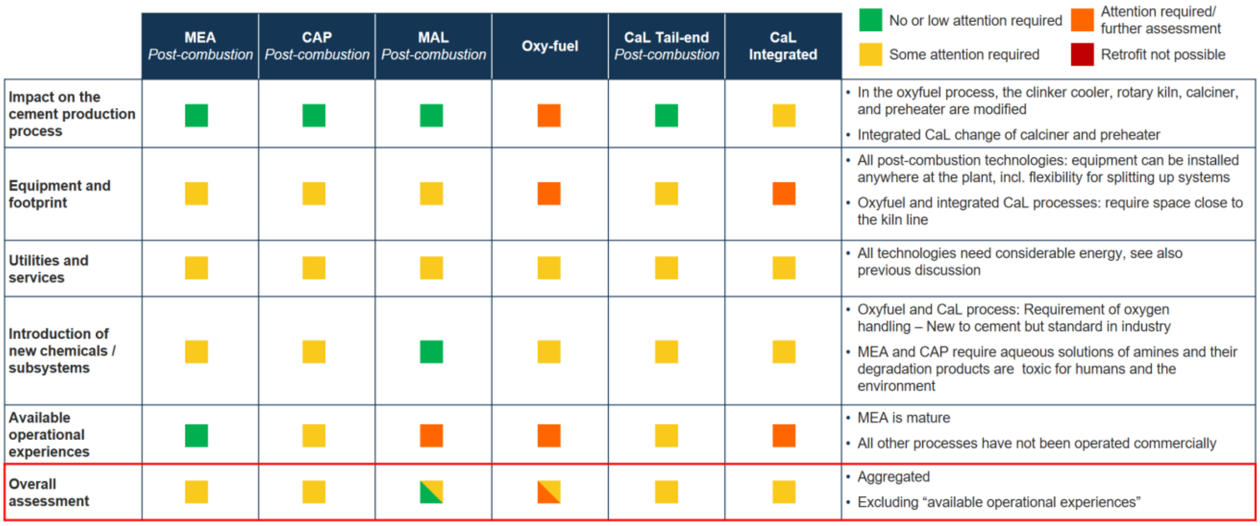

Figure 26: Summary of retrofittability

Overview of CCS Technologies

The aim of our modelling and analysis is the evaluation of all CCS technologies on the same baseline and in the Swiss context. We calculate the energy demand, CO2 emission mitigation and cost per capture technology, and qualitatively evaluate the retrofittability and TRL. Figure 27 shows an overview of the analysis results.

Oxyfuel requires the least amount of additional energy whereas the tail-end configuration of CaL demands the most. As for the CO2 impact, CaL integrated configuration is the most effective CCS technology as only 47 $kg_{CO2}/ton_{clinker}$ remain post-capture. MEA, MAL and CaL tail-end have almost equal cost of CO2 avoided, while the lowest cost of capture corresponds to the oxyfuel technology. All technologies require attention when evaluating retrofit feasibility, however some more than others e.g., MEA is easier to install than oxyfuel. Membrane technology MAL has the lowest TRL of 4 whereas chemical absorption, particularly MEA, has the highest TRL of 8 and is ready for commercialization.

All CCS technology require further development and research for applicability in the cement industry. Technologies with higher TRLs need to be demonstrated commercially at-scale which will build experience, minimize risk and reduce the cost of capture for cement producers. Lower TRL solutions need additional research to increase readiness level and ensure the safety and reliability of the technologies.

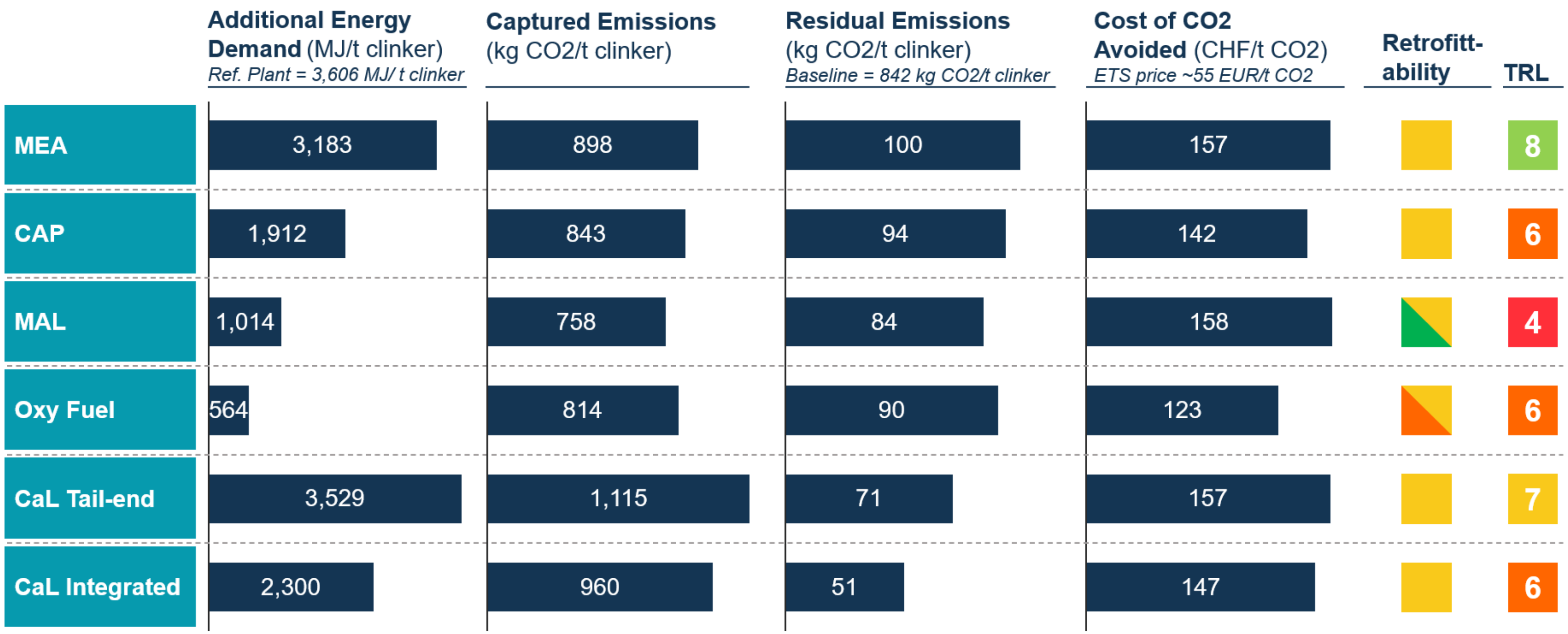

Figure 27: Overall performance of CO2 capture technologies

6 Carbon Dioxide Removal

Carbon dioxide removal (CDR), also referred to as negative emissions technologies, are methods of withdrawing CO2 from the atmosphere and storing it durably [64]. To distinguish between CO2 avoidance and CDR, we adopt these two definitions [65]:

- **Avoidance:** Measures that target CO2 emissions prior to their release into the atmosphere
- **CDR:** Measures that remove CO2 from the atmosphere and store it permanently

The IPCC has mentioned the need for large-scale CDR to prevent overshoot and limit global warming to 2°C and even more so to 1.5°C [66]. Today, a range of CDR technologies at different development and TRL levels exist. They also vary in cost, energy requirements, and most importantly their potential for reliable and permanent removal of CO2.

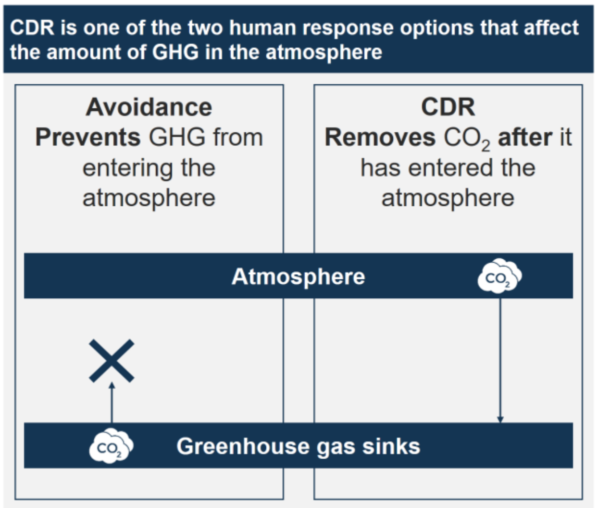

Figure 28: Carbon dioxide removal

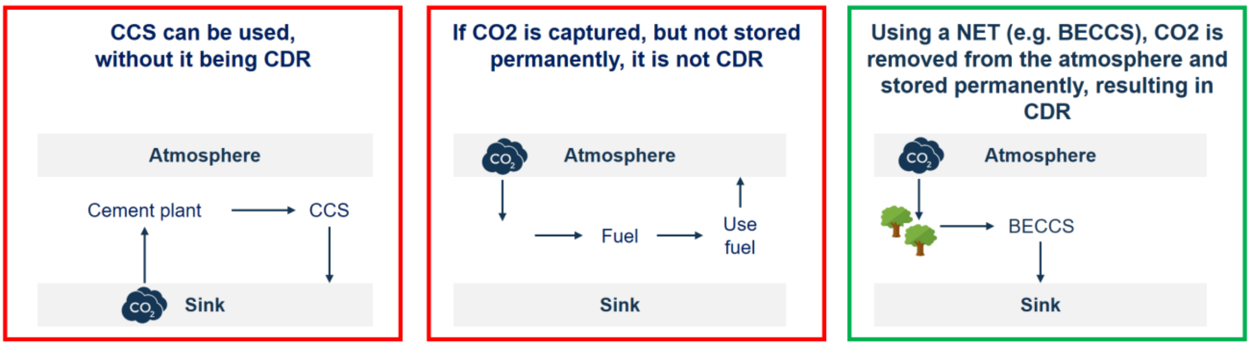

Figure 29: What is considered CDR? (Red is not CDR, green is CDR)

Not all reversed emission streams are CDR as shown in Figure 29. There are two fundamental principles for a solution to be considered CDR:

1. CO2 must originate from the atmosphere
2. CO2 must be sequestered permanently

In Figure 29, the scenario in the first box to the left is not considered CDR because fossil fuels are burned, captured and stored and thus the CO2 never reaches the atmosphere. Depicted in the middle box, CO2 originated from the atmosphere and is stored in a fuel (e.g., synthetic natural gas CH4). When the fuel is burned the CO2 re-enters the atmosphere rendering neutral and not negative emissions (CO2 is thus stored only temporarily). In last green box, CO2 is removed from the atmosphere and stored in biomass which is then burned. In combination with carbon capture (discussed in 6.2), this is considered CDR as the CO2 is stored permanently.

Switzerland has been identified to have a strong position and potential in different CDR approaches including: direct air capture (DAC), biochar, bioenergy with carbon capture and storage (BECCS) and enhanced carbon uptake via cement. Currently, carbon removal credits are not valid under the ETS and are traded on the voluntary market in Switzerland and beyond. There currently is a lack of coherent framework for trading CDR credits; the EU is developing such a framework to be published in 2023 [67].

Demand for CDR credits is expected to increase significantly by 2030 and 2050 as can be seen in Figure 31. High-quality removal credits, i.e. credits that are permanent, additional and verifiable, are already scarce today. In fact, CDR marketplaces are regularly sold out and are scrambling to find suppliers of high-quality credits [68]. The majority of currently traded offset credits are avoidance offsets which are often considered low-quality and will likely loose relevance. Relevant player like the Science-Based Targets initiative do not recognize avoidance credits and push for a move towards carbon removals. A number of initiatives are working on setting ground-rules for the voluntary carbon credit market projected to be worth up to 1,000 billion CHF using a CO2 price of 100 CHF/ton$_{CO2}$ [31].

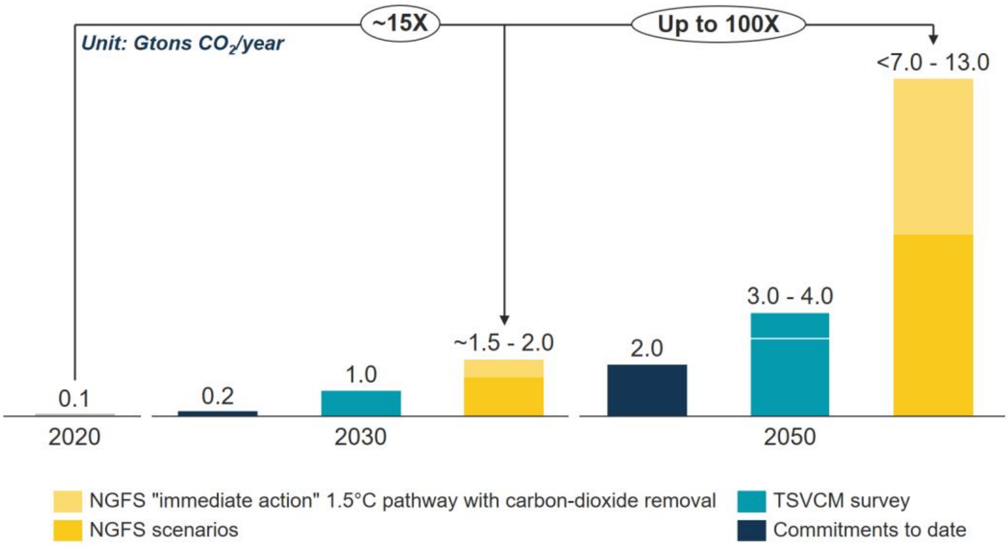

Figure 30: Global voluntary demand scenarios for carbon credits[37] [69]

For the purpose of this study, we explored the potential of two key CDR technologies relevant to the cement sector today: enhanced carbon uptake via cement (also referred to as ACC) and bioenergy with carbon capture and storage (BECCS). The first can be performed by the cement industry or externally by an independent company, which will have an impact on emissions accounting and potential revenue streams. BECCS is considered to be performed by the cement industry with the installation of CCS and the combustion of biomass on-site. In Chapter 7, we quantify the CDR potential per scenario using only BECCS.

[37] TSVCM: Taskforce on Scaling Voluntary Carbon Markets; NGFS: Network for Greening the Financial System

We do not account for ACC in the scenarios as it remains unclear if the cement industry or other value chain stakeholders will be performing ACC and who will get to claim the removals.

6.1 Enhanced Carbon Uptake via cement and concrete

Carbon utilization and sequestration in recycled concrete aggregates and fines is proposed as an innovative method to permanently store CO2[38]. Rather than an offset for clinker production, this could also be viewed as a separate carbon removal technology based on a widely available waste stream. Recycled concrete fines from demolition waste are composed of hydrated cement paste, sand and aggregates [70]. The hydrated cement paste is exposed to pure CO2 resulting in a carbonated paste composed of calcium carbonate (CaCO3), same constituent as limestone. This carbonated paste is thus a CO2-sink and can be used as follows:

1. SCM: Replacing clinker in cement thus reducing clinker demand while sequestering CO2. In Switzerland, limestone is already used up to ~20% in cement (recommended limit due to the low reactivity of limestone). In this case, only the absorbed CO2 is accounted for. Nevertheless, reactive calcium carbonate can potentially be mixed into cement above the 20% together with pozzolanic materials [12]. This measure is applicable on the cement producer level.
2. Concrete aggregate substitute: Gravel and sand can make up to 80% of concrete by weight. Some of these aggregates are limestone. This limestone can be replaced with the carbonated fines resulting in carbon negative concrete. Yet, experts believe carbonated aggregates lower the compressive strength of concrete and can thus only be used in light weight applications limiting the replacement rate. This measure is applicable on the concrete producer level.

Today the quantities of CO2 uptake in stored in concrete aggregates remains low. For reference, Neustark, a Swiss start-up, currently sequesters $10kg_{CO2}/m^3_{concrete}$ equivalent to 6% of the total Swiss cement emission intensity. Also, it is unclear to what extent these carbonated aggregates can replace SCMs or natural aggregates without the deterioration of concrete performance.

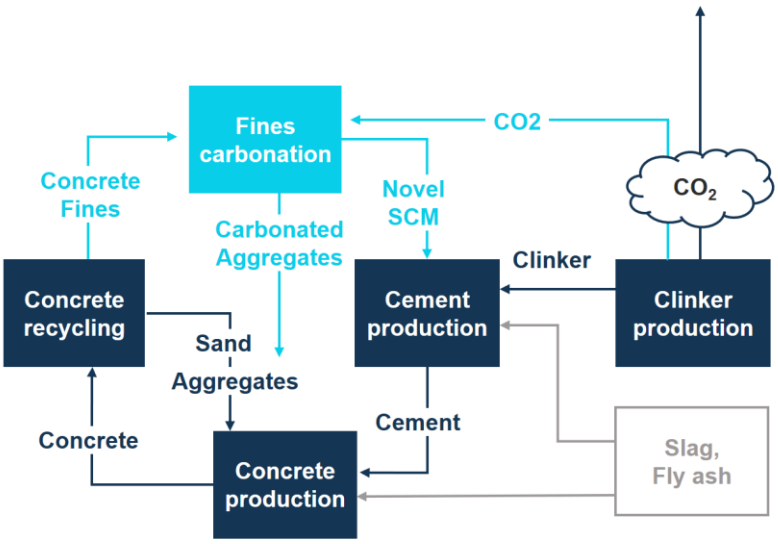

Figure 31: Flow diagram on the use of carbonated recycled concrete fines as SCMs or concrete aggregate substitute

[38] Also known as active carbon curing (ACC)

CO2 can also be injected into concrete during batching and mixing, making the concrete a CO2 sink. The CO2 binds to calcium silicate clinker in the OPC to form nano-scale CaCO3 which accelerates cement hydration and improves the compressive strength of concrete thus reducing the amount of cement required in the mixture [71]. According to an interviewed expert, this can be done up to 5% by mass of cement, after that limit, the mechanical properties of the concrete deteriorate. Although these are small amounts, given the quantities of concrete produced per year, it is an effective method to store CO2. CarbonCure, a Canadian start-up, bases its technology on this approach. They offer concrete producers an integrated and digital solution allowing them to inject CO2 into the concrete mixture before the concrete is transported to the construction site.

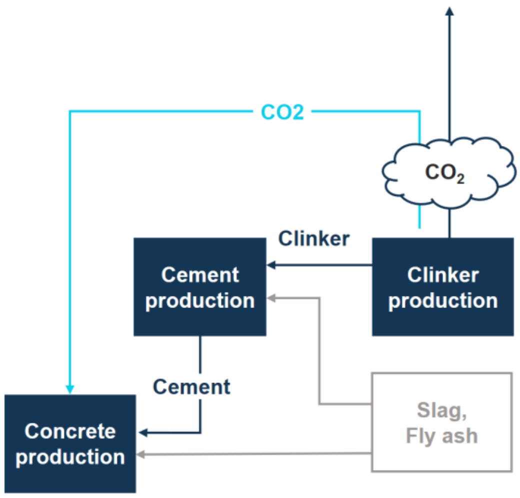

Figure 32: Flow diagram on the injection of CO2 in concrete mixing

Moreover, multiple global start-ups are active in the field of ACC with varying claims for CO2 sequestration. Table 14 shows an overview of the startups. We consolidate their claims and present our remarks per company. Where possible we attempt to validate the claims and compare the CO2 sequestration potential to the Swiss CO2 baseline. The results are displayed in Figure 33. We successfully calculated the performance of Neustark, CarbonCure, and Solidia in the Swiss context, yet the claims of the remaining companies we could not verify at this time[39].

ACC startups use different metrics and baselines to communicate their impact, making it challenging to quantify and compare their true CO2 reduction potential. Disclosing the baseline is key because it can inflate the potential of the technology in certain markets such as Switzerland which uses a SCMs already. Using CEM I (~95% clinker content) as a baseline inflates the mitigation potential for novel SCMs as these companies account for replacing clinker in addition to the CO2 absorbed. Whereas in Switzerland the clinker-cement ration is 76% (~19% limestone) and therefore the CO2 impact is not identical.

[39] There is a scientific paper currently being drafted on this topic.

Table 14: ACC startups

Category	Startup	Method	Claimed Impact	Remarks
Reactive Additives/ SCM	neustark	Storing CO2 in recycled concrete granulates and using them as SCM[40]	CO2 Storage = 10 kgCO2/m$^3_{concrete}$ [72] Swiss cement CO2 Reduction = 6%	Plan to get to 150 kg$_{CO2}$/m$^3_{concrete}$ by 2025. Unclear how this will be achieved.
	FORTERA	Using on-site CO2 captured CO2 and producing reactive calcium carbonate cement for use as SCM[25]	Cement CO2 Reduction = 60% [73]	Unclear from their website how 60% reduction is achieved. Can also be used in precast products (5% CH market).
Inert Additives	Blue Planet	Replacing conventional fine and coarse recycled aggregates (sand and gravel) with synthetic CO2-sequestered limestone aggregate.	1 ton CO2-sequestered aggregate has 440 kg$_{CO2}$. CO2-cured aggregates for concrete, potential for negative emissions [74]	Numbers seem to be inflated. Carbonated aggregates lower concrete compressive strength so can only be used in light weight applications. Light weight aggregates will not replace natural aggregates. Market probably notably smaller than claimed.
Concrete Products	CARBON CURE	Injecting CO2 into concrete during the mixing process.	CO2 Storage = 17 kg$_{CO2}$/m$^3_{concrete}$ [71]	Used in ready-mix concrete, but carbonation detrimental to reinforced concrete so scale-up in unclear. Also used in precast products.
	SOLIDIA	A novel CCSC binder carbonated with CO2 in chambers to form a fully cured and stable concrete.	CO2 Reduction = 30% cement + 40% CO2 absorbed i.e., 70% total [75]	Requires wollastonite as raw material or a specific binder based on wolloastonite composition. Applies only

[40] Can also be used as an inert additive/ aggregate substitute. We believe that is how they achieve their claimed emission reductions

		to precast products equivalent to 5% CH market. Bigger market in EU ~23%.

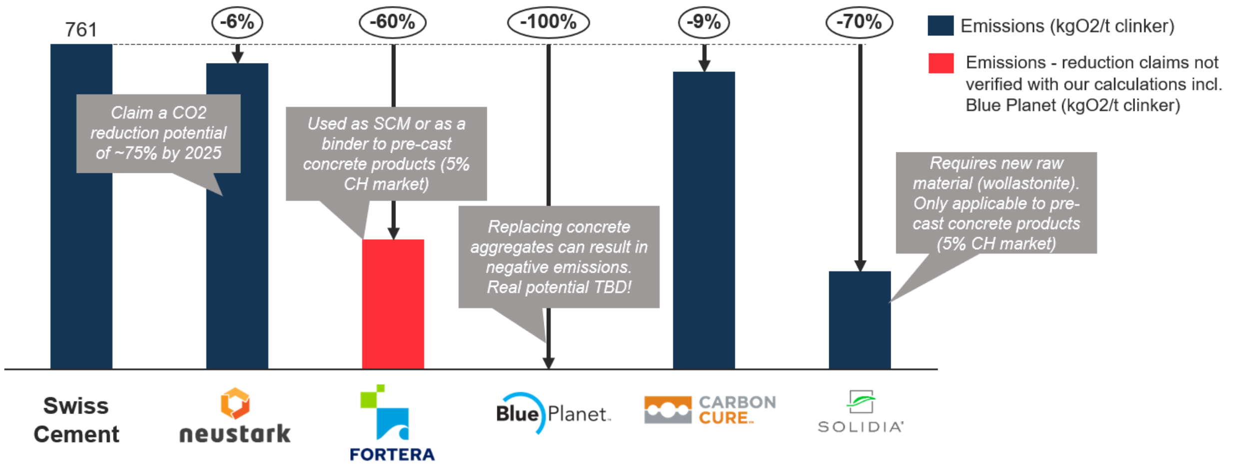

Figure 33: Theoretical CO2 reduction potential per startup applied to the Swiss cement emission baseline

As mentioned previously, enhanced carbon uptake is not considered in the decarbonization pathways discussed in the Chapter 7 for the Swiss cement industry. This does not exclude the fact that cement companies can integrate this into their businesses in the future and benefit from the negative emissions. Yet, for the purpose of this analysis we do not include it.

6.2 Bioenergy with Carbon Capture and Storage (BECCS)

BECCS is a combination of two climate change mitigation technologies: Combustion of biomass and carbon capture and storage [76]. BECCS results in a net transfer of CO2 from the atmosphere into the ground (considering geological CO2 storage). This hinges on the condition that the emissions from the supply of biomass and those of CCS operation do not exceed the emissions absorbed by the biomass throughout its lifetime. In fact, biomass supply chains may result in high amount of direct and indirect GHG emissions and impact biodiversity and soil.

The cement industry in Switzerland currently uses waste wood as a source of fuel to fire it`s kilns. As mentioned in the introduction of this report, biomass constitutes 17% of the cement fuel mix with an ambition by the industry to increase this share to 60% by 2050 [41].

No official consensus on CDR assessment criteria exists yet[41]. However, some criteria to determine the quality and validity of a CDR solution have emerged from practice and via initiatives such as Carbonplan[42] as well as publicly available CDR procurement data by companies like Stripe or Microsoft. Table 15 shows the performance of BECCS in the cement industry across the emerging CDR criteria. As evident by this evaluation, by capturing the biogenic CO2 generated by burning biomass as fuel (BECCS), the cement plants could produce high-quality CDR credits that they can claim for their own business or sell on the voluntary market.

[41] Refer to the Carbon Dioxide Removal Primer [217], and online book, for more information on CDR and assessment criteria.

[42] Carbonplan, is a non-profit organization, with an online CDR database that assesses and rates different global CDR projects based on multiple metrics such as permanence, negativity, volume etc. [77].

Table 15: BECCS in cement industry performance along emerging CDR criteria

Parameter	Explanation	Assessment	Remarks
Permanence	How long will the CO2 be safely removed from the atmosphere?	✓	> 1000 years expected
Additionality	Does the CDR activity cause new climate benefits or would the carbon removal have happened anyway?	✓	
Carbon leakage	Are emissions shifted elsewhere because of the CDR activity?	!	To monitor if the shift from secondary fossil fuels (waste) to biomass, redirects non-biogenic emissions to other industries (e.g., burning tires in incinerators without CCS)
Negativity	How emission-intensive is the CDR process relative to its carbon removal potential?	!	Cradle-to-grave LCA to verify
Verifiability	How is the CO2 removal monitored and verified?	✓	
Side benefits/risks	What are the consequences to ecosystems, biodiversity, food security, etc.?	✓	No concerns if waste or sustainable biomass streams are used as considered in our scenarios

As indicated at the start of this report, key to this study was the establishment of a coherent emissions baseline and this was thus prioritized at the beginning of the project and was the first task performed by the authors. Appendix A summarizes the energy consumption by the cement industry in 2019 and the respective scope 1 and biogenic emissions. Quantifying biogenic emissions allows us to estimate the potential for BECCS in the event that the cement industry installs CCS in the upcoming years. In 2019, the annual biogenic emissions amounted to 259 kilo $ton_{CO2\text{-}biogenic}$ which effectively translates to 80 $kg_{CO2\text{-}biogenic}/ton_{clinker}$. With a CCR ratio of 90% (assuming MEA capture technology), the Swiss cement industry could indicatively realize up to around 72 kg_{CO2} of carbon removal per ton of clinker produced (see Figure 34). The biomass is considered to be carbon-neutral at the gate as it comes mainly from waste material, so no grey emissions upstream are considered. Downstream emissions from the capture and CO2 transport would have to be added. Details on the calculation of value chain emissions will depend on the final methodology adopted by the EU.

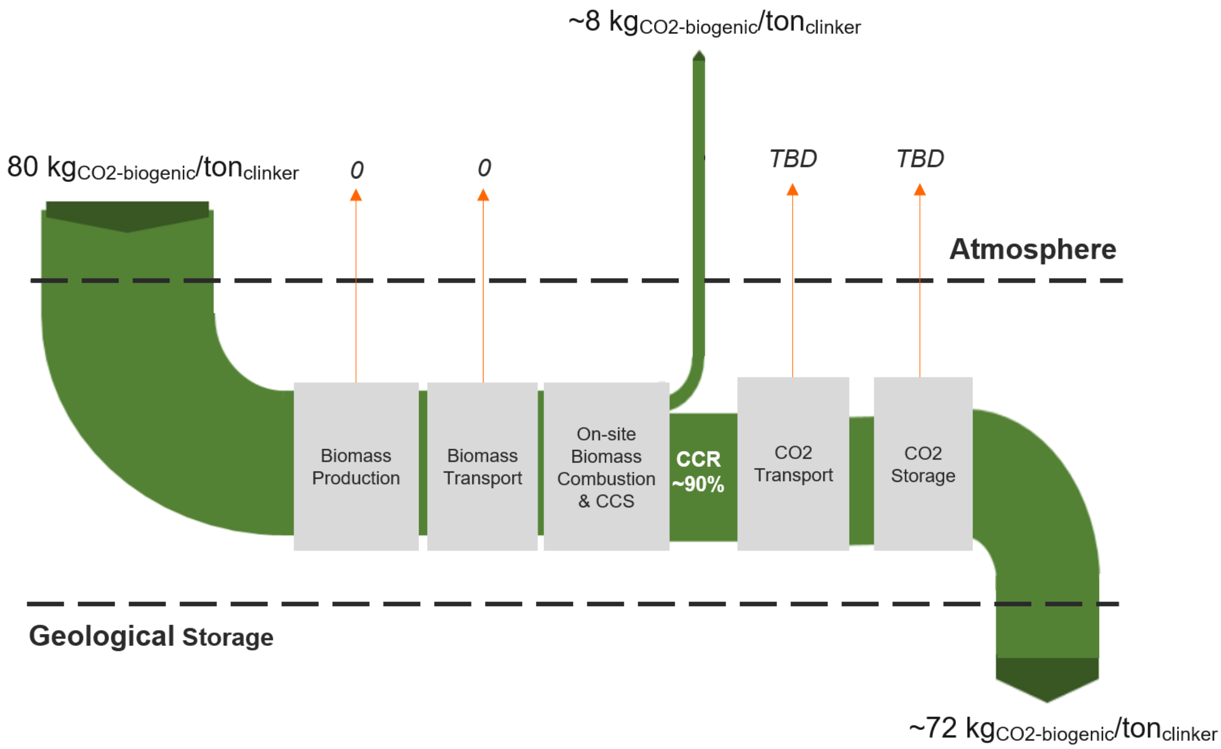

Figure 34: Sankey diagram of BECCS in Swiss cement industry

We compare the price and volume of CDR from the Swiss cement industry to other CDR projects. For this, we extract a number of CDR projects from Carboplan`s CDR database that have received more than 3/5 rating [77]. This means that the projects have a high permanence and additionality rating; forest-based solutions are therefore excluded in this evaluation. For comparison, the cost of CO2 avoided or the CO2 abatement cost of using the CCS MEA technology at a Swiss cement plant was assumed as price for the CDR credit: 157 CHF/ton_{CO2}. The price is highly competitive with existing CDR solutions, particularly in comparison to other high-quality credit providers such as Climeworks which currently charges 691 CHF/ton_{CO2} and estimates a price of 98CHF/t CO2 at scale for capture only. With today`s share of biomass in the fuel mix (17% biomass), the potential annual captured biogenic CO2 amounts to ~72 $kg_{CO2-biogenic}$/$ton_{clinker}$. With an annual production of 3,227,000 $ton_{clinker}$, the annual captured biogenic CO2 is equivalent to ~232'000 $ton_{CO2-biogenic}$ which could be realized as CDR credits. As will be shown in Chapter 7, future increases in the share of biomass in the cement fuel mix will increase the overall quantity of realized negative emissions dramatically. While other, more decentralized CDR solutions build up capacity linearly, BECCS on cement plants can realize high volumes with one installation already. Figure 35 shows the price and volume of these projects in relation to the potential CDR from Swiss cement. In comparison to existing CDR solutions, BECCS from the CH cement industry offers an attractive option in price and volume.

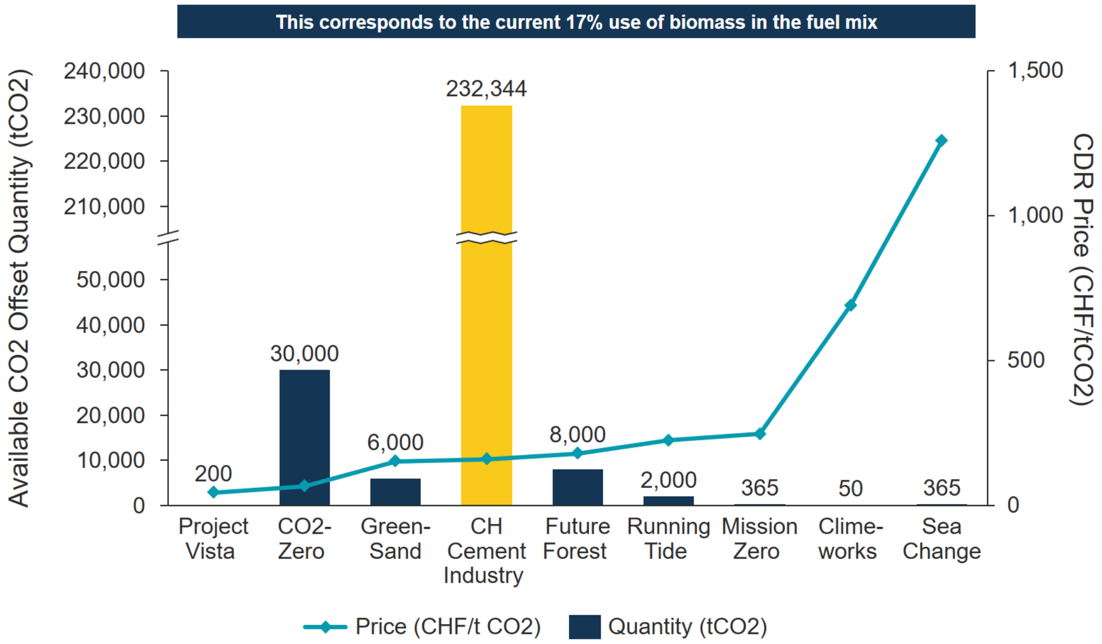

Figure 35: Comparison of international CDR projects CO2 offset quantity and price

Assessing the future potential for BECCS in the cement industry requires the estimation of future biomass availability and its fitness for use as an alternative fuel. A 2017 study quantifies the biomass availability for use in energy applications in Switzerland [32]. The analysis considers the sustainable biomass potential, taking into account ecological and technical limitations of biomass usage. It shows that there is a remaining domestic availability of sustainable biomass from varying sources as seen in Figure 10. Nevertheless, the feasibility of use in the cement industry needs to be assessed on a case by case basis as issues such as price, location and logistics, calorific value and regulatory constrains vary between the different options. The demand for biomass is expected to rise in the upcoming years as more and more industries rely on biomass as a decarbonization lever (refer to section 5.2 for additional information on the availability of biomass). This will likely lead to increased biomass prices and limited availability.

7 Decarbonization Scenarios for the Swiss cement industry

One of the main aims of this study is to identify the available and in-the-pipeline technologies to decarbonize the cement sector in Switzerland and provide the respective CO2 mitigation potential and cost. In Chapter 5, we assessed the various mitigation options individually and independently including their potential impact and application in the Swiss context. In Chapter 6, we discussed the two CDR approaches available to the cement industry that provide an additional avenue to drive down emissions and generate additional revenue.

CO2 Abatement Curve

A marginal abatement cost (MAC) curve is used to demonstrate the emission abatement potential and costs of different mitigation options [28]. It is a useful policy tool to provide initial insights into the various decarbonization options. Figure 36 illustrates the MAC curve resulting from our analysis. The y-axis represents the abatement cost in CHF/ton_{CO2} and the x-axis shows the abatement potential in $kg_{CO2}/ton_{clinker}$ per approach. To understand the magnitude of the CO2 abatement potential per technology (x-axis), one must keep in mind that the baseline is 762 $kg_{CO2}/ton_{clinker}$ corresponding to the current clinker emission intensity. In the MAC curve we display only scope 1 emissions.

Table 16 provides an overview of the assumptions taken in Chapter 5 for the analysis of the individual mitigation options and the resulting CO2 abatement potential and cost per technology.

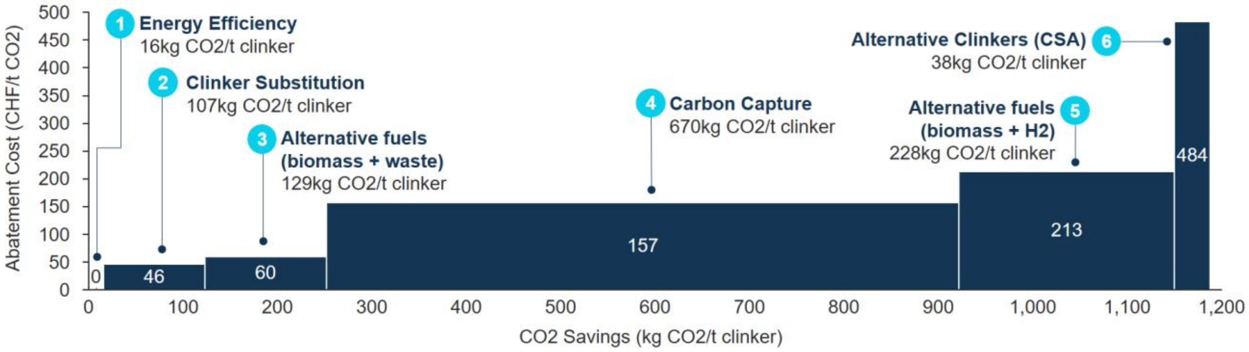

Figure 36: CO2 abatement curve of the different decarbonization options for the Swiss cement industry

What is noticeable is the profound impact of CO2 capture in terms of CO2 savings potential in relation of the other solutions. A fuel mix of biomass and green hydrogen comes in second place in terms of CO2 impact as it completely eliminates fuel emissions (30% of the total emissions) albeit at a higher cost than CCS (213 CHF/ton_{CO2} rather than 157 CHF/ton_{CO2}). The most expensive option, with a limited CO2 savings potential of 5%, is the use of alternative clinkers, for which we use CSA as a proxy. At the current price of CSA (equivalent to three times the price of OPC) the abatement cost is as high as 484 CHF/ton_{CO2}. Energy efficiency has an abatement cost of zero, but also has a limited CO2 savings impact of 2%. When compared to the ETS price of ~86 CHF/ton_{CO2}, clinker substitution and alternative fuels based on biomass and waste are economical options that together can save a third of clinker emissions.

Table 16: CO2 abatement potential and cost per mitigation option

Mitigation Option		Assumptions	CO2 Abatement Potential %	CO2 Abatement Cost CHF/ton$_{CO2}$
1	**Energy Efficiency** *Section 5.1*	Decommissioning and upgrading old equipment is economical.	2%	0
2	**Clinker Substitution** *Section 5.3*	Reducing the clinker-cement ratio from the current average of ~76% to 65% by 2050. SCM price of 110 CHF/ton compared to clinker cost of 75 CHF/ton. CO2 emissions of SCMs not considered.	14%	46
3	**Alternative fuels (biomass + waste)** *Section 5.2*	Increasing biomass use to 60% replacing all primary fuels and reducing the current share of waste fuels to 40%. Future price of biomass 9CHF/GJ considered.	17%	60
4	**Carbon Capture** *Section 5.5*	Technology with 88% of the emissions captured from the cement plant stack. Abatement cost equivalent to cost of CO2 avoided.	88%	157
5	**Alternative fuels (biomass + H2)** *Section 5.2*	Increasing biomass use to 60% replacing all primary fuels and covering the remaining energy demand with H2. Future price of biomass 9 CHF/GJ and H2 2 CHF/kg considered.	30%	213
6	**Alternative Clinkers (CSA)** *Section 5.4*	CO2 reduction is limited to 5%, equivalent to a CSA market penetration of 12% and a CO2 reduction potential of 41%. CSA price equivalent to 300CHF/ton$_{CSA}$ (3x the price of OPC). .	5%	487

Decarbonization Scenarios

This study also aims to show how the evaluated technologies can be combined with the goal of reaching net-zero by 2050 in the Swiss cement industry. In this chapter we present multiple decarbonization scenarios and their respective CO2 mitigation potential and cost per approach.

We model five decarbonization scenarios as listed in Table 17. All scenarios except one, include the use of carbon capture as a mitigation option. The scenarios are selected so that they represent a spectrum of possible approaches, with the extreme scenarios relying only on CCS as a decarbonization lever on the one hand and not using CCS at all on the other. In between the two extreme scenarios, we take a step wise approach in that we test the impact of single mitigation options in combination with CCS (CCS + clinker substitution and CCS + alternative fuels) and then join them all in one scenario (diversified approach).

Table 17: List of the modelled decarbonization scenarios

Decarbonization Scenario	Description and Assumptions
Only CCS	Only CCS is deployed as a decarbonization measure
CCS + Clinker Substitution	Clinker-cement reduced to 65% by 2050. CCS captures the remaining emissions.
CCS + Alternative fuels	Fuel mix with 60% biomass and 40% waste. CCS captures the remaining emissions.
Diversified Portfolio	Clinker-cement reduced to 65% by 2050. Fuel mix with 60% biomass and 40% waste. CCS captures the remaining emissions.
No CCS	CCS is not implemented. Clinker-cement reduced to 65% by 2050. The entire market shifts from OPC to alternative binders, in this case CSA, with a theoretical CO2 reduction potential of 41% and a cost of 300CHF/ton_{CSA} (3x the price of OPC). Fuel mix with 60% biomass and 40% H2.

In modelling these five scenarios, we use the CO2 savings potential and cost per mitigation option as listed in

Table 16. Per scenario, we apply the mitigation options as listed in Table 17. The aim is to test different technology combinations and their overall abatement potential and annual decarbonization cost for the Swiss cement industry. The baseline for calculation is the 2019 scope 1 and biogenic clinker emission intensity, equivalent to 2,457 kilo ton_{CO2} and 258 kilo $ton_{CO2\text{-}biogenic}$ respectively. We include biogenic emissions to quantify the potential of BECCS and any possible revenue from the sale of net negative emissions. We also consider the clinker production and energy consumption of 2019 as a baseline, with 3.227 million $ton_{clinker}$ produced per year and 11,478 TJ of thermal energy and 1,365 TJ of electric energy consumed annually. To compare all scenarios equally, we consider that all scenarios must achieve net-zero and therefore account for the purchase of carbon credits for any leftover emissions.

As a first step, we calculate the emissions that remain after implementing the respective decarbonization levers per scenario. In case the scenario has BECCS potential, we calculate the net scope 1 emissions by subtracting the BECCS emissions from the remaining emissions. If the net scope 1 emissions are positive, the cement industry purchases CDR credits to offset the leftover emissions; if they are negative, they sell the net negative emissions on the voluntary market as CDR credits. We assume the cost of CO2 avoided at a Swiss cement plant using CCS (157 CHF/ton_{CO2}) as price for a CDR credit. The same price point is used for the sale and purchase of credits, i.e. we do not consider the situation where cement companies sell their BECCS CDR emissions at a high cost and purchase cheaper credits to compensate. Furthermore, per scenario, we calculate the additional energy requirements in case of carbon capture and the resulting annual clinker production in case of clinker substitution[43]. Energy efficiency is applied in all scenarios as it is economically attractive and seeing that the equipment is most likely to be upgraded by 2050 anyways.

The results of the CO2 mitigation pathways are presented in the form of waterfall charts, showing the CO2 reductions from today`s levels until 2050. The costs per scenario are also displayed below (Figure 37 - 41).

a. <u>Only CCS Scenario:</u>

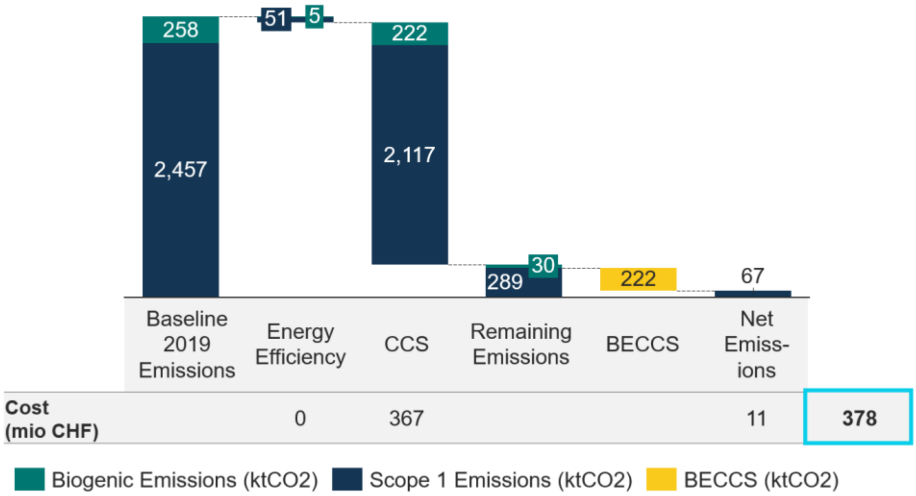

Figure 37: Results of the CCS scenario

In the CCS scenario, only CO2 capture is used as a decarbonization measure (in addition to energy efficiency which is applied in all scenarios). The results show that after applying CCS, 289 kilo ton_{CO2} remain. These are offset with the 222 kilo $ton_{CO2\text{-biogenic}}$ captured in the process, resulting in a net balance of 67 kilo ton_{CO2} which are offset through the purchase of carbon credits. The overall annual cost of this approach for the whole cement industry is **378 million CHF** including the purchase of credits to offset the net emissions. In this scenario, the clinker production remains at **3.227 million $ton_{clinker}$** per year and the additional energy for carbon capture is equivalent to **8,923 TJ thermal energy and 1,349 TJ electric energy**[44].

[43] Additional thermal and electric energy 2,765 MJ/$ton_{clinker}$ and 418 MJ/$ton_{clinker}$ respectively for MEA CCS. Refer to section 5.5 for more information.
[44] As a reminder, the cement industry in 2019 consumed 11,478 TJ of thermal energy and 1,365 TJ of electric energy.

b. <u>CCS + Clinker Substitution Scenario:</u>

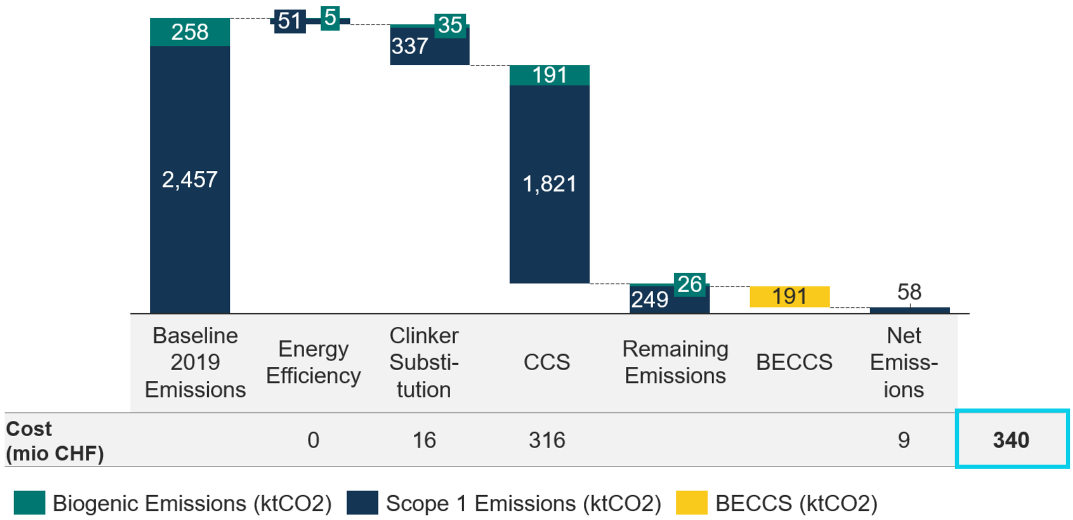

Figure 38: Results of the CCS + clinker substitution scenario

Clinker substitution reduces both scope 1 and biogenic emissions. In the CCS + clinker substitution scenario carbon capture and clinker substitution are used as mitigation options. Our calculations show that 289 kilo ton$_{CO2}$ remain which are offset with the 191 kilo ton$_{CO2\text{-biogenic}}$ captured in the process, resulting in 58 kilo ton$_{CO2}$ net emissions offset through the purchase of carbon credits. The overall annual cost of this approach for the whole cement industry is **340 million CHF** including the purchase of credits to offset the net emissions. In this scenario, the clinker production drops to **2.76 million ton$_{clinker}$** in 2050 and the additional energy for carbon capture is equivalent to **7,631 TJ thermal energy and 1,154 TJ electric energy**. The energy requirements in this case are lower than the only CCS scenario.

c. <u>CCS + Alternative Fuels Scenario:</u>

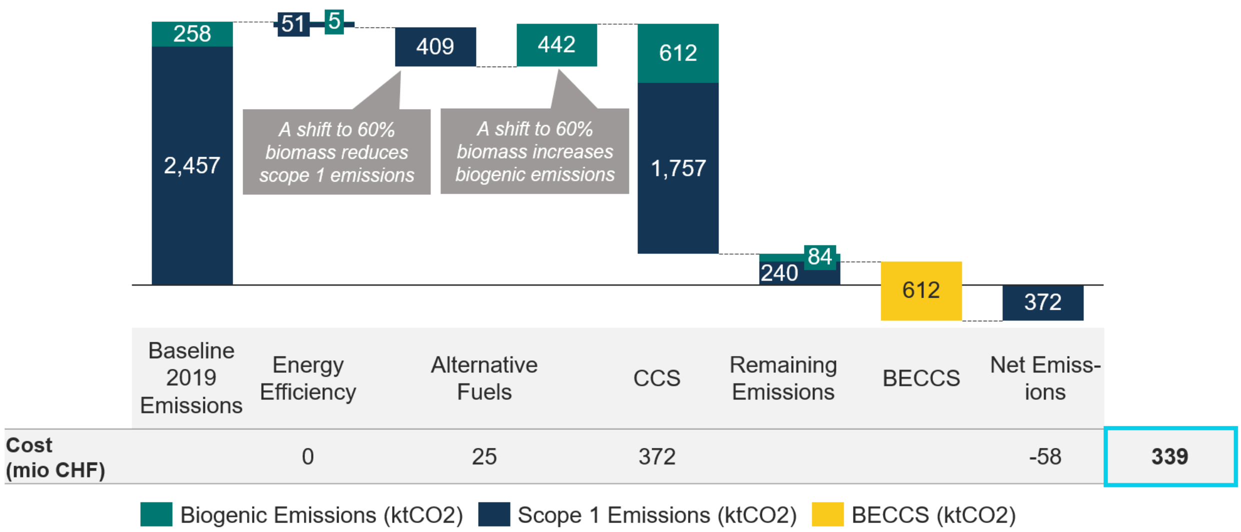

Figure 39: Results of the CCS + alternative fuels scenario

Increasing the share of biomass in the fuel mix from 17% to 60% increases biogenic emissions by 175% and results in an additional 442 kilo ton$_{CO2\text{-}biogenic}$. The additional biogenic emissions and the remaining biogenic emissions after energy efficiency are subject to carbon capture resulting in 612 kilo $ton_{CO2\text{-}biogenic}$ as BECCS. The 612 kilo ton$_{CO2\text{-}biogenic}$ offset the remaining 240 kilo ton$_{CO2}$ scope 1 emissions and results in 372 kilo ton$_{CO2}$ negative emissions. Since net emissions are negative, these can be sold as credits on the voluntary CDR market and generate a revenue of 58 million CHF/year. The total annual cost of this approach including the revenue from carbon credits sales is **339 million CHF**, almost equivalent to the previous scenario. In this scenario, as in the only CCS scenario, the clinker production remains at **3.227 million ton$_{clinker}$** per year and the additional energy for carbon capture is equivalent to **8,923 TJ thermal energy and 1,349 TJ electric energy**.

d. <u>Diversified Portfolio Scenario:</u>

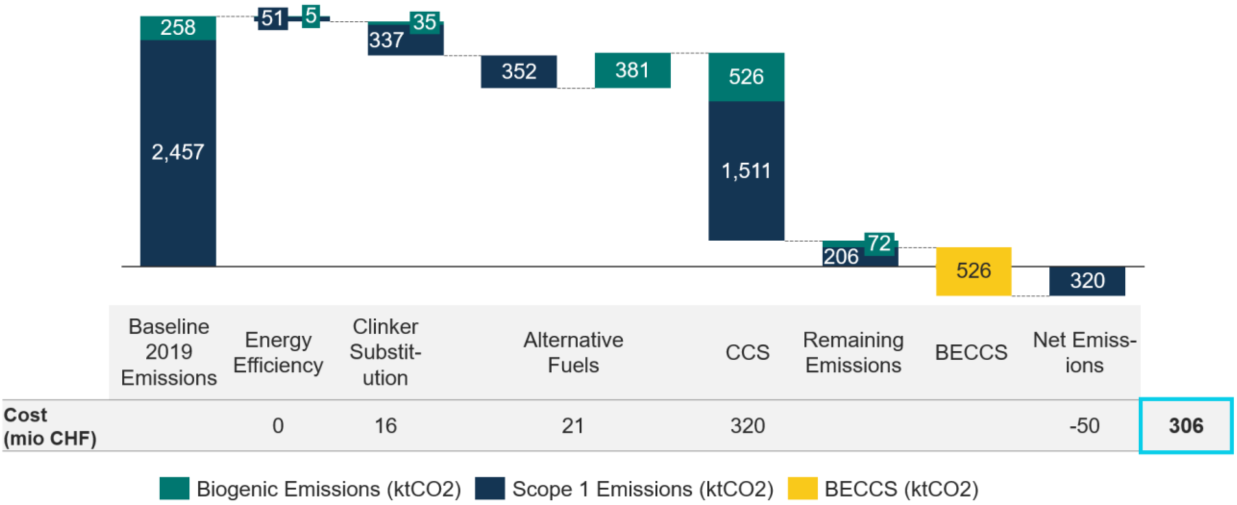

Figure 40: Results of the diversified portfolio scenario

Clinker substitution is the first lever that cuts the quantity of emissions to be captured in the last step. As in the previous scenario, increasing the share of biomass in the fuel mix from 17% to 60% increases biogenic emissions by 175% in the diversified portfolio scenario resulting in an additional 381 kilo ton$_{CO2\text{-}biogenic}$. In addition to the existing biogenic emissions, these are subject to carbon capture resulting in 526 kilo ton CO2-biogenic as BECCS. The 526 kilo ton$_{CO2\text{-}biogenic}$ offset the remaining 206 kilo ton$_{CO2}$ scope 1 emissions and result in -320 kilo ton$_{CO2}$ negative emissions, which are sold as credits on the voluntary CDR market and generate a revenue 50 million CHF/year. The total annual cost of this approach including the revenue from carbon credits sales is **306 million CHF**. In this scenario, the clinker production decreased to 2.76 million ton$_{clinker}$ per year and the additional energy for carbon capture is equivalent to **7,631 TJ thermal energy and 1,154 TJ electric energy**.

e. <u>No CCS Scenario:</u>

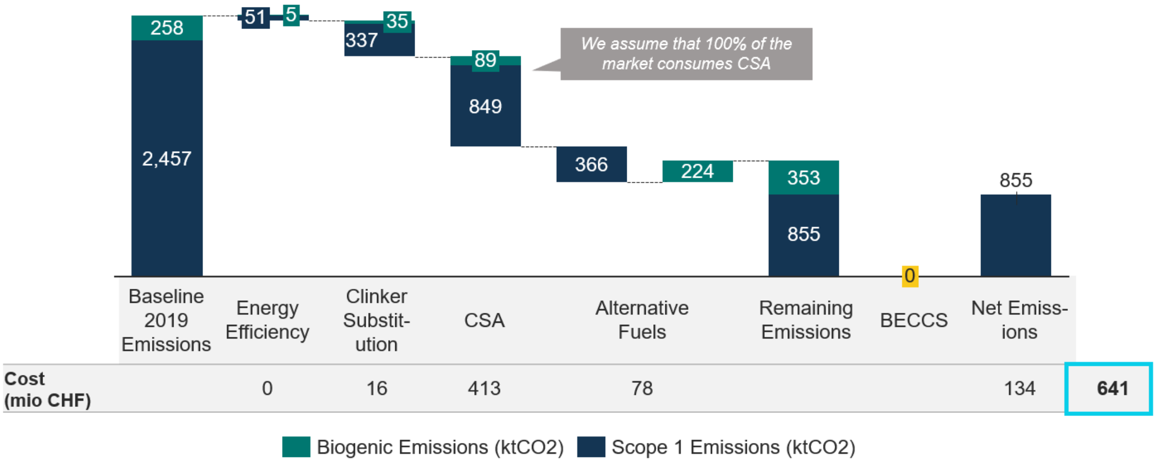

Figure 41:Results of the no CCS scenario

We test a scenario where CCS is not implemented. The aim is to see whether getting to net-zero is possible without CCS and how costly it would be to offset the remaining emissions. We assume that the entire market shifts from OPC to alternative binders, in this case CSA, with a theoretical CO2 reduction potential of 41%[45]. Compared to the previous scenario, not only do we increase the share of biomass from 17% to 60%, we also replace the 40% waste with green H2 to ensure that the entire fuel mix is fossil CO2-free with only biogenic emissions. After implementing energy efficiency measures, clinker substitution, alternative fuels and shifting the entire market to CSA, 855 kilo ton_{CO2} remain, i.e. a 65% reduction in scope 1 emissions. These remaining emissions are offset through the purchase of carbon credits resulting in an overall industry decarbonization cost of **641 million CHF**. This scenario is by far the most expensive, almost double the cost of other scenarios. In this scenario, the clinker production is reduced to **2.76 million $ton_{clinker}$** by 2050 while there are **no extra energy** requirements since carbon capture is not installed.

[45] CSA has a CO2 mitigation potential of 41% and we assume that 100% of the market shifts to CSA use.

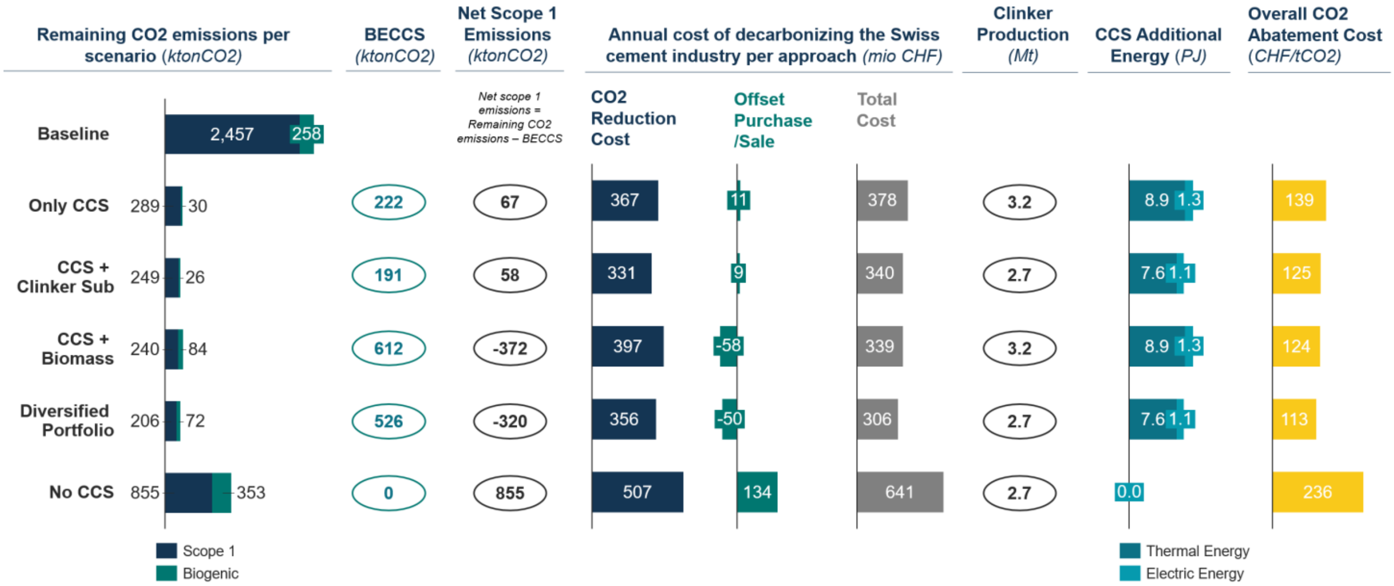

Figure 42: Summary of the decarbonization scenarios in absolute values [46]

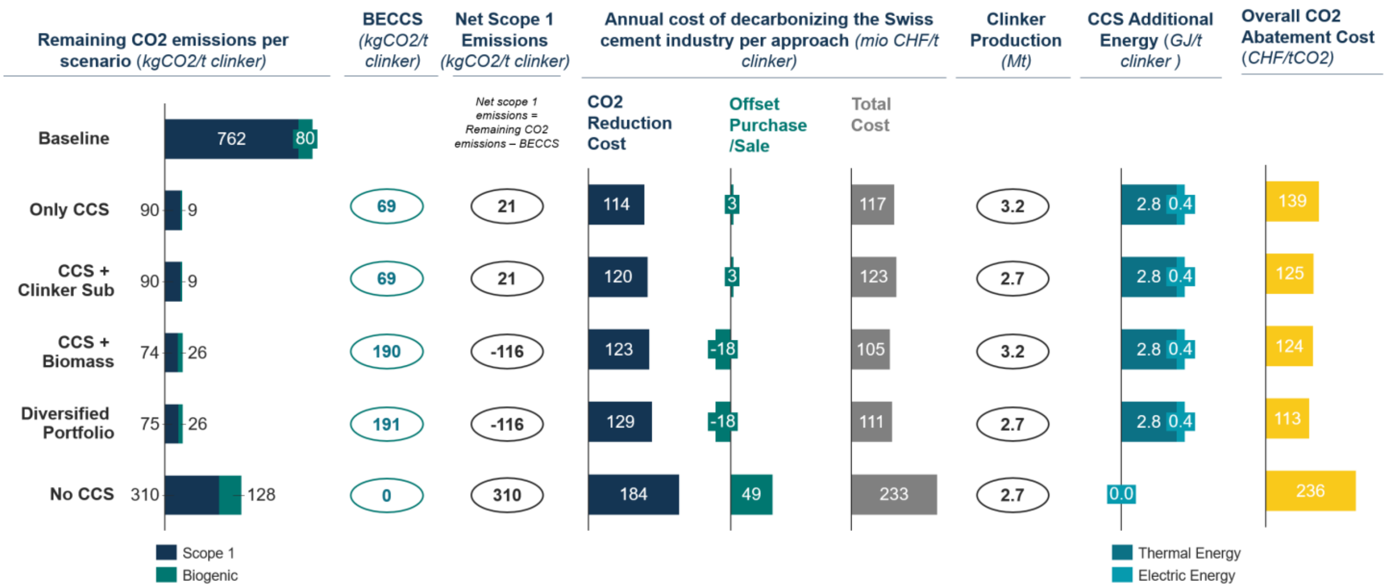

Figure 43: Summary of the decarbonization scenarios in relative values (i.e. per $ton_{clinker}$)

[46] Net scope 1 emissions = Remaining CO2 emissions – BECCS
These emissions are compensated through the purchase of carbon credits.

Figure 42 shows an overview of all scenarios. Focusing on CCS could deliver almost full decarbonization at 378 million CHF per year. Adding clinker substitution leads to a similar outcome, but at lower cost than the pure CCS scenario. The strong increase in biomass (from 17 to 60%) foreseen by cemsuisse would allow for net negative emissions and revenues from the sale of carbon credits. The approaches can be combined into a diversified portfolio, lowering the cost further. In the diversified portfolio, the overall CO2 abatement cost is the lowest among all scenarios, at 113 CHF/ton_{CO2}. Without CCS, the absolute decarbonization costs are almost double all other scenarios driven by the use of green hydrogen and CSA as clinker replacement. Note that on a per ton clinker basis, the alternative fuel approach has the lowest annual decarbonization cost at 105 million CHF/$ton_{clinker}$.

As mentioned in Section 4.1, we do not account for demand-side decarbonization measures, namely cement reduction. Despite being one of the potentially most effective means of decarbonizing the cement industry, multiple sources estimate that the cement demand in Europe will remain constant until 2050 [25] [26]. Nevertheless, any reduction in annual cement production directly eliminates the emissions associated with the production of that quantity. As a result, if cement production is to drop in Switzerland over the next years, the associated emissions can be directly deducted from the scenarios discussed above. This decrease in overall emissions could lead to a reduction of overall decarbonization costs as the emissions-to-be-abated through the decarbonization measures discussed in this project are reduced.

Comparison to the cemsuisse Roadmap 2050 [41]

In this study, we draw on multiple sources including but not limited to the cemsuisse Roadmap 2050 in selecting the assumptions for the analysis and modelling activities. Here, we aim to compare our assumptions to those adopted by cemsuisse:

Alternative fuels: In this study, we consider, similar to cemsuisse, a 60% biomass fraction in the 2050 fuel mix. In our calculations, we scale today's biomass consumption linearly up to 60%, which results in an overall scope 1 emission reduction of 17% (the waste/secondary fossil fuel fraction of 50% in 2019 is scaled down linearly to 40%). In the Roadmap 2050 by cemsuisse, the impact of increasing biomass to 60% results in a 21% emission reduction. The difference between both results could be due to varying fuel distributions.

Clinker substitution and alternative clinkers: We distinguish between clinker substitution and alternative clinkers whereas cemsuisse bundles both into one decarbonization lever. We consider a 2050 clinker-cement ratio of 65% compared to today's 76%. This results in an emission reduction of 14%. As for alternative clinkers, we assume that their emission reduction potential in 2050 amounts to 5%, resulting in a total mitigation of 19%. Cemsuisse, considers a cumulative reduction of 17% for both clinker substitution and alternative clinkers.

Cement production: While cemsuisse expects concrete demand to remain steady, their roadmap includes a 40% reduction in cement production until 2050 due to more efficient usage, equivalent to a 40% drop in emissions. Our study, on the other hand, excludes this and assumes a steady cement production until 2050 in line with multiple other analyses as mentioned above [25].

Carbon capture: cemsuisse includes 1.12 mio ton_{CO2} of CCS and CCU to eliminate the remaining emissions after the implementation of the mitigation options discussed above. Since we adopt multiple scenarios in this study, there is no one value that can be compared but rather a range. Figure 37 to 41 shows graphical representation of the decarbonization scenarios from the "only CCS" scenario with 2.117 million ton_{CO2} and 0.222 million $ton_{CO2\text{-}biogenic}$ and the "no CCS" scenario with zero emissions captured, respectively. Carbon capture in these scenarios is adopted as a final decarbonization lever to eliminate any remaining emissions, whereas cemsuisse assumes to apply carbon capture after a cement production reduction of 40%.

Sensitivity Analysis

In order to better understand the impact of selected variables on the scenarios, we conducted selected sensitivity analyses by testing the effect of changes to the variables on the results of the decarbonization scenarios. We focus on testing the impact of one key variable (clinker-cement ratio, share of biomass and price of CSA alternative clinker) in the respectively relevant scenario (CCS + clinker substitution, CCS + alternative fuels and no CCS). Table 18 shows the three sensitivity analyses with the variables and key model inputs.

Table 18: Sensitivity analysis scenarios and key inputs

Sensitivity Analysis (SA)	Case	Name	Key Inputs
SA1: Clinker Substitution *Variable: Clinker-cement ratio*	Original	CCS + Clinker Substitution 65%	Clinker-cement = 65% CO2 abatement potential = 14% CO2 abatement cost = 46 CHF/ton$_{CO2}$
	Variable	CCS + Clinker Substitution 55%	Clinker-cement = 55% CO2 abatement potential = 28% CO2 abatement cost = 46 CHF/ton$_{CO2}$
SA2: Alternative Fuels (Biomass) *Variable: Share of biomass*	Original	CCS + Alternative fuels 60%	Share of biomass = 60% Biogenic emission increase = 175% CO2 abatement potential = 17% CO2 abatement cost = 60 CHF/ton$_{CO2}$
	Variable	CCS + Alternative fuels 40%	Share of biomass = 40% Biogenic emission increase = 97% CO2 abatement potential = 10% CO2 abatement cost = 54 CHF/ton$_{CO2}$
SA3: CSA *Variable: Price of CSA*	Original	No CCS	CSA price = 300 CHF/ton$_{CSA}$ CO2 abatement potential = 41%[47] CO2 abatement cost = 487 CHF/ton$_{CO2}$
	Variable	No CCS + ½ CSA price	CSA price = 150 CHF/ton$_{CSA}$ CO2 abatement potential = 41% CO2 abatement cost = 160 CHF/ton$_{CO2}$

In SA1, we test the impact of changing the clinker-cement ratio on the results of the CCS + clinker substitution decarbonization scenario. In this report and in the CCS + clinker substitution scenario, we

[47] As a reminder, here we consider that the whole market shifts to CSA cements, so its full CO2 mitigation potential (41%) is considered.

consider the Swiss cement industry to reach a clinker-cement ratio of 65% in 2050, whereas other international sources consider lower ratios [8][5]. For this reason, in SA1, we test the impact of lowering the ratio to 55%. Lowering the clinker-cement ratio to 55% increases the CO2 abatement potential of clinker substitution to 28% versus the 14% achieved with a ratio of 65%. The abatement cost remains constant. In SA2, we test the sensitivity of the CCS + alternative fuel decarbonization scenario on the share of biomass in the fuel mix. Originally, in the scenario we consider a 60% share of biomass, which in the sensitivity analysis we reduce to 40% biomass to consider a more moderate target for biomass given the predicted future increase in prices and demand from other industries. The resulting CO2 mitigation potential of a 40% biomass share is 10%, with an increase in biogenic emissions of 97% and a CO2 abatement cost of 54 CHF/ton$_{CO2}$[48]. Lastly, in SA3 we assess the influence of CSA price on the no CCS decarbonization scenario. The price of CSA considered in the no CCS pathway is 300 CHF/ton$_{CSA}$. In SA3 we cut the price of CSA in half to 150 CHF/ton$_{CSA}$ to account for a future where the use of CSA is fully developed and it is readily available in Europe. This reduces the CO2 abatement cost of this mitigation option from 487 to 160 CHF/ton$_{CO2}$. All of the discussed values are then used in the respective scenarios to test their impact on the pathway CO2 saving potential and industry level cost.

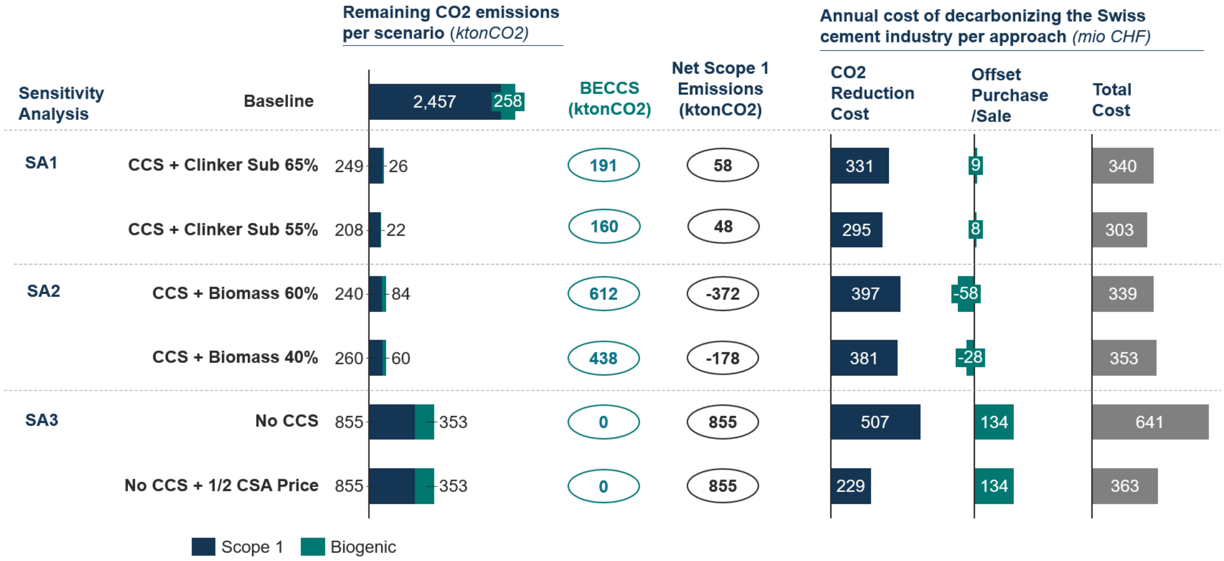

Figure 44: Results of the sensitivity analysis on the decarbonization scenario results

Figure 44 shows the overall results of the sensitivity analysis on the selected decarbonization pathways. In SA1, we notice that an additional 10% reduction in the clinker content of cement (clinker-cement ratio drops from 65% to 55%) reduces the total industry decarbonization cost by 11% from 340 million CHF per year to 303 million CHF. The main takeaway from SA2 is that lower shares of biomass result in lower BECCS potential and less negative emissions, minimizing the revenue from the sale of carbon credits. This results in an overall higher decarbonization cost for the cement industry, with 353 million CHF instead of 339 million

[48] These values can be compared with the original values in

Table 16.

CHF per year. The third and last sensitivity analysis, SA3, shows the significant impact the price of alternative clinker CSA has on the costs of decarbonization. Cutting the price of CSA by 50% reduces the industry cost from 641 million CHF to 363 million CHF.

In conclusion, CCS is the main driver of decarbonization, biogenic fuels can deepen decarbonization and SCMs can mitigate costs. For full decarbonization of the Swiss cement CCS is required. Replacing current fuels with biomass offers the potential to achieve carbon removal, without adding to the cost, on the condition that biomass can be acquired at the assumed price (9 CHF/GJ) and from sustainable sources. Using SCMs to their full potential can be pursued independently and can lower the cost of decarbonization. Alternative clinkers like CSA do not currently offer an advantage especially at today`s high prices. The sensitivity analysis of selected variables has shown that further reductions in the clinker-cement ratio drives down decarbonization costs, lower shares of biomass result in overall higher decarbonization costs due to the lower revenue from CDR credit sales and that the cost of alternative clinkers plays a major role in the costs of a pathways where no carbon capture is used.

PART II – Barriers to decarbonization and policy options

8 Introduction

In Part II, we explore the deployment and scale-up barriers of the decarbonization technologies discussed in Part I of this report. Through a series of interviews with key stakeholders and experts, we identify the main technical, economic, commercial, regulatory and public acceptance hurdles that impede the rollout of low-carbon technologies in the Swiss cement industry. Following this, we explore policy options to potentially overcome these barriers and facilitate the transition to low-carbon cement production, drawing on examples from other countries.

Due to the long lifetimes of cement production assets, investments and equipment upgrades need to be assessed in alignment with the climate targets to avoid lock-in of conventional high-carbon technologies and the creation of long-lasting path dependencies [78]. With ever more stringent climate goals and increasing CO2 prices, this increases the risk of stranded assets [78]. As shown in Part I, the low-carbon breakthrough technologies that can bring the Swiss cement industry to net-zero emissions are known, yet for most no viable business case exists (yet). By developing new and optimizing existing policy instruments, governments could play an important role in sending positive signals to the industry and incentivizing investments in decarbonization technologies [78].

9 Methodology

9.1 Collection of barriers to technology deployment and diffusion

To best understand the barriers preventing the deployment of the cement decarbonization technologies and solutions discussed in the first segment of this report, we conduct interviews with relevant project stakeholders and sector representatives (see Table 1), in addition to external experts[49]. For each decarbonization technology, we collect the respective obstacles to diffusion across six main categories, namely technical, economic, commercial, organizational, regulatory and public acceptance. For some technologies and in some categories, no barriers were identified; for example, there are no issues with public acceptance for the implementation of energy efficiency measures in cement plants. After all interviews are conducted, the results were synthesized and presented in a stakeholder workshop for review and discussion.

[49] The external experts interviewed for the purpose of this study are from the following organizations: Ostschweizer Fachhochschule, WWF Schweiz, Agora Energiewende, Perspectives Climate Group and Carbon Market Watch.

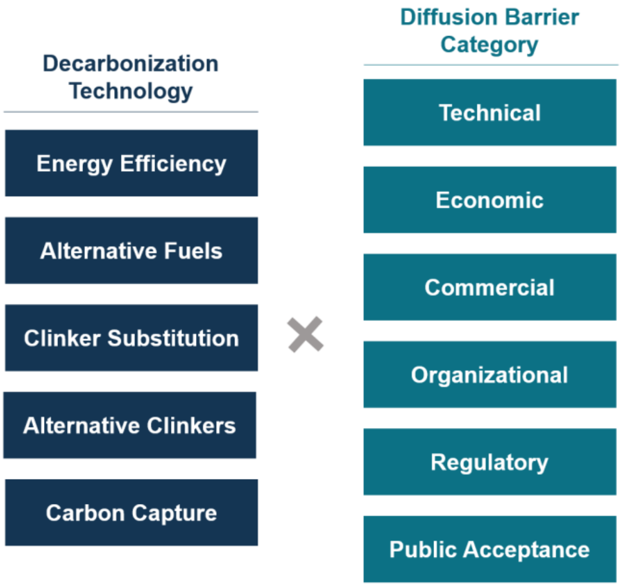

Figure 45: Decarbonization technologies assessment across multiple dimensions

9.2 Policy option inventory and deep dives

The goal of Part II of this study is to present a spectrum of policy options to potentially overcome the identified deployment barriers and accelerate the transition to a low-carbon cement industry. To that end, we perform a literature review to collect relevant policy instruments that could be implemented in the Swiss context and tailored to the cement industry. We construct a policy inventory with definitions based on existing literature [79]–[81]. The inventory also includes examples of how these instruments have been used globally targeting the cement and construction industry (see Table 20). Where cement-focused examples were not found, we include examples from other industries that could serve as a basis for which cement-focused policies could be designed. We group the different policies under the following categories: standards and regulations, pricing instruments, subsidies and incentives and financial policies. These categories are explained in greater detail in Chapter 12.

For each of the decarbonization technologies, we list number of policies[50] that could potentially overcome the discussed deployment barriers (see Table 21). Out of the longlist of policy options, we perform an analysis of four policy approaches that are relevant in the climate policy discussion today, especially in Europe. Our work is based on scientific literature and reports published by European and international organizations such as Agora Energiewende, Energy Transitions Commission, IEA, European Commission, among others. We present the findings in a stakeholder workshop to collect feedback from sector representatives and the associated governmental agencies. The interviewed external stakeholders also provide insights into the discussed policy options which are considered with reference to scientific literature.

[50] The proposed list of policies is not exhaustive.

10 Barriers to decarbonization

The cement decarbonization technologies discussed in this study face varying challenges to implementation with different degrees of complexity. Energy efficiency, a common industry practice, for example, is the most familiar decarbonization approach and faces the least implementation obstacles. On the other hand, carbon capture, faces multiple complex barriers that extend beyond the cement industry and even beyond Switzerland. These barriers will be discussed in this section of the report. The listed barriers include technical, economic, commercial, organizational, regulatory and public acceptance barriers.

Energy Efficiency

As mentioned, energy efficiency measures are commonplace in the cement industry and as seen in Part I of this study, they have a slightly negative abatement cost and are thus cost effective in most cases (see Section 5.1). This also explains why the stakeholder interviews revealed almost no barriers to the implementation of energy efficiency improvements with the exception that large modifications to the plant equipment are dependent on investment cycles. This implies that cement producers are likely not to make significant investments in energy efficiency (e.g., upgrading pre-heater and kiln) unless it is somewhat in line with the decommissioning of older equipment.

Alternative Fuels

Theoretically, no technical limitation exist for the substitution of primary fossil fuels with alternative fuels (biomass and waste) up to 95%. Yet, this high substitution rate is dependent on multiple factors: availability of alternative fuels, especially biomass, a level playing field for access to waste streams, price of alternative fuels and pre-treatment possibilities (see Section 5.2).

The availability of alternative fuels is a concern for all interviewed parties. All stakeholders agreed that the future availability of green hydrogen in Switzerland is uncertain, especially given the energy intensity and quantities needed by the cement industry. Green hydrogen requires a significant amount of renewable energy for production and given the current rate of renewable ramp up in Switzerland, cement producers do not think this is a viable fuel option, even when relying on hydrogen imports.

Access to industrial and municipal waste is also often highlighted by sector representatives as a constraint. The Swiss Ordinance on the Avoidance and the Disposal of Waste “applies to the avoidance and disposal of waste and to the construction and operation of waste disposal facilities” [82] and specifies which waste materials can be used as a heating fuel in the production of cement. For example, it allows the use of tires, waste wood, unmixed plastic waste that cannot be recycled, organic solvents, and sewage sludge. Article 24 of the Ordinance states that cement kilns are not permitted to burn municipal waste and therefore waste-to-energy plants have full access to this waste stream [82]. According to a cemsuisse representative, there also is an ongoing national discussion regarding access to sewage sludge as a fuel as it is considered a biogenic energy source. This is particularly relevant since starting 2026, phosphorus will need to be recovered from sewage sludge and recycled by law and there has yet to be an established method of doing this in and beyond Switzerland [83]. Sewage sludge can be used as a fuel and as raw material in clinker production. Nevertheless, with the phosphorus regulation upcoming and no technical solution in sight, there is a risk that sewage sludge might be excluded from the cement industry fuel mix, increasing their dependence on other biogenic waste streams to achieve the aspired rates of alternative fuels.

Biomass use in the kiln fuel mix is likely to play an increasingly important role in the future due to its climate neutral emissions and the potential for BECCS and negative emissions in the cement industry. However, the uncertainties regarding the availability of waste and sustainably sourced biomass are a point of concern for industry representatives. As all industries attempt to meet their climate targets, the demand for biomass is expected to increase in the upcoming years, according to interviewed stakeholders, who believe that other limitations could arise from land availability and improved recyclability of biomass. This increased demand could lead to a spike in prices. With high decarbonization ambitions and a goal of 60% biomass in the fuel mix according to the cemsuisse Roadmap 2050 report [41], the cement industry perceives this as a key challenge.

A key aspect for consideration is the national level impact of waste streams and their use as an energy source. As the cement industry moves away from fossil fuels and minimizes non-biogenic emissions, the combustion of secondary fossil fuels (e.g., plastics, tires etc.) becomes less attractive from a climate perspective as their combustion results in fossil fuel (scope 1) emissions. What remains unclear is where this waste will flow if not to cement kilns. This could potentially result in shifting the associated fossil emissions to other industries such as waste-to-energy which are not part of the compliance market but have voluntary agreements for emission reductions. According to industry stakeholders, shifting away from waste fuels in the cement industry would require significant amounts of zero-carbon energy carriers such as clean electricity, green H2 and biomass. Zero-carbon power today is expensive, and the required kiln electrification technology is not commercially available. Green hydrogen is considered a high value fuel and the future availability remains uncertain, potentially leaving biomass as the most important alternative fuel option. In fact, the Energy perspectives 2050+, which analyze and model four different scenarios for a future energy system in Switzerland compatible with the 2050 goal of net-zero GHG emissions, posit that biomass will play an important role in the future of the Swiss energy system especially for the generation of negative emissions, namely BECCS [84]. Therefore, the use of biomass is planned to be prioritized in the long-term at large point sources where CCS technology is possible, including cement plants and waste-to-energy. While not considered in this study, electricity based energy carriers could potentially be other alternative fuel options [33][90].

Clinker Substitution

As outlined in Part I of this study, clinker substitution is one of the key decarbonization levers for the industry with relatively low CO2 abatement cost (see Section 5.3). Yet, the stakeholder interviews reveal barriers in multiple areas: technical, raw material and normative. From a technical viewpoint, experts identify the longer concrete setting times associated with low clinker-cement ratios as a challenge to their standard and wide-spread use in the industry. Additional setting time leads to on-site delays with economic repercussions for the construction project at hand. This results in demand-constrains, as the market is not ready to work with such lagged setting times. To address this, improving the early strength of highly blended cements mainly using superplasticizers will be a key research focus in the next years, according to an interviewed expert.

The limited availability of SCMs in Switzerland and generally in Europe established in Part I of the report is a topic of concern for cement manufacturers. With LC3 on the horizon, Swiss cement producers are individually assessing the local availability of Kaolinite-rich clays near production sites. As SCMs such as GBFS and fly ash become scarcer in Europe, the demand and hence prices are likely to increase. Even today, reactive SCM prices in Switzerland are significantly higher than limestone (inert SCM) which is approaching the technical replacement limit in the Swiss cement mix, as stakeholders report.

Switzerland`s concrete norm SIA 262 limits the use of some highly blended cements and freedom of designers to minimize the overall cement quantity in a concrete mix due to a predefined minimum cement quantity [85]. Appendix E covers in depth the current limitations of SIA262.

Alternative Clinkers

Today, alternative clinkers are perceived as a niche application by cement producers for technical, resource availability and other reasons. Technically, producing two types of clinkers and thus cements in one plant results in the interruption of the steady process of producing clinker resulting in downtime and process inefficiencies. It would also require additional and separate onsite storage space. The local and regional availability of the raw materials necessary for the manufacturing of most alternative clinkers, in addition to their price, are significant barriers to roll-out. Two other identified key hurdles are the lack of market demand for these products and the absence of standardization in Europe. In general, alternative clinkers are perceived to be too early stage with low TRLs by industry stakeholders.

Carbon Capture

Our interviews reveal that carbon capture as a decarbonization technology for the cement industry has the highest barriers to implementation today. The challenges identified extend beyond the cement industry across the value chain to more foundational open questions such as the financing and availability of a CO2 transportation network, energy requirements, etc.

Technically, some of the carbon capture technologies are already commercial in other sectors. In the cement industry, most global ongoing and upcoming carbon capture projects are in the pilot and demonstration phase, mainly in Europe and the USA (see Appendix F for list of pilot projects). As most mature carbon capture technologies are post-combustion, it is unlikely that the CO2 capture process will interfere with the cement manufacturing process. Yet, for other technologies such as oxyfuel and calcium looping, stakeholders voiced technical concerns, for instance, around potential impacts on clinker quality and the stable production process as they require the modification of key production equipment.

An upstream bottleneck is access to energy carriers (e.g., renewables, gas, H2 etc.), as Section 5.5 has shown that the installation of CCS in Switzerland would almost double the energy requirements of the cement industry. Hence, according to the interviewed industry stakeholders, long-term access to the clean energy sources required to meet this demand is a decisive factor in CCS investment decisions.

Downstream, today, cement companies have the option of transporting captured CO2 via train, which in the short term and for smaller CO2 quantities is feasible and can be used for pilot projects or small-scale applications. However, the ramp up of large-scale industry-wide CO2 capture and transport likely demands a CO2 transport pipeline network which is currently neither available in Switzerland nor in neighboring countries.

Economically, CCS is capital intensive and has high operational costs, significantly increasing the cost of producing clinker as seen in Section 5.3.3. The industry stakeholders stress the following: As cement is a price sensitive product and despite the fact that cement manufacturers are part of the ETS compliance market with rising CO2 prices, under the current setup of receiving free allocations, these companies are unlikely to invest in the technology without financial support for fear that added costs would render them uncompetitive. In addition, the future costs of fuels and electricity are perceived as critical, given the quantities of energy required to power the capture process. The financing model for a potential CO2 network in Switzerland was also mentioned by multiple interviewees as an open point of discussion with respect to its potential financial implications for emitters.

Commercially, on a company level, CCS requires a substantial investment and is viewed as highly risky and uncertain in light of the barriers outlined above. Interviewed stakeholders also highlight supra-national issues including the need for cross-border agreements for CO2 transport and long-term CO2 offtake contracts with countries such as Norway which offer storage capacity. The current regulations for CO2 accounting in Switzerland disincentive CCS/CCU as the Swiss CO2 ordinance prohibits the accounting for such emission reductions in the ETS [86]. This means that cement companies must surrender allowances for the captured and stored emissions. However, the Federal Council proposes to change this in the coming years as is discussed in Section 11.2.

Moreover, the current restrictions around expanding or establishing new raw material pits pose an investment risk for low-carbon technologies with long lifetimes such as CCS according to industry players. Whereas some manufacturers have large long-lasting material reserves, others do not and will likely not invest in CCS as the technology lifetime exceeds material availability.

Industry representatives also highlight the perceived lack of a clear national vision for carbon capture including plans for the rollout of a CO2 network. In their mind, this hinders their investment decision since there is no long-term security for CO2 offtake. At the same time, CCS is acknowledged as a necessary measure in achieving a net-zero future in the Energy perspectives 2050+ and also mentioned in Switzerland's long-term climate strategy [87][88]. However, at the moment, the Federal Council has no constitutional president to regulate transport and storage [89].

Lastly, as opposed to the other decarbonization technologies, carbon capture is not widely discussed in the public sphere. In the eyes of the cement industry representatives, the possible lack of public acceptance is also seen to impede the national momentum towards this technology as it may create political barriers. However, so far there has been no open opposition in Switzerland from NGOs, cantons or other actors.

Table 19: Summary of key barrier to decarbonization technology diffusion

Technology	Key Barriers
Energy efficiency	– Upgrade to pre-heater and kiln depends on investment cycle
Alternative fuels	– Uncertainty regarding the availability of fuels (e.g., availability of green H2 and other renewable energy sources, availability of biomass and competition with other sectors) – Uncertainty regarding future cost of fuels – Future access to municipal and industrial waste
Clinker substitution	– Concrete code prescribes the quantity and type of cements to be used in concrete mixture, and concrete additives – Future and local availability of SCMs – Demand-side constrains
Alternative clinkers	– Low TRL – Raw material availability and efficiency of the production process – Standardization not available in EU – Demand-side constrains regarding a completely new product on the market
Carbon capture	– Significant energy demand – Notable increase in the cost of producing clinker – Infrastructure availability – CO2 accounting – Public acceptance – Long-term investment security which hinges upon multiple factors like CO2 pricing, long-term CO2-offtake contracts, raw material availability, and infrastructure availability

Overall, we note that while all the discussed technologies are associated with implementation barriers, carbon capture faces the most complex obstacles as it hinges on national and international decisions, in particular on renewable energy availability and a local and cross-border CO2 network. The Swiss government has signaled the future availability of zero-carbon and alternative fuels, in addition to acknowledging the need for CCS and negative emissions as part of the long-term climate strategy [30][85]–[87]. Nevertheless, for the cement industry, numerous challenges for investing in CCS remain.

International cement carbon capture projects

As part I of this study concludes that CCS is an essential technology for reaching net zero by 2050, we perform a survey of ongoing and planned CCS project internationally. Appendix F lists relevant projects with information relating to location, type of project (e.g. demonstration, commercial etc.), capture capacity, funding mechanism etc.

The list of projects reveals that most projects are located in Europe, are in demonstration phase and publicly funded. To highlight some examples: The Norwegian Longship project plans to install the first large-scale commercial CCS for the Brevik cement plant capturing 400,000 ton_{CO2} per year [62][91]. The project is set up as a public-private partnership with the government providing partial funding and is currently in the detailed planning stage. Another example is the EU HORIZON 2020 ACCSESS project where HeidelbergCement will test carbon capture at one of its cement plants in Górażdże, Poland, and will conduct a study to explore the best capture option for another plant in Hannover, Germany [92]. In partnership with other industry players, the consortium aims to develop a CO2 transport system from the two cement facilities (as well as a Waste-to-Energy plant in Switzerland and a pulp and paper plant in Sweden) to storage in Norway.

As several companies and industrial clusters in Germany, the Netherlands, Norway and the UK are developing cement carbon capture projects, these projects could potentially provide blueprints for Switzerland with their setups as public-private partnerships and project structures. Building on experience from European pilots in the cement industry and other industries (e.g., power sector), where CCS has already been commercialized at-scale, could enable knowledge transfer and technology validation.

Initial carbon capture feasibility and demonstration projects have already been set up in Switzerland: DemoUpCARMA (Demonstration and Upscaling of CARbon dioxide MAnagement solutions for a net-zero Switzerland) is a project which focuses on the demonstration of CCUS to achieve negative emissions by bringing together 21 academic and industry partners [95]. The project also investigates the potential of creating a CO2 network for cluster of Swiss emitters, including cement plants, and CO2 storage sites.

11 EU and Swiss Climate Policy Landscape

To further understand the current barriers faced by the cement industry in the deployment of low-carbon technologies, it is essential to review the current policy landscape not only in Switzerland but also in the EU as it is Switzerland`s main trade partner. Due to this relationship and alignment of climate ambitions, it is useful to have an overview on both levels.

11.1 EU Policy Landscape

11.1.1 Fit for 55

On July 14th, 2021, the European Commission published the "Fit for 55" policy package as part of the European Green Deal with the goal of making Europe the first climate neutral continent by 2050 in a fair, cost-efficient and competitive way [96]. This package is a set of inter-connected proposals with new legislation and improvements to existing ones, resulting in a policy mix of standards, carbon pricing, targets and support measures in the areas of climate, energy and fuels, transport, buildings and more [96].

In the following section we focus on the suggested policy changes that are expected to impact the Swiss cement industry. For example, one of the key elements of the package are the suggested changes to the EU ETS to align with the binding 55% net emission reduction target by 2030 compared to 1990 under the EU Climate Law [97][98]. Proposed changes to the EU ETS include the introduction of the maritime sector to the existing ETS starting in 2026, but more importantly the increase of the Linear Reduction Factor (LRF)[51] from the current 2.2% to 4.2% from 2024 [99]. This implies that industries subject to the ETS will need to decarbonize faster.

Currently, cement manufacturers in Europe and Switzerland obtain free allowances to emit under the ETS since they are considered to be at a risk of carbon leakage, meaning that if they are to pay the full cost of pollution, then production - and associated emissions - could shift to countries with less ambitious climate goals and regulations. These free allocations are distributed based on a benchmarking approach which considers the 10% most efficient installations within each sector [100]. Therefore, efficient installations, closest to the benchmark, get all or most of their emissions covered by free allowances. As mentioned in Part I of this report, Swiss cement plants belong to the more efficient ones in Europe and therefore cover most of their obligations with free allowances. Inefficient installations shall make greater efforts to reduce emissions or purchase more allowances to meet their obligations [100]. In this context, it has been argued that operators profiting from free allocations have little incentive to reduce their emissions, and in some cases are even given the opportunity of windfall profits due to over-allocation [96][97]. The "Fit for 55" package proposes the phase out of free allocations by 10% annually starting 2026 to reach zero in 2035 while simultaneously introducing a CBAM as a carbon leakage protection mechanism [96]. CBAM is proposed to come into force in 2023 for a three-year transitional phase with only reporting requirements. Switzerland will be exempt from the EU CBAM due to the ETS linkage agreement [103][104].

Under a CBAM, importers of ETS-covered products shall buy certificates or carbon allowances covering the scope 1 embedded emissions of their products. For now, indirect emissions are excluded but this is to be revised in 2026 [103]. Imported product emissions shall be calculated based on actual emissions; however, depending on data availability importers may have to purchase certificates based on the average emissions of the product from the exporting country, or emissions would be assumed to be equivalent to the 10% worst performing installations in the EU [105]. As the number of free allowances for local producers is reduced, importers shall purchase CBAM certificates with a price linked to the EU ETS price, subjecting them to the same CO2-pricing as their EU counterparts [104]. The sale of CBAM certificates and purchase of allowances by EU producers which used to receive free allocations will increase revenues for the EU and

[51] The LRF determines the rate as which emissions decrease under the EU ETS since it reduces the emissions cap and thus the annual number of free and auctioned allowances.

can be used in multiple avenues. In this context, it is relevant to note that the European cement association CEMBUREAU has voiced opposition to the reduction of free allocations with the introduction of CBAM, at least in the initial phase of the policy up to 2030 [106]. CBAM has shown to be a controversial policy and is likely to be subject to rounds of negotiations within the EU but also with international trade partners. According to an interviewed policy expert, a number of issues remain unclear, including how the incoming funds will be used, the compatibility of the policy with World Trade Organization (WTO) rules, exports and tax rebates, and more.

With regards to CCS and CCU, the EU Directive 2009/29/EC states that "an obligation to surrender allowances shall not arise in respect of emissions verified as captured and transported for permanent storage to a facility for which a permit is in force in accordance with Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide" [107]. Article 12 of the ETS Directive 2003/87/EC [108] was amended to include CCS in phase three of the ETS (2013-2020), meaning that captured and safely stored emissions will be counted as "not emitted" and thus do not require the surrender of allowances.

CCU was not included in the 2009 amendment. However, the 2021 "Fit for 55" proposal for amending Directive 2003/87/EC calls for its inclusion and "establishes that surrender obligations do not arise for emissions of CO2 that end up permanently chemically bound in a product so that they do not enter the atmosphere under normal use" [109]. As a result, companies capturing CO2 and using it in the production of fuels, plastics, building materials and more, do not need to surrender emission allowances on the condition that the CO2 is stored permanently and not released into the atmosphere during "normal use". For example, synthetic hydrocarbon fuels are not considered a permanent storage of CO2 as the molecule is re-released into the atmosphere during "normal use" of the product i.e. combustion of synfuels [110]. Multiple watch groups, advisors and activists have voiced concern over a one-size-fits-all approach to CCU from a regulatory perspective as multiple CCU options still result in CO2 emissions [110].

Another important development is the establishment of the Innovation Fund, funded by the EU ETS proceeds, which supports the demonstration of innovative low-carbon technologies with projects focusing on energy storage, innovation renewable energy generation, CCS, CCU and innovative low-carbon technology to replace carbon-intensive counterparts [111]. It is intended for technologies that are not commercially viable at scale without support but are mature enough to be deployed at a pre-commercial demonstration scale. Switzerland does not have access to this funding scheme.

The "Fit for 55" proposal will go through the EU legislative process with multiple negotiation rounds and likely amendments before being approved and set into force by the Council of the EU and the European Parliament.

11.1.2 Carbon Removal Regulations

With regards to CDR, highly relevant for the cement industry, particularly in relation to BECCS and the business case of CCS, currently neither an EU standard for the measurement and verification of removals, nor an incentive structure for CDR under the current climate policy exist. As mentioned above, under the EU ETS, installations have no obligation to surrender allowances for CO2 that is captured and permanently stored [107]. Thus, it supports the reduction of emissions but does not cover the removal of CO2 from the atmosphere [112][113]. Currently, CO2 removals are only covered by voluntary and unregulated schemes.

In December 2021, the European Commission, published a communication on Sustainable Carbon Cycles whereby it shared its ambition and vision for carbon removals in the Union [114]. The communication highlights the prioritization of emission reductions over removals as a means to reach the climate goals. The document emphasizes the need for the establishment of a regulatory framework focusing on the certification and verification of removals. Precedence shall be given to "domestic" i.e. EU CO2 removal projects. Starting 2028, each ton of CO2 captured, transported, used and stored will be reported and accounted for based on its origin (fossil, biogenic or atmospheric) increasing overall transparency.

In an open letter to the Commission, multiple climate policy and environmental organizations have voiced some concerns [115]. The letter stresses the potentially negative interactions with existing policies such as the ETS which have their own targets. The trading of CDR certificates under the ETS would undermine the goal of the policy as an emission reduction tool as it equates emission reduction with removals. Emission reduction should be prioritized and distinguished from removals. Polluters should not be given the opportunity to avoid carbon pricing and cutting emissions in their activities through the purchase of CDR credits under the ETS. At this point, it remains unclear whether the Commission will allow CDR certificates to be traded as part of the ETS. The letter also addresses the need to clearly define the permanence of the removals, stating what is considered short and medium storage vs. long-term permanent storage. Also, the Commission is asked to specify who will be liable in case the emissions re-enter the atmosphere.

11.1.3 Swiss Climate Policy Landscape

One of the cornerstones of the Swiss climate policy is the CO2 levy that is imposed on fossil combustible fuels (e.g., coal, heating oil, natural gas, etc.) to accelerate the uptake and incentivize the use of carbon-neutral, low-carbon and zero-carbon fuels and energy sources. The levy is currently set at 120 CHF/ton$_{CO2}$ since the start of 2022. Nevertheless, according to the Swiss CO2 Act: “Installation operators that participate in the ETS shall on application be refunded the CO2 levy on thermal fuels” [116]. The cement industry is obliged to participate in the Swiss ETS and is therefore exempt from the CO2 levy.

The Swiss ETS began as a voluntary system in 2008 and was subsequently enforced in 2013 and made mandatory for large energy intensive industries such as cement. In 2020, the Swiss ETS was linked to the EU ETS and enables “the registry-to-registry transfer of emission allowances issued under either ETS” [117]. Additionally, according to the Swiss-EU agreement “emission allowances that can be used for compliance under the ETS of one Party shall be recognized for compliance under the ETS of the other Party” [117]. Linking the systems provides the benefit of increased liquidity and transparency in the Swiss market with the same price signal as in the EU, while granting Swiss operators additional flexibility to meet their emission targets. As mentioned in Chapter 11 on the technology deployment barriers, under current Swiss ETS regulations, allowances must be surrendered for any emissions that are captured and stored [86]. This could be considered a disincentive for the cement industry as it substantially affects the business case of CCS.

However, at the end of 2021, the Federal Council initiated a consultation (“Vernehmlassungsverfahren”) on parts of the CO2 Act. Included in the consultation document [89] is to allow the accounting for CCS in the Swiss ETS similar to current EU regulations and to define clear accounting and reporting rules at the ordinance level. Storage eligibility would follow the same guidelines set out in the EU CCS Directive 2009/31/EC47; however, national storage options should also be explored. The consultation document also posits that the storage of CO2 in long-lived products such as building materials should be eligible, as envisaged by the European Commission in its "Fit for 55" package of proposed revision of the ETS. Similarly, all forms of CO2 transport should be allowed (e.g., trucks, trains, ships, pipelines). These modifications could incentivize companies to install CCS especially in light of increasing CO2 prices.

BAFU is currently examining how double counting could be avoided (in the case of CO2 exports to foreign storage sites) and which limit values are appropriate for any pollutant emissions in connection with CO2 capture [89]. Regulation regarding the associated infrastructure, specifically a CO2 pipeline and inland storage, will fall under the responsibility of the cantons, as there is no constitutional basis for comprehensive regulation by the federal government. The consultation document also states that the federal government has voiced its willingness to take the coordination role in the case of national interest and if this is desired by involved stakeholders. Furthermore, they plan to credit negative CO2 emissions from the capture and storage of biogenic CO2 emissions resulting from the combustion of biomass (BECCS) in an installation covered by the ETS. Yet, accounting will likely be done outside of the Swiss ETS, meaning that this will count as a project for CO2 compensation under the Ordinance [89].

The ongoing discussions on the EU level, also regarding the phase out of free allocations are relevant for Switzerland as they may need to harmonize the content and timing of policies. The potential introduction of

EU CBAM will also be a point of discussion, as legally Switzerland does not have to implement it in case it moves forward on an EU level. However, the resulting asymmetry of costs for imported goods from third countries between the EU and Switzerland may require the introduction of a similar mechanism with the equal stringency to ensure a same level playing field; without its introduction, imports into Switzerland may not see rising costs whereas EU imports may.

12 Policy options for the rollout of decarbonization technologies

As discussed in Part I of this study, the decarbonization technologies for the cement industry exist, albeit at varying stages of maturity and cost. Well-designed and coherent policies could help overcome the implementation barriers discussed in Chapter 10, in addition to the willingness of the industry to substantially decarbonize. Most of the breakthrough technologies have relatively high CO2 abatement costs with no clear business case (yet) and additional costs are hard to pass on completely to consumers due to carbon leakage and international competition [78]. Public support and tailored policies could help to provide long-term investment security and support the industrial decarbonization efforts.

National policymaking is a complex process involving multiple actors with often conflicting interests. The choice and design of certain policies might lead to positive outcomes for some and negative consequences for other stakeholders; these include the government, targeted industry, consumers, labor organizations, other value chain actors, environmental organizations, public and more [118]. Working Group III of the Intergovernmental Panel on Climate Change (IPCC), notes in its fourth assessment report that governments often opt for a policy mix rather than relying on a single instrument to reach climate goals. These instruments could have varying levels or stringency which could be revised and adjusted over time. They could be legally binding or voluntary. The interaction between different instruments targeting a single industry, but also cross-sectorial impacts is to be assessed to ensure compatibility. Additionally, the enforcement and monitoring of regulations using workable methods and systems is of great importance to minimize administrative burdens [118].

Multiple carbon policy instruments exist and ultimately aim to incentivize or enforce actions to reduce CO2. We categorize these policies, based on the IPCC`s fourth assessment report, as follows:

Regulations and Standards:

A standard specifies the actions that an organization or individual shall or shall not undertake to comply with an environmental objective [118]. Standards have two main approaches: (1) technology specific or prescriptive standards mandate the use of specific clean technologies, products or processes as a means to achieve certain environmental objectives. For example, carbon capture may be mandated as a technology to decarbonize cement; (2) performance standards require a certain environmental performance to be achieved, but do not specify the technology or methods of achieving this performance. Following the example above, as opposed to the prescriptive standard, a performance standard would limit the quantity of emissions in kg_{CO2}/ton_{cement}. A familiar example of standards are mandatory energy efficiency standards.

Pricing Instruments (Carbon Pricing):

Carbon pricing is a policy instrument that follows the polluter-pays principle and captures the external cost of GHG emissions by placing a price on CO2 [119]. This provides a price signal and creates an economic incentive to reduce emissions. For this instrument to have its desired decarbonization effect, CO2 needs to be priced adequately. This approach is a potential source of revenue for the government and could be used to fund other support mechanisms. The most common forms of carbon pricing are the following (other mechanisms will be discussed in subsequent chapters):

a) Charges and taxes:

A GHG charge or tax is a fee paid by the polluter for every unit of GHG released into the atmosphere. Commonly these charges are applied to commodities directly linked to emissions such as fuels. An example of this in Switzerland is the CO2 levy imposed on fossil combustible fuels such as heating oil to incentivize the shift to cleaner low-carbon fuels [120]. Depending on the value of the charge, it could be an effective incentive to switch to alternative fuel options since it creates competition between fossil fuels and clean fuels. However, it does not guarantee a specific emission level. In setting an emission charge, multiple factors may need to be accounted for including but not limited to: value at which the tax is set, exemptions from the tax if any, how the revenue of the tax will be used, increasing stringency over time, at what point should the tax be collected (impacting the admin fees), response of customers to price signals and other factors that may distort the tax such as subsidies in targeted industries (see Section 14.4 for more detail) [118].

b) Tradable permits

Commonly known under ETS, tradable emission permits are allowances to emit a certain amount of GHGs. Emission trading is a market-based approach that can be designed to cover the emissions from a handful of sectors or theoretically the entire economy [121]. The government sets a cap to the overall amount of GHGs that can be emitted per year and companies shall hold a permit or allowance for every ton of CO2 they emit within this year. The cumulative number of permits in the market shall be equivalent to the cap set by the state [118]. Companies either receive free allowances to emit (to prevent carbon leakage) or purchase these allowances to emit through an auction or secondary market. Ultimately, companies must surrender allowances equivalent to the amount of $CO2_{eq}$ emitted in that year. Therefore, the company must decide either to pay the cost of emissions or to reduce emissions.

Incentives and Subsidies:

Subsidies aimed at emission reduction incentivize the investment in and use of low-carbon technologies and fuels. Common examples include feed-in tariffs to support the production of renewable energy and direct subsidies on clean technology investments such as the subsidy given by some Swiss cantons for the replacement of oil, gas or electric heaters with heat pumps for building heating [122]. These subsidies or price supports can be paid out as a lump-sum or as a remuneration as in the case of the feed-in tariff. One potential way of financing subsidies is through the revenue generated from other instruments such as CO2 levies. This is the case in Switzerland where a third of the fossil combustible fuel CO2 levy is invested to promote and subsidize cleantech [120]. R&D funding either through public institutions (e.g., academic and research institutions) or through private firms is another form of subsidy. It accelerates the development of innovation and diffusion of new technology. Switzerland is one of the countries with the highest public and private spending of R&D in relation to its GDP [123]. Multiple government and cantonal agencies provide targeted funding in Switzerland. The EU has launched its Innovation Fund as discussed in Section 11.1.

Other policy categories include **financial policies** which incentivize the investment in large capital-intensive assets and **information-based policies** which aim to level the information asymmetry between companies and the government regarding the feasibility and cost of breakthrough decarbonization technologies. A final approach are **voluntary agreements** between industry and government either on an industry or company level, whereby emission reduction targets are set and the involved party is given incentives to reach the targets such as tax reliefs [79]. An example of this is the successor agreement between the Federal Department of the Environment, Transport, Energy and Communications (DETEC) and the Association of Plant Managers of Swiss Waste Treatment Installations (VBSA), which extends the original agreement signed in 2014 for emission reduction from waste incineration [124]. The new agreement signed in March 2022 obliges the VBSA to have its members' waste incineration plants to install at least one CO2 capture plant with a minimum capture capacity of 100,000 ton_{CO2} by 2030, in addition to reducing their net sectoral CO2 emissions in accordance with the original agreement. As a result of the agreement, the waste incineration operators continue to be exempt from the Swiss ETS.

Since this report is focused on the cement industry, an energy-intensive and trade-exposed industry, we include a category of policies that **mitigate carbon leakage and competitive impacts,** i.e., avoiding putting Swiss cement producers at a disadvantage with international competitors. This is especially relevant in light of the EU's plans to phase out free allocations of ETS allowances starting in 2026. Although a CBAM is the carbon leakage mitigation option currently being discussed in the EU, Switzerland has the option to choose another approach. We therefore touch upon the different carbon leakage prevention mechanisms.

Table 20 provides an overview of policy options with their respective definitions and highlights examples of relevant international policies in force or in the pipeline, where possible from the cement industry. However, while not a fully comprehensive analysis of all global policies, it is to be noted that little precedent for decarbonization policies aimed at the cement industry exist. The few existing policy schemes directly relevant for the cement sector are mainly to be found in Standards and Regulations, less in the other categories with the notable exception of the Swiss and EU cement sectors' coverage under ETS as well as the Dutch policy initiatives aimed at multiple industries addressed later in this report. Further research is necessary to validate this initial finding and its implications for policy making.

With an overview of potential policy mechanisms for decarbonization presented, Table 21 then outlines how a selection of these policy options could be matched with the barriers found to inhibit the decarbonization of the Swiss cement industry in Section 10. The selection and linkage to barriers was made based on existing cement decarbonization policies referenced in Table 20 as well as suggestions from literature and expert interviews. To move forward with these policy options, both the individual barriers and policy instruments may require further detailed scrutiny with regards to their feasibility and effectiveness outside of the scope of this project.

Table 20: Long list of policy options and international examples

Policy	**Description** [78]–[81], [125][126]	Examples
Standards and Regulations		
Procurement standards	Purchaser shall comply with a standard on the type or/and minimum quantity of materials or products acquired. Applicable to the public and private sector, usually beginning with public procurement. In the private sector, procurement standards are often introduced on a voluntary basis and made mandatory at later stages.	Introduced in 2017, the *Buy Clean California Act* requires public agencies to set a cap on embodied carbon and require Environmental Product Declarations (EPD) for certain materials used in public construction projects (structural steel, concrete reinforcing steel, flat glass, and mineral wool board insulation) [127]. Passed in 2021, the *Buy Clean Colorado Act* aims to set a cap on embodied carbon for materials used in the construction of public projects (asphalt, cement ad concrete, glass, steel and wood) [128]. An EPD will be required as part of the project awarding process. The *Low-Embodied-Carbon Concrete Leadership Act* (New Jersey and New York) aims to establish a stakeholder advisory group to set guidelines for state agencies procuring low-embodied-carbon concrete [129].
Production standard: carbon disclosure	Producer reports on the embodied carbon emissions of a product.	In 2020, the City of Portland, Oregon, US, introduced a new policy requiring EPDs (third-party verified) for all concrete used in city projects [130]. *Also see examples from procurement standards which all require an EPD as a carbon disclosure tool.*
Production standard: carbon cap	An upper limit for embodied carbon in a product (locally produced and imported). This could potentially be introduced on a voluntary basis and made mandatory at later stages, with pre-announced caps and increases in stringency over the years.	In 2019, the County of Marin, California, US, amended the *California Building Standards Code* to include limits on the embodied carbon and cement content of concrete mixtures of different strengths [131]. Compliance can be demonstrated either through the embodied emission approach (EPD submission for compliance) or by abiding to the cement limits (batch certificate submission for compliance). *Also see examples from procurement standards which set an embodied carbon cap.*
Product standard: non-carbon specification	An indirect approach to reducing CO_2 is setting other product requirements that have an impact on CO_2. This could be quotas for alternative or recycled materials, limit on cement content etc.	In the example of County of Marin`s *California Building Standards Code* above, the amended building code limits the amount of cement in a concrete mixture. An indirect approach of reducing emissions.

		The EU circular economy action plan sets out to increase the recycled content in products [125].
Production standard: energy intensity or energy efficiency	Energy performance standards for equipment, manufacturing processes or products.	The Chinese *GB 16780-2007* is a national energy-efficiency standard for the cement industry limiting the coal, electricity and overall energy consumption in new and existing cement plants [132]. Iran set energy consumption standards for different industries including cement. The standard covers existing and new cement plants and limits the electricity and fuel intensity of the cement plant depending on the production technology used (e.g., dry kiln with preheater and grate cooler, dry kiln with preheater and satellite cooler etc.) [133].

Pricing Instruments

Carbon emission tax *[Section 13.4]*	A fee that is imposed on emitters to internalize the cost of CO2 and incentivize emission reduction. CO2 taxation can take on many forms: tax embodied product emissions with the consumer bearing the cost, tax emissions at the production site, tax emissions at the production site that exceed a certain threshold etc. The social and political acceptance of this policy can be dependent on how the tax revenues are used.	In 2008, Switzerland introduced a carbon tax ("*Lenkungsabgabe*") on fossil fuels (heating oil, natural gas). The revenue is redistributed to the population/economy and energy-efficiency and renewable energy subsidy programs [134]. The 2021 *Dutch Climate Agreement* introduced a CO2 levy parallel to the EU-ETS system for industrial emissions (production- and energy-related emissions). The levy starts at 30 EUR/ton$_{CO2}$ increasing up to 125 EUR/ton$_{CO2}$ by 2030 (see Section 13.4) [135]. *Other examples of global CO2 taxation (and other carbon pricing examples) can be found in the World Bank`s Carbon Pricing 2021 report* [136].
ETS (Emissions Trading System)	ETS is a cap-and-trade scheme where operators of installations subject to this scheme buy, trade and surrender allowances based on their emissions and a system wide cap.	The *EU ETS* is the most known ETS, with a jurisdiction of 27 member states and Iceland, Liechtenstein and Norway. In 2020, Switzerland was the first country to successfully link their own ETS system with the EU ETS market [137]. *Other examples of global ETS can be found in the International Carbon Action Partnership's Emission Trading Status Report 2022* [138].

Material pricing mechanisms *[Section 13.4]*	Rather than taxing embodied emissions, this involves taxing virgin raw material or material products to incentivize material recovery and development of secondary materials market.	In 2002, the UK introduced a tax on primary virgin aggregate (rock, sand, and gravel) to encourage the use of alternative and recycled raw material. Similar examples exist in Sweden and Italy [139].
Incentives and Subsidies		
Direct funding	Direct funding to support multiple stages of a technology or project: R&D, demonstration, commercialization etc.	The EU`s *Innovation Fund* of 38 billion EUR for the commercial demonstration of innovative low-carbon technologies 2020 to 2030 [111]. The UK provides various direct funding opportunities: *Carbon Capture and Storage (CCS) Infrastructure Fund, Carbon Capture and Utilization Demonstration (CCUD) innovation program, Industrial Fuel Switching Competition (Competition funding)* [79] Starting 2021, Germany provides funding for CCU/CCS technology development specifically targeting energy-intensive primary industries where process-related GHG emissions are hard to avoid with the technologies available [125]. In 2021, Sweden announced its support of bioenergy carbon capture and storage (BECCS) using reverse auctions to award the provider of the lowest price per ton [140]. *Many of the ongoing CCS/CCU projects in the cement industry are publicly funded. See Appendix F for a list of global projects.*
Carbon Contracts for Difference (CCfD) *[Section 13.2]*	A dynamic subsidy approach where the state enters a contract with the beneficiary with a fixed "strike" CO2 price over an extended period of time. Complementary to ETS participation, CCfDs hedge the risk of a fluctuating CO2 price and give beneficiaries long-term investment security. If the CO2 price drops below the strike price, the beneficiary receives a compensatory payment with the difference from the state and vice versa.	In 2020, the Netherlands introduced the *Sustainable Energy Transition Scheme (SDE++)* to subsidize the unprofitable fraction of an investment in low-carbon technology such as CCS over a period of 12-15 years by covering the price difference between the cost of production and market value [141]. Since 2015, the UK provides CfDs (not CCfDs) to develop low-carbon electricity generation capacity in the UK, particularly offshore wind power generation [125].

Tax reliefs and rebates	An exemption from or reimbursement of an imposed CO2 or environmental tax. Could also be indirect reliefs (e.g., lower corporate tax).	In Switzerland, operators participating in the ETS are exempt from the CO2 levy and shall commit themselves to reducing GHG emissions [134]. *Climate Change Agreements (CCA)* in the UK are voluntary agreements between government and industry granting discounts on the *Climate Change Levy (CCL)* which is a tax on industrial, commercial and public sector energy use [79].
Accelerated depreciation	Accelerated depreciation is an accounting and income tax method that aims to incentivize investment in low-carbon assets. If asset depreciation is accelerated, expenses on the balance sheet are higher in the earlier years resulting in a lower income and reduced tax liabilities (can be seen as a tax abatement).	In 2008, Peru introduced *Accelerated Depreciation Benefits* allowing a 20% depreciation for technologies in the renewables sector [125]. In 2018, Japan allowed economic energy efficiency operators benefit from 30% accelerated energy efficiency investment depreciation [125].
Early asset replacement, retirement and repurposing	Incentives or financial compensation to replace or phase out key assets before the end of lifetime to replace with new low-carbon technologies (net CO2 mitigation potential positive).	In 2020, the Maltese government announced the *Construction Industry Scheme* which aims to encourage operators in the construction industry to invest in new technology that generate less emissions by granting a cash contribution of up to 40% of the replacement costs [142] .

Financial Policy

Equity funds	A form of stock funds used to finance project capital costs.	Poland's 2021 national recovery plan includes setting up financial instruments such as dedicated funds and equity support [125].
Green bonds	Green bonds are bonds used to raise capital specifically for decarbonization projects.	The *EU Green Bond Standard (GBS)* is a voluntary standard to improve the quality and uptake of green bonds [143]. In 2020, the UK released their first *Sovereign Green Bond* enforcing the competitiveness and growth of their financial sector to boost innovative ideas and new technology uptake [125].
Loans	Loans with favorable terms or conditional loans can incentivize investment in low-carbon technology.	The *KfW Renewable Energy Program Storage* in German offers low interest loans for stationary battery storage related to photovoltaic installations [144].

Public investment banks	Provide long-term strategic finance to high risk and capital-intensive projects.	The UK`s public *Green Investment Bank* targets green infrastructure investment and aims to leverage private sector funding [145].
Loan Guarantees; Credit Lines	A risk-sharing mechanism between the state and industry for large capital investments.	In 2020, the EU Commission set up a *State aid Temporary Framework* including loan guarantees to companies, however, not exclusively for the energy sector [146]. In 2021, USA`s *Innovative Energy Loan Guarantee Program* provided up to 3 billion USD in funding for deploying offshore wind [125] Since 2015, the Swiss "Technology Fund" provides loan guarantees to innovative technologies in specific areas of climate change mitigation [219].
Partial Risk Guarantees	Provide debt servicing balances the risk between private investors and the state against the fraction of the loan amount.	India's 2016 *Partial Risk Guarantee Fund for Energy Efficiency (PRGFEE)* covers 50% of the value of loans to participating financial Institutions on energy efficiency projects [125].
Public Ownership	State ownership as a model for capital-intensive projects.	The Federal Republic of Germany is the single shareholder in the national railway company Deutsche Bahn AG, responsible for most railway operations and owning the majority of railway infrastructure [147].
Public-Private Partnerships (PPP)	Contractual agreement between private and public for project financing and risk management.	The Norwegian PPP *Northern Lights/Longship* project aims to pilot CCS in the first phase and then offer commercial services for the collection of CO2 from across Europe via ships and storage in Norwegian storage sites in the second phase [91]. The Dutch PPP *Aramis* project aims to investigate the development of CO2 transport facilities to provide access to offshore storage [148].
Information-based Policies		
Knowledge sharing	Drive stakeholder engagement and promote knowledge sharing.	The EU organized the first CCS/CCU high-level forum for relevant stakeholders, EU institutions, and EU countries to facilitate the deployment of the technology [149]. The *FISSAC* project in Spain, involves stakeholders across the construction and demolition value chain to develop methods and a platform to facilitate information

		exchange and support industrial symbiosis networks and replicate pilot schemes on a local and regional level [150].
Data infrastructure	Improving data collection, sorting, storage monitoring etc. to identify opportunities for process optimization and value chain CO2 reduction.	The Dutch *Stichting National Environmental Database* contains national environmental data used to calculate the life-cycle environmental performance of construction products and installations [151] .
Product labelling	Standardized labelling of products with the embodied energy or/and carbon content to inform the consumer.	The *EU`s Energy Performance Certificates (EPCs)* provide consumers with information on buildings they plan to rent or buy, including an energy performance rating and recommendations for cost-effective improvements [152]. *Also see examples from "production standard: carbon disclosure" which require an EPD as a carbon disclosure tool.*
Industrial symbiosis schemes	Partnerships which strengthen cooperation through sharing and reusing resources and creating shared value.	The UK's *National Industrial Symbiosis Program (NISP)* was voluntary agreement identifying material flows between participating firms, saving 9.6 million tons of raw materials and created savings for members of 156 million GBP between 2005 and 2010 [153].

Table 21: Policy options to overcome the decarbonization technology deployment barriers[52]

Decarbonization Technology	Key Barriers[53]	Policy Options [78][79][120][121][154]
Energy efficiency	– Upgrade to pre-heater and kiln depends on investment cycle	– **Early asset replacement or retirement** Incentives or financial compensation to replace inefficient clinker production equipment before end of life with more efficient technology. – **Energy efficiency standards** Minimum energy efficiency standards or energy consumption caps per ton clinker produced could phase out inefficient kilns. – **Accelerated depreciation** Incentivize the investment in upgraded and efficient kilns by deducting tax in the early stages of the asset's lifetime. – **CO2 levy on fuels** An embodied CO2 tax imposed on fossil fuels or all fuels, could incentivize the investment in more efficient production equipment. Such a levy currently exists in Switzerland, but the cement industry is exempt due to participation in ETS.
Alternative fuels	– Uncertainty regarding the availability of fuels (e.g., availability of green H2 and other renewable energy sources, availability of biomass and competition with other sectors) – Uncertainty regarding future cost of fuels – Future access to municipal and industrial waste	– **Direct funding** Direct public funding of renewable energy production and associated infrastructure (e.g., green H2, renewable power etc.). – **PPP** PPP to develop renewable energy production and associated infrastructure (e.g., green H2, renewable power etc.) – **CO2 levy on fuels** An embodied CO2 tax imposed on fossil fuels or all fuels, could incentivize a transition to low-carbon fuels, by making them more cost competitive with conventional fuels. Such a levy currently exists in Switzerland but cement industry is exempt due to participation in ETS.

52 As the Emission Trading System (ETS) is already in place, it is not listed here as a policy option. Sufficiently high ETS allowance prices are likely to incentivize investment into these decarbonization technologies.
53 Refer to Chapter 10 for additional details.

		– **Fuel mix carbon cap** A fuel mix carbon cap could encourage a shift to low- and zero-carbon fuels (e.g., biomass). An embodied carbon cap per ton clinker could yield similar outcomes. – **Non-carbon specification** A quota for alternative fuels or waste material in the fuel mix could increase the uptake of these fuels depending on the stringency of the quota. Alternatively, a cap on the fossil fuels in the fuel mix could lead to a similar outcome. – **Industrial symbiosis schemes** Encouraging information sharing, cooperation and partnerships between the cement and other industries (e.g., waste-to-energy) could lead to optimized uses of waste as a fuel (or even as raw material for the cement industry), possibly using the Energy Perspectives 2050+ as a reference.
Clinker substitution	– Concrete code prescribes the quantity and type of cements to be used in concrete mixture, and concrete additives – Future and local availability of SCMs – Demand-side constrains	– **Modification of the Swiss concrete norm SIA 262 *(Discussed in detail in Section 13.1)*** A shift to performance-based approach: Excluding prescriptive limits on minimum cement quantity, cement types, and concrete additive quantity if performance is proven. (*Alternatively: Relaxing the limits on minimum cement content and maximum additive content and allowing a wider range of cements to be used).* – **Non-carbon specification** A quota for highly blended cement use in buildings or other construction work (similar to recycled materials quota). – **Cement carbon cap** An embodied carbon cap per ton cement could encourage the uptake of highly blended cements depending on the stringency of the cap. – **Direct funding to compensate for onsite delays** Compensating construction projects for financial losses incurred due to the longer setting times and resulting on-site delays associated with the use of highly blended cements. – **Low-carbon public procurement** Mandatory low-carbon procurement by public bodies. – **Knowledge sharing and technical training** Communication and coordination across the construction value chain to share knowledge

		related to the use of low-clinker cements. Education campaigns on the use of new cements and their properties. – **Direct funding of R&D** Supporting R&D of new and innovative cements.
Alternative clinkers	– Low TRL – Raw material availability and efficiency of the production process – Standardization not available in EU – Demand-side constrains regarding a completely new product on the market	– **Direct funding of R&D** Supporting R&D of new and innovative clinkers and TRL improvement of existing alternative clinkers. – **Classification and standardization** Classifying alternative clinkers and including them in the EU and Swiss norms. – **Low-carbon public procurement** Mandatory low-carbon procurement by public bodies. – **Knowledge sharing and technical training** Communication and coordination across the construction value chain to share knowledge related to the use of alternative clinkers. Education campaigns on the use of alternative clinkers and their properties.
Carbon capture	– Significant energy demand – Notable increase in the cost of producing clinker – Infrastructure availability – CO2 accounting – Public acceptance – Long-term investment security which hinges upon multiple factors like CO2 pricing, long-term CO2-offtake contracts, raw material availability, and infrastructure availability	– **Early asset replacement or retirement** Incentives or financial compensation to replace key clinker production equipment before end of life with integrated carbon capture technologies such as oxyfuel, LEILAC and integrated calcium looping. – **Direct funding** Direct funding of pilot and demonstration of carbon capture for cement plants. – **Carbon Contracts for Difference (CCfD)** ***(Discussed in detail in Section 13.2)*** Supporting cement manufacturers by subsidizing the unprofitable fraction of the additional cost of capturing CO2 through CCfDs. – **Phase out of free allocation and replace with other carbon leakage mitigation options** Reducing free allocations so that cement producers are increasingly likely to be exposed to ETS price signals. Simultaneously replacing with another form of carbon leakage mitigation: (1) carbon border adjustment mechanism (CBAM): pricing mechanism applied on imported goods to address the carbon asymmetry between jurisdictions (discussed in

detail in Section 13.3), (2) standards on producers: imported and locally produced products shall comply with minimum requirements related to carbon content, or (3) standards on purchasers: minimum standard for the procurement of locally produced and imported materials based on embodied CO_2.

- **Carbon levy on end products *(Discussed in detail in Section 13.4)***
  Carbon levy on domestic and imported cement either based on weight or CO_2 content. The former could incentivize the reduction in cement consumption and the latter incentivizes the reduction in cement consumption and a shift to alternative materials.
- **Cement carbon cap**
  An embodied carbon cap per ton cement could encourage the installation of carbon capture depending on the stringency of the cap.
- **Accounting of CCS in Swiss ETS**
  Allowing CCS to be accounted for the Swiss ETS as in the EU. Already proposed by the Swiss Federal Government.
- **Credit BECCS**
  Crediting and certifying negative emissions resulting from BECCS. Allowing the sale of verified CO_2 removal credits and their use for compensation. Already proposed by the Swiss Federal Government.
- **CDR reverse auction**
  State purchasing of CDR certificates through reverse auctions and awarding the provider of the lowest price per ton. As shown in Chapter 6, in comparison to existing CDR solutions, BECCS from the Swiss cement industry offers an attractive option in price and volume giving the industry a competitive advantage.
- **Industrial symbiosis schemes**
  Encouraging information sharing, cooperation and partnerships between the cement and other industries (e.g., waste-to-energy) to kick-off the planning and development of carbon transport infrastructure.
- **PPP**
  PPP to develop carbon transport infrastructure

13 Policy options deep-dives

In this chapter, we investigate selected policies that are in discussion on a Swiss and EU level and that could potentially accelerate the transition to low-carbon cement production in Switzerland. The selection of the policies is based on their prominence in the EU policy discourse, industry and academic literature as well as feedback collected in a workshop conducted with project stakeholders from industry and the administration.

13.1 Changes in concrete standards

Category: Regulations and standards

Value chain impact: Downstream

Monitoring, reporting and verification (MRV): Not necessary (As this approach impacts the type and quantity of cement and alternative material used in concrete, it has an indirect impact on CO2. Thus, no CO2 MRV required for the implementation of this policy.)

Status in Switzerland: Under discussion in Switzerland, already implemented in EU

Background

As discussed in the section on deployment barriers, the Swiss concrete standard SIA 262 in its current prescriptive form creates a barrier to the reduction of the cement and clinker quantity used in Switzerland [85]. Before discussing the changes envisioned for the concrete standard, it is key to emphasize the importance of smart and optimized material use within a structure. There are multiple approaches to minimizing the use of concrete as a building material, which include: substitution with alternative materials such as wood, increasing the share of recycled concrete used as aggregates in a fresh concrete mix[54] and avoiding over-specification (e.g., choosing the appropriate exposure class) and optimizing dimensioning of the structural element [25][155]. Here, the key stakeholders are concrete producers, engineering offices, demolition and construction companies and standardization bodies. These modifications are highly related to the education and practices of professionals in the sector but could also be driven by changes to building standards and structural norms. Yet, this is beyond the scope of this study and this section will focus on discussing the opportunities for improvement on the cement and concrete level in relation to the existing concrete code SIA 262.

[54] Recycled aggregates have a lower strength compared to virgin aggregates which calls for more cement in the mix. Yet, depending on the aggregate transportation distances, CO2 savings are possible [25]. This needs to be assessed on a case-by-case basis. Recycled aggregates can also be used as raw material in the cement production process.

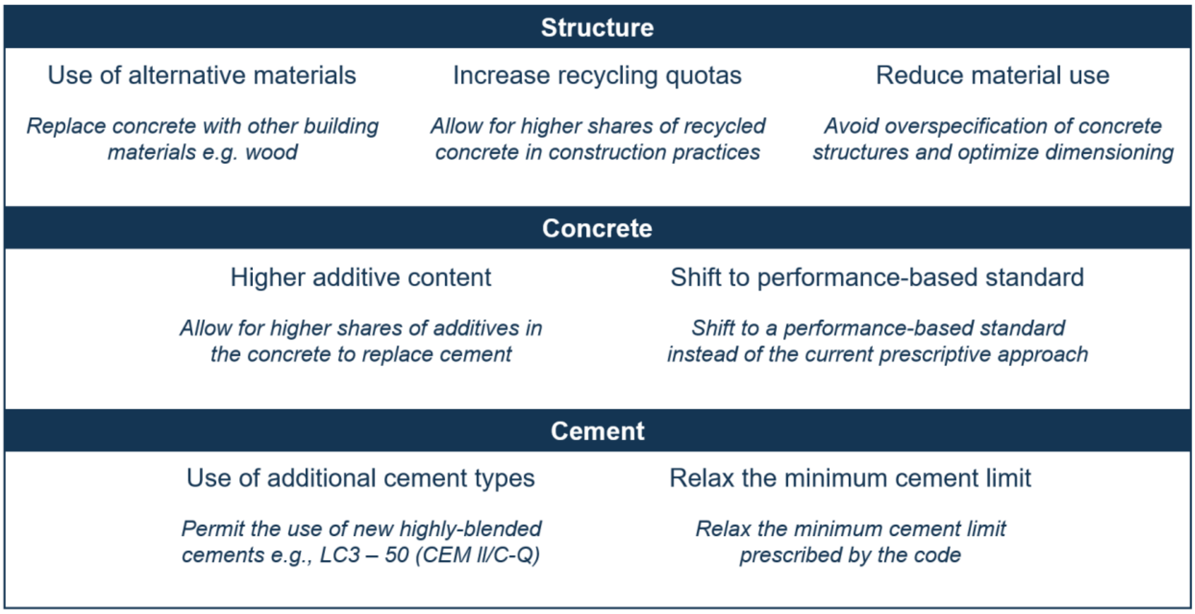

Figure 46: Levels of intervention to reduce concrete and cement consumption

Shift to performance-based concrete specification

A strictly performance-based specification outlines and describes the functional and performance requirements of the end product, in this case concrete, and avoids limitations on material selection, proportioning and construction methods. Performance specifications should specify the test methods and criteria that will be used to enforce the performance requirements [156]. These tests include pre-qualification tests of the concrete and on-site testing. This approach gives the concrete producer or contractor the flexibility and freedom to use different concrete mixes so long as the quality requirements are met, and they are also held accountable for the concrete performance. Prescriptive-based specifications on the other hand, focus on the properties of raw material, mixture proportions, batching etc. as a means to achieve a required performance. This includes requirements such as: type of cement to be used, limitations on SCM, minimum cement content[55], maximum water-cement (w/c) ratio etc. [85]. This approach restrains the freedom of concrete producers in using novel and highly blended cements and minimizing the cement quantity within a concrete mixture. It does however guarantee that the supplied concrete satisfies the overall performance requirements without the need for testing. The responsibility of actual performance, therefore, does not fall on the concrete supplier.

A shift from a prescriptive to a performance-based concrete code could allow concrete producers and designers to take advantage of the wide range of materials available today compared to the prescriptive approach [156]. Nevertheless, each approach comes with its respective advantages and disadvantages as listed in Table 22:

[55] Cemsuisse notes the following: “Many small concrete producers must use higher than minimum cement contents in their concrete because they do not fulfill the requirements of the performance tests required today. This is due to the suboptimal sieving curves of the used aggregates. These producers would require additional equipment, space and investment to minimize cement content.”

Table 22: Advantages and disadvantages of performance- vs. prescriptive-based concrete specifications [56][156]

Advantages	Disadvantages
Performance	
– Increased control over the end product: flexibility in material choice, material combinations, equipment, mix proportions etc. to optimize the concrete performance while achieving lower costs and/or emissions	– Performance tests may be more expensive and time consuming, requiring more expertise, training and lab capacity which may not be worthwhile for small products, more demanding for concrete manufacturers
– Opportunity to focus on new concrete behaviors and characteristics, to optimize the benefits of the different additives	– Results in an additional liability and responsibility for concrete producers to guarantee performance
– Shift from specified relationships between concrete performance and concrete mixes to direct testing of concrete properties	– Quality control and proving durability and long-term performance may be more challenging
– Broader portfolio of standardized products with low cement content	– Risk that performance requirements are higher which might lead to higher cement content
Prescriptive	
– Specification has control over design aspects such as material choice, mixing, process etc. facilitating quality control and implementation	– Limited flexibility in optimizing the concrete beyond the specifications, do not cover every application
– Usually limits the concrete producer responsibility regarding the concrete performance	– Limited opportunity for concrete producers to make use of unique access to materials, material combinations, equipment etc.
– More straight forward use, basic specification testing is simple	– Basic specification tests may give misrepresentative results as they are performed under standard conditions and not under field conditions
– Creates a level playing field for all concrete producers to compete	– Reduces the incentive for a concrete producer to optimize mixture and go beyond prescriptions

The challenge and opportunity is to develop and implement specifications that can maximize the advantages of both approaches while minimizing their respective drawbacks. One potential solution is to allow a range of specification types from pure prescriptive to pure performance that can apply to varying situations. An example of this can be seen in the British Standard BS 8500 which offers five concrete classifications ranging from pure prescriptive to pure performance based [156][157]. On the one hand are prescriptive "design concretes" which derive from exposure classes and are defined by limiting criteria such as cement type and content, maximum w/c ratio etc. and is not subject to third party certification. On the other end are performance "proprietary concrete" may be developed by concrete producers to achieve a

[56] The findings of the Swiss stakeholder workshop and expert interviews are included.

certain performance using defined test methods [157]. This follows the Equivalent Concrete Performance Concept (ECPC) permitted by European concrete standard EN 206-1[57].

Interestingly, before the introduction of EN 206-1 in Switzerland, concrete durability was determined through testing trial mixes and it was considered a step backwards to exclude testing from the standard [158]. In the meantime, the prescriptive approach has been well accepted. Nevertheless, with today's focus on CO2 abatement, this approach has reached its limits and a need is voiced to transition toward performance-based standards. This would require the determination of durability characteristics including the tests required and their limiting values to ensure reliable performance, a challenging task given the complexity of the concrete value chain and the conflicting stakeholder interests. A shift to a fully performance-based standard would also unlock the other existing restrictions on increasing the share of additives and minimizing the quantity of cement in the concrete mix.

Changing norms is a lengthy and complex process according to an interviewed Swiss concrete expert, as it involves the negotiation and planning of industry players with often conflicting interests. It also requires additional education of professionals to build up the required competence. Alternatively, targeting each barrier in this context individually, standardization bodies could relax the limits on minimum clinker content which has a direct impact on the amount of clinker used in the construction industry. Although reducing cement consumption could be solved through the adoption of a performance-based standard, this is another valid approach. The extent of the limit reduction requires a technical study and is beyond the scope of this report. Additionally, increasing the range of cementitious materials and blended cements allowed in the Swiss code would reduce cement consumption. As an example one can mention the inclusion of the upcoming 50% clinker LC3 cement (CEM II/C-Q) in the SIA 262 register for standardized cements in Switzerland [159].

13.2 Carbon Contracts for Difference (CCfD)

Category: Incentives and subsidies

Value chain impact: Midstream

MRV: Not necessary (As the cement industry already reports emissions under the ETS, there is no need for a new MRV system)

Status: Under discussion in EU. Implemented in the Netherlands

Potential complimentary policies: Climate and innovation fund, phase out free allocations and carbon leakage protection, public procurement etc.

Background

Key breakthrough low-carbon technologies have significantly higher CAPEX and OPEX compared to more traditional decarbonization technologies and approaches. Today, there is no business case for the commercial full-scale installation of such technologies and no market willingness to pay the resulting higher cost of low-carbon cement. This issue was to be addressed by the ETS carbon pricing, by increasing the price of CO2 intensive materials and levelling out the playing field with low-carbon alternatives. Yet, over the past few years, the EU ETS price has appeared to be too low to trigger the commercialization of these technologies (~25 EUR/t_{CO2}). In 2022, the EU ETS underwent a noticeable price increase reaching 98EUR/t_{CO2} [36]. However, as manufacturing industries such as cement have continued to receive free allocations, this has to a degree dampened the incentive to invest in such technologies [96][97]. A critical barrier to investment, as mentioned by all Swiss cement producers, is the instability and price risk associated with the fluctuating ETS price. It thus could be seen to pose a unstable basis for investment decisions [160].

[57] For details on EN 206-1, ECPC and SIA 262, refer to Appendix E.

CCfD is a risk mitigation instrument which provides industry players with the long-term security required to unlock capital and invest in first-of-a-kind technologies [160]. It could ensure a fair level playing field for first movers installing the decarbonization technology compared to competitors by subsidizing the higher cost of low-carbon cement. In addition, it could provide an incentive for the first mover as slower moving competitors later might need to make the investment without subsidy if ETS allowances prices are above CCS costs. Concretely, CCfD is a funding mechanism that works complementarily to ETS, in which a company enters in an agreement with the government on a fixed CO2 price (referred to as “strike price”) over an extended period of time (e.g., 15 years) hedging the risk of fluctuating and low CO2 prices [161]. In practice, this means that if the ETS price is below the agreed upon strike price, then the company or agent is guaranteed the price difference for each ton of CO2. Conversely, if the ETS price is higher that the strike price, the agent shall pay the price differential to the state (see Figure 47).

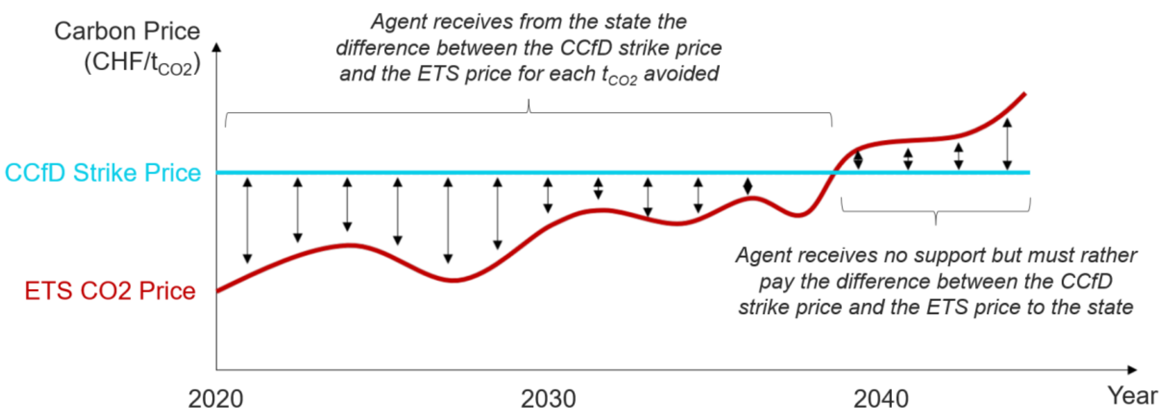

Figure 47: Illustration of CCfD mechanism

Policy expert interviews suggest that there are different approaches to determining the strike price: Over the duration of the contract, the strike price can be a fixed value in CHF/ton$_{CO2}$ or a dynamic price based on a formula that accounts for annually fluctuating operational parameters like energy prices, CO_2 transportation and storage costs etc. This hedges the risk of unexpected costs for the agent such as a spike in commodity prices and simultaneously protects the government from overpaying in case of future technology price reductions for example. Concerns exist among experts and practitioners around the setting of an appropriate strike price. This can be challenging due to the information asymmetry between the two involved stakeholders as the company has access to the true cost of technology whereas the state does not [160].

However, numerous approaches to dealing with this dilemma have been discussed. For instance, CCfDs could be used after the implementation of a publicly funded pilot project in collaboration between the producers, technology providers, public authorities and other key players [160]. This would give a first impression, within a plausible range, of the costs of the technology which would be public information. Competitive tendering is another potential avenue which could lead to a fairer strike price as companies have an incentive to drive down costs to be awarded the contract. Rather than negotiating with individual companies, in this case, the state publishes a public tender for applications. The tender does not have to target the cement industry directly but could be open to multiple ultra-low-carbon basic materials predefined by the state. The winning project could be selected based on multiple criteria including but not limited to: volume of high-carbon material replaced, cost per unit CO2 reduced, consistency with national climate strategy, economic justification, social benefits etc. [160]. Another approach, used in the Netherlands, for example, is setting a fixed strike price per technology category which companies can directly apply for if they deem the price sufficient [141]. In principle, this approach incentivizes agents to optimize cost to be covered by the strike price.

Complementary policies, financing and risks

Multiple instruments could potentially operate complementarily to CCfDs; for example, a national climate and innovation fund targeting the piloting and demonstration of industrial decarbonization projects. In this context, an option could be to give priority to proven pilot projects to be automatically eligible for CCfDs to commercialize the technology. This has the potential benefit of giving companies and project partners continuity and long-term perspective to commercialization, overcoming the "valley of death"[58][162]. According to policy experts at the Institute for Sustainable Development and International Relations (IDDRI) and Science Po, this approach minimizes the administrative burden, leverages public funds effectively and minimizes information asymmetry [160]. Given that there are currently no ongoing CCS cement projects in Switzerland, this approach could likely provide an incentive to motivate first movers. In this way, CCfDs could possibly be used as a short- and mid-term solution to support the rollout of low-carbon cement production. The phase out of free allocations and introduction of a border protection mechanism could then be seen as subsequent policies.

Depending on the type and number of projects funded under the scheme, CCfDs could end up posing a burden on state finances. However, keeping in mind that the state only pays out the difference between the strike price and the ETS price and in light of recent and expected further increases in ETS prices over the upcoming years, state financial burden could potentially be smaller than expected. A feasible option for sourcing the required funds could be to tap into the sales of emission allowances, as today in Switzerland these funds flow into the general national budget. In a similar way, the EU Innovation fund is funded by ETS allowance revenue [218]. In the long run, the subsidies could potentially come from a border or national climate surcharge on final products.

CCfDs are associated with some risks that need to be accounted for when designing the mechanism. An operational risk due to the first-of-a-kind nature of these installations relates to project and product delays and/or not achieving promised scale. As this funding scheme is product-based, the beneficiary only receives a subsidy for the actual production, minimizing the state's financial risk [160]. On a system level, this scheme could trigger significant CO2 savings in industries covered by the ETS, leading to concerns around potential market distortive effects, as the balance of available allowances is influenced and thus the CO2 price [163]. The interaction with ETS parameters like the annual emission cap and linear reduction factor needs to be considered as there is a risk of a waterbed effect[59]. The industry benchmarking is also likely to be impacted. Additionally, one needs to be aware of possible "double subsidies" provided to heavy industry (free allocations and CCfD) which could face public objection. Therefore, a comprehensive impact assessment could be sensible to help evaluate and mitigate the mentioned risks.

Precedent and potential setup in Switzerland

There is an ongoing discussion in the EU and individual member states on integrating this mechanism into climate policy. Legally, it could in principle be implemented on a national and EU level as can be seen with the Dutch example outlined below. However, national implementation for EU member states does require authorization from the Commission if the funding is provided by the government, which is usually the case[60] [78]. CCfDs are typically set up as a state aid [164]. The Treaty on the Functioning of the European Union

[58] "Valley of death" describes the phase in technology development between R&D and commercialization where a technology must be demonstrated and validated; usually characterized with increased private financing and high failure risk.

[59] "Waterbed effect" refers to the situation when a government intervention targeting emission reductions in a sector covered within the ETS has no impact on the overall emissions as they arise elsewhere.

[60] Consider the example on the SDE++ scheme in the Netherlands for information regarding the EU authorization process.

(TFEU) prohibits state aid in order to prevent it from "distorting competition in the internal market and affecting trade between member states in a way that is contrary to the common interest" [165]. Yet, in some cases state aid may be compatible with the TFEU and must therefore undergo a compatibility assessment under article 107(3)C of the treaty. The EU document "Guidelines on State aid for climate, environmental protection and energy 2022 (2022/C 80/01)" provides this compatibility assessment. In brief, the guideline permits state aid in the situations where the aid corrects market failures related to a certain environmental or energy objective. A typical example are negative externalities which have been addressed through the EU ETS in an attempt to internalize the cost of emissions. Yet today, the ETS does not cover the cost of CCS which could thus justify the use of state aid to address the remaining market failure.

While Switzerland is not an EU member state, in its article 23(1)(iii) the 1972 Free Trade Agreement (FTA) between Switzerland and the EU it is stated that "public aid which distorts or threatens to distort competition by favoring certain undertakings or the production of certain goods" is incompatible with the agreement in so far as it may affect trade between the EU and Switzerland [166]. However, the Swiss administration's current understanding posits that the FTA's state-aid provision would not be directly applicable in Switzerland [220][221].

Within Switzerland, the Subsidy Law could potentially apply in the case of CCfDs. It states that financial aid and compensation can be awarded if the federal government has an interest in the fulfillment of the task, if the task cannot be fulfilled without the subsidy and if it is performed in efficient and economic manner (among other prerequisites) [167]. Additionally, the Federal Constitution requires the respect of the principle of competitive neutrality which is based on similar grounds as the EU TFEU [168]. The legality of this policy option would require further assessment beyond the scope of this study.

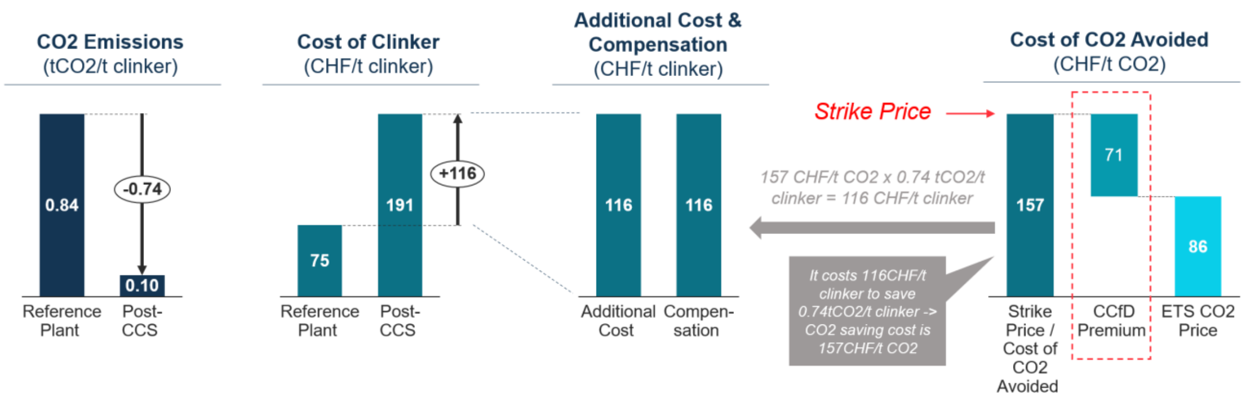

Figure 48: Illustration of CCfD scheme for MEA CCS in Switzerland

With respect to the Swiss context, the results of the techno-economic synthesis in Part I show that the cost of CO2 avoided or the CO2 abatement cost of using MEA CCS technology on a Swiss cement plant amounts to 157 CHF/ton$_{CO2}$. At the current CO2 price of ~86 CHF/ton$_{CO2}$, the full decarbonization costs cannot be covered. For the sake of this illustrative example, we assume that the state negotiates a strike price equivalent to the cost of CO2 avoided. A CCfD now aims to subsidize the unprofitable share of the abatement cost which is the difference between the strike price and ETS CO2 price. This price differential which the state provides is referred to as the CCfD premium and is equal to 71 CHF/ton$_{CO2}$ in the illustrative example[61]. Based on the results from Part 1 and with the current cement industry emissions of 2.72 million

[61] For additional information on CCfDs, refer to «Klimaschutzverträge für die Industrietransformation» report recently published by Agora Energiewende [182].

tons CO2 (scope 1 and biogenic)[62], the estimated annual cost of this policy in this illustrative scenario could amount (cumulative CCfD premiums) to approximately 170 million CHF.

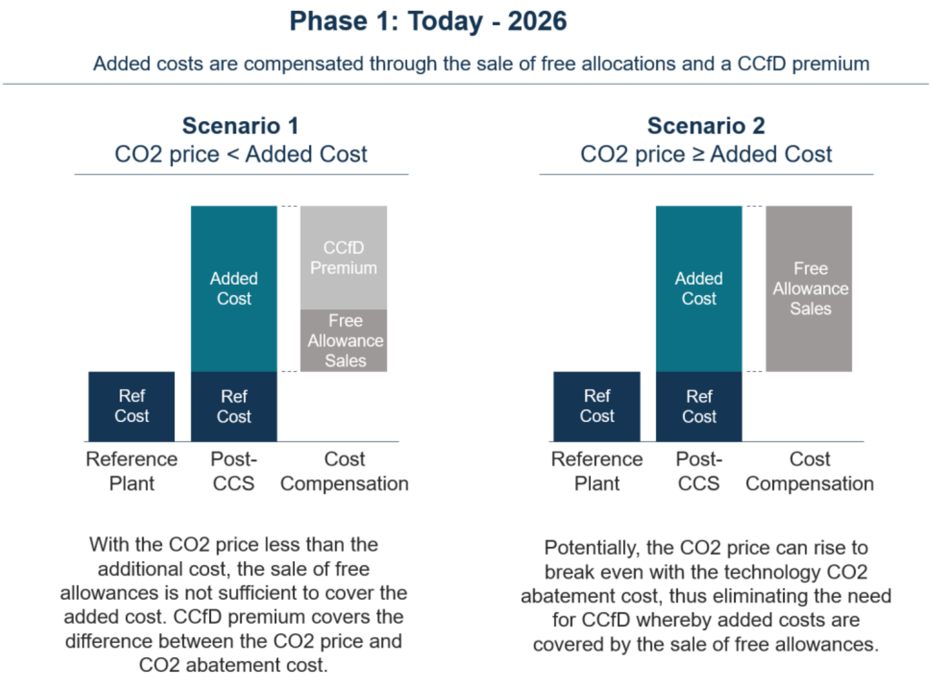

Figure 49: Cost compensation of low-carbon cement technology through the sale of free allowances and a CCfD premium

In Figure 49, we show two illustrative scenarios of how the additional CCS costs could be recovered depending on the CO2 price. We assume that the reference plant is of the top performing cement plants, meeting the ETS free allocation benchmark and thus receiving all the allowances required to cover emissions. In this case, the installation of CCS would enable the operator to sell the free allocations to (partially) recover added CCS costs. In scenario 1, the CO2 price is less than the added cost of decarbonization, i.e. the sale of free allowances is not sufficient to cover the added cost. A CCfD premium covers the difference between the CO2 price and CO2 abatement cost. In scenario 2, the CO2 price is equal to or greater than the added CCS cost which eliminates the need for a CCfD premium and allows for cost recovery through the sale of free allowances. For less efficient cement plants, performing below the ETS benchmark, the additional CCS costs are recovered through the sale of the allocated free allowances (which do not cover all their emissions) in addition to the cost saved for not having to purchase any additional allowances due to the installation of CCS. This is not depicted in the scenarios above.

[62] Since biogenic emissions are not covered by the ETS, the inclusion of their associated CCS costs (capture, transport and storage) in the CCfD scheme is dependent on the final policy design and mechanism of determining the strike price. In line with the results of Part 1 of this study, in this illustrative example, biogenic CCS costs are included.

POLICY EXAMPLE: Netherlands: Renewable Energy Transition Incentive Scheme (Stimulering Duurzame Energietransitie SDE++)

The SDE++ is an financial instrument that targets the diffusion of renewable energy and heat production and other low-carbon technologies including carbon capture by subsidizing the unprofitable component which would cause the agent not to realize the emission reductions otherwise [141]. It is an operating subsidy over a period of 12 to 15 years, which covers the difference in price between the cost of production using sustainable energy or the reduction of CO2 emissions and the respective market value. The aim is to stimulate competition between multiple technologies while offering investors long-term security.

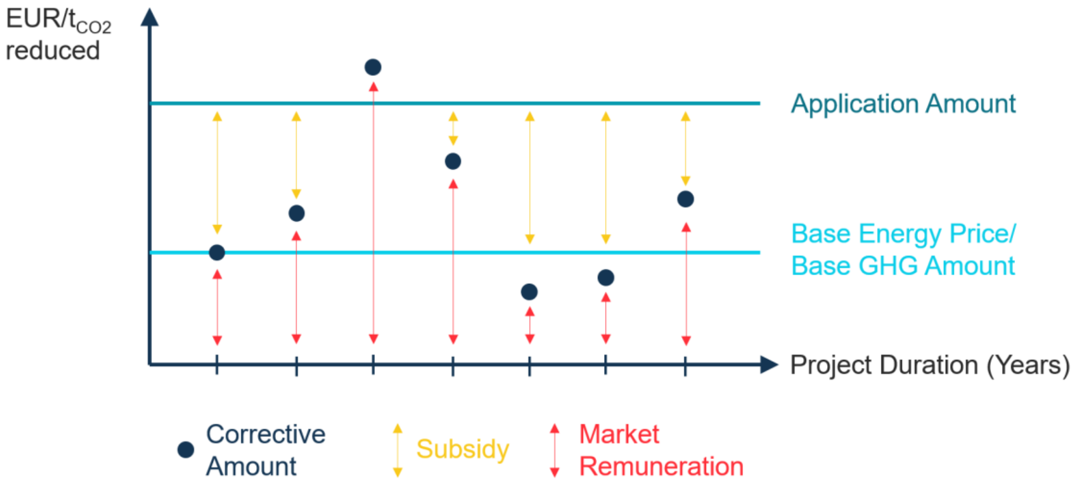

Figure 50: Illustration of the SDI++

There is a maximum amount that a beneficiary can apply for depending on the technology deployed, which is set by the Netherlands Environmental Assessment Agency. This is referred to as "Base Amount". The beneficiary may apply for a subsidy lower than the Base Amount which increases competitiveness and likelihood of being awarded. This is referred to as "Application Amount" and is fixed over the lifetime of the project[63]. The "Correction Amount" reflects the revenues or avoided costs of the project, which can be revenue from the sale of electricity, heat or gas produced, avoided cost for the purchase or production of heat, and avoided cost of purchasing emission allowances for sectors covered by the ETS not receiving free allocations or revenue from the sale of free allocations in the case of industries such as cement [169]. The lower limit for the Correction Amount is the "Base Energy Price /Base GHG Amount" which are based on 2/3 of the expected revenue from over the overall duration of the SDE++ (e.g., long-term price of electricity, gas, ETS etc.). The subsidy covers the "unprofitable" part which is the difference between the Application and the Correction Amount. If the Correction Amount is equivalent to the Base Energy Price/ Base GHG Amount, then the producer receives the full subsidy. If the market value and thus the revenue increases, then the unprofitable part decreases reducing the subsidy value. The subsidy is adjusted annually based on the actual production rates and the annual corrective amount [141].

The SDE++ is open in 4 phases per year, with increasing subsidy value (see Table 23). There is a maximum subsidy intensity which can be claimed (300 EUR/ton$_{CO2}$ in 2021[64]) and a total budget available to distribute per year (5 billion EUR in 2021). If the required subsidy is greater than the limit, the producer

[63] Refer to [141], page 40 for CCS.
[64] Examples of technologies that fall under Phase 4 include electrolytic hydrogen production, bio-LNG produced by all-purpose fermentation (liquid gas) etc.

can still apply but will not be able to cover all the unprofitable costs. The subsidy limit is to be decreased over the years till 2030 to incentivize technology cost reductions [170].

Table 23: SDE++ 2021 tender round [171]

Phase	Start and end date	Subsidy limit (EUR/ton$_{CO2}$)
Phase 1	5 October 09:00 CET to 11 October 17:00 CET	60
Phase 2	11 October 17:00 CET to 25 October 17:00 CET	80
Phase 3	25 October 17:00 CET to 8 November 17:00 CET	115
Phase 4	8 November 17:00 CET to 11 November 17:00 CET	300

Subsidies for CCS are part of the SDE++. The physical state of the CO2 (gaseous or liquid form) is one of the factors that determines the Base Amount and thus the subsidy received by the producer. Most CCS projects fall under Phase 3 of the subsidy limit (up to 115 EUR/t$_{CO2}$). The applicant shall also submit a declaration from the parties responsible for transport and storage and the quantities if CO2. This declaration shall be issued by the party responsible for transport and storage. The Dutch government has reserved 2.1 billion EUR as part of the SDE++ for Air Liquide, Air Products, ExxonMobil and Shell to capture CO2 at their facilities at the Port of Rotterdam. The storage project Porthos will then transport the CO2 and store it in the North Sea [93].

As this is a national policy, it was implemented in the Royal decree 'Besluit stimulering duurzame energieproductie en Klimaattransitie' (SDEK) under the framework law for subsidies (Kaderwet EZK- en LNV-subsidies)[169]. In 2020, the European Commission requested additional information from the Netherlands regarding the compatibility of the scheme with the Article 107(3)(c) of the Treaty on the Functioning of the European Union. In conclusion, the commission did not raise any objections on the grounds of compatibility[65].

13.3 Carbon Border Adjustment Mechanism (CBAM)

Category: Carbon leakage mitigation + pricing instrument

Value chain impact: Downstream

MRV: Mandatory (CBAM tariffs depend on the CO2 content on imports, MRV is required)

Status: Under discussion in EU

Potential complimentary policies: ETS, phase out free allocations, CCfDs, carbon tax/levy, climate and innovation fund etc.

Background

The cement industry is part of the ETS and receives free allowances to emit as a carbon leakage mitigation instrument. This approach may weaken the incentive to invest in low-carbon technologies, lowering the impact of the compliance market as a tool for internalizing the external environmental costs [172]. CBAM is an alternative carbon leakage mitigation and CO2 pricing instrument that could replace free allowances while internalizing the cost of CO2 and exposing cement manufacturers to environmental costs [78]. CBAM aims to level out the price of carbon between domestic products exposed to a high CO2 price and their imported counterparts subject to low or no CO2 pricing [173]. This way, domestic producers are not put at

[65] To revise the details of the scheme and the communication and justification given to the European Commission, refer to [169].

a disadvantage but rather compete fairly with importers producing in countries with less ambitious and stringent climate policies. Essentially, importers pay an adjustment tariff exposing them to similar CO2 pricing had the product been manufactured locally. Conversely, to offset the export disadvantage, exporters could receive a tariff relief or rebate to adjust for the CO2 price paid domestically (see Figure 51) [78]. Effectively, local manufacturers of basic materials such as cement, which have so far received free allocations, would thus be exposed to a CO2 price creating a price signal, potentially incentivizing investments in the low-carbon technologies discussed in Part 1. Additionally, this approach could encourage trade partners to reduce emissions to avoid paying high market entry tariffs. The revenues from the CBAM tariff may be used in multiple avenues (e.g., national budget, climate innovation fund, directly distributed to support customers affected by possible higher material prices etc.). A potential outcome of this approach may be a possible rise in basic material prices as free allocations are phased out and producers start to pay for the CO2 they emit following the polluter-pays principle.

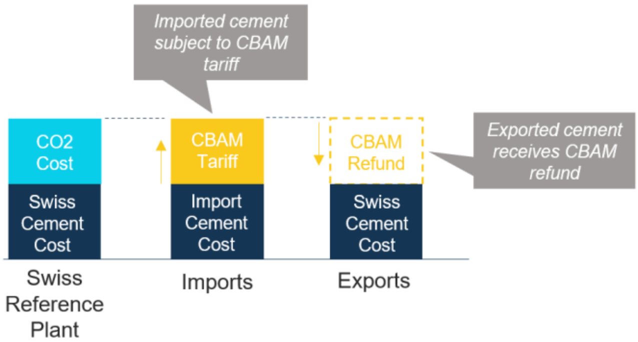

Figure 51: Illustration of a hypothetical CBAM

As mentioned in Section 12.1, CBAM is the carbon leakage mitigation option proposed in the EU`s “Fit for 55” package. Under the current EU proposal, the phase out of free allowances shall begin in 2026 at an annual reduction of 10% while CBAM is ramped up at the same rate [105]. As CBAM is complimentary to the EU ETS, importers shall purchase certificates with a price linked to the CO2 allowance price. The EU is currently discussing a setup where national authorities manage verification and certificate sales. An importer shall register and await verification from this authority, as well as declare the quantity and embodied emissions imported and surrender the corresponding certificates. In case information regarding embodied emissions is unavailable, default values could be applied. The revenues from CBAM are to flow into the EU`s general budget [104]. The instrument is planned to cover cement, iron and steel, aluminum, fertilizers and electricity. Given that the Swiss ETS is linked to that of the EU with producers in both jurisdictions exposed to the same ETS price, an introduced EU CBAM would not apply to Swiss imports [104].

The emissions included in the scope of CBAM is a relevant point of discussion. Scope 1 emissions are first in line as they are also covered by the ETS. However, it has been argued that scope 2 or indirect emissions that result from the production of the electricity used in the manufacturing process should also be included [105]. This is relevant since EU electricity production is covered by the ETS and is thus required to purchase allowances to cover its emissions [105]. Additionally, this is thought to encourage importers to use cleaner electricity. Lastly, the EU proposal excludes export rebates as they are not compatible with WTO rules [174].

Figure 52 and Figure 53 build on the theoretical scenarios depicted in Figure 49 (covering the additional cost of CCS installed on a Swiss cement plant). Figure 52 shows the stage between 2026 and 2035, with the gradual phase-out of free allowances and phase-in of CBAM. In scenario 2.1, the CO2 price is lower than the added cost of CCS and is therefore insufficient to cover the decarbonization cost premium or “added cost” of CCS. Assuming costs could be passed on to customers, the compensation for the added costs could be covered through the higher cement prices coupled with the avoided CO2 cost due to the installation of CCS, the sale of the remaining fraction of free allocations and a CCfD premium. In Scenario 2.2, the ETS CO2 price is equal to or higher than the added CCS costs, so cost compensation is covered through the sale of cement at higher prices and the sale of the remaining fraction of free allowances. In both scenarios, CBAM gradually replaces free allocations as a carbon leakage tool.

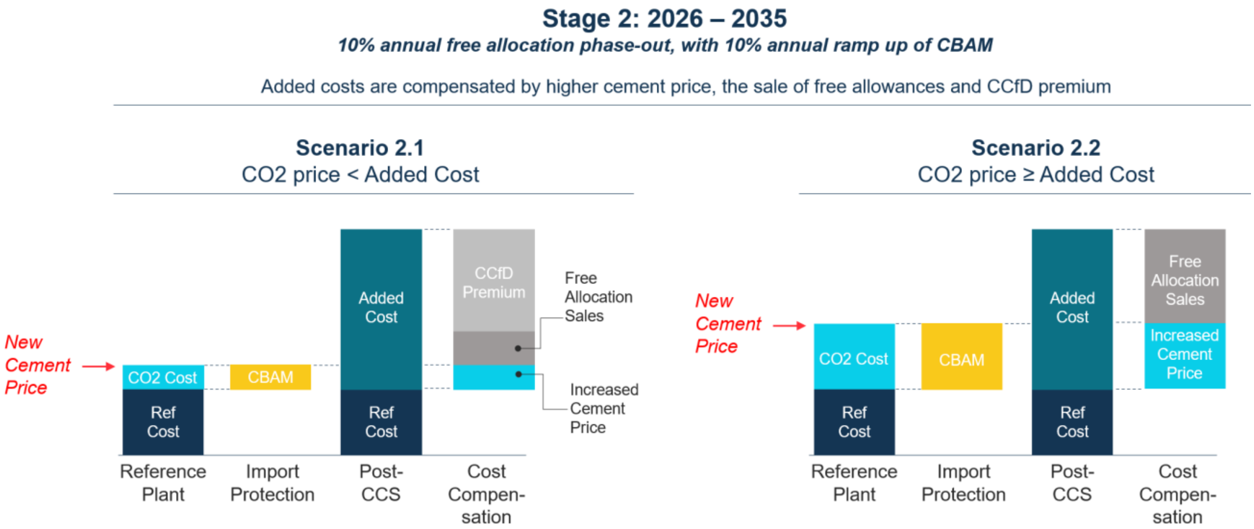

Figure 52: Cost compensation of low-carbon cement technology during the phase-out of free allocations[66]

Figure 53 shows the stage after 2035, with the complete phase-out of free allocations and the full introduction of CBAM. In scenario 3.1, despite having the cement industry pay for all their emissions, a low CO2 price is insufficient to cover the added cost of CCS. Therefore, in addition to the increased income due to higher cement prices, a subsidy such as CCfD could be helpful in making these low-carbon technologies economically viable. In contrast, with a high CO2 price as in Scenario 3.2, decarbonization costs can be solely covered by the higher cement prices.

[66] “New Cement Price” assumes that the higher production costs of cement due to the reduction of free allocations, i.e. cement companies need to purchase (more) allowances to cover emissions, are passed on to the market.

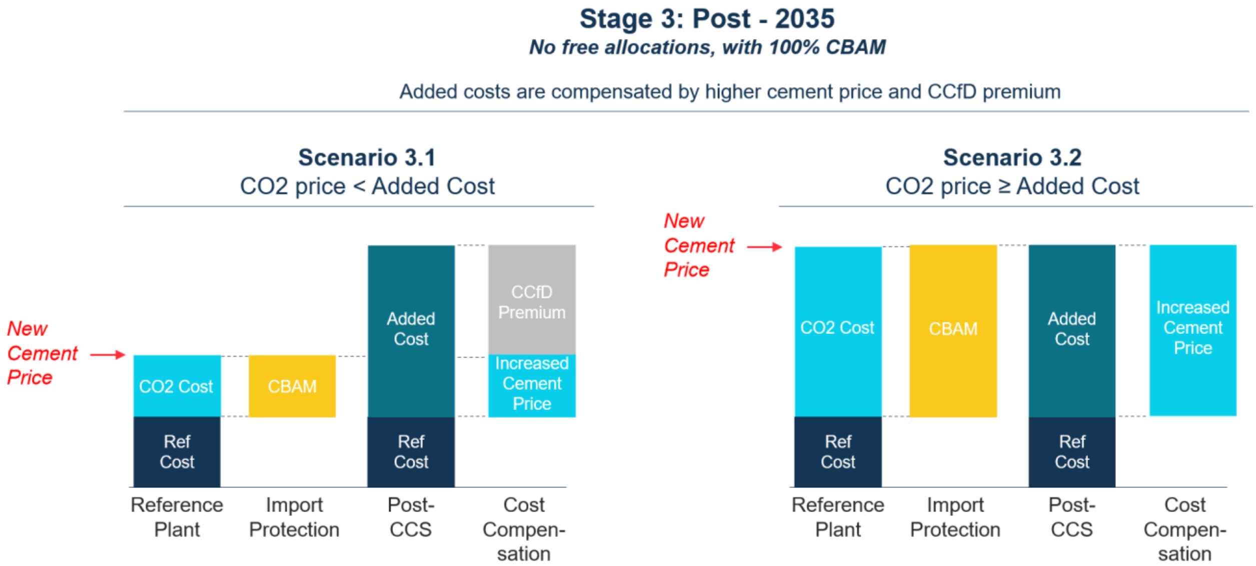

Figure 53: Cost compensation of low-carbon cement technology after the total phase-out of free allocations and with the full introduction of CBAM

Challenges and risks

CBAM is perceived to be a complex mechanism with an expected high administrative burden and operating cost [79]. This relates to the establishing the carbon content of imported products which may prove to be challenging due to the unknown material composition and lack of emission monitoring in other jurisdictions. The use of general assumptions and default values could overcome this challenge but would have to also be assessed from a legal perspective. The EU's proposed solution for this is to base these values on the average in the country of production using existing data or to base it on the average worst performing 10% in the EU [173]. However, given that the EU is globally the least emission-intensive producer in many CBAM-covered sectors, this approach could potentially underestimate import emissions [175].

What also remains unclear is the compatibility of CBAM with WTO trade policies as the EU is currently receiving criticism from other countries arguing that it is a protectionist policy [176][78][174]. According to the World Economic Forum, the legal analysis regarding compatibility with WTO obligations are preliminary and provisional. The following issues have been raised to date: (1) inconsistency with the rule of non-discrimination between imports from WTO member states, (2) CBAM tariff could exceed the custom duty ceilings agreed upon in the EU, and (3) potentially inconsistent with the national treatment rule which requires that imported and domestic products are treated equally in the market[67] [177].

Other than the current EU proposal, CBAM has not been implemented yet globally. Canada and Japan are considering similar instruments and California has a similar scheme in place [104]. Switzerland has also evaluated the introduction of border adjustment mechanisms; a 2013 study posited that such an approach would only make sense for Switzerland if it were undertaken as part of a broader climate coalition for example in partnership with the EU [178].

CEMBUREAU, the European cement association, published a position paper in 2020 on the topic of CBAM listing some design principles they perceive to be integral to the introduction of this instrument [106]:

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[67] This is specifically if domestic producers continue to receive free allowances whereas imports are subject to CBAM surcharge.

1. CBAM shall be introduced in a transitional phase complimentary to ETS free allowances to minimize uncertainty and risk of a sudden shift in policy
2. CBAM shall be based on verified emissions from imports rather than industry averages and shall include indirect emissions from electricity consumption
3. Adopt a transparent CBAM methodology compatible with WTO
4. CBAM shall be applicable to all sectors under the ETS to avoid internal market distortions especially in relation to the construction industry
5. CBAM shall include an export exemption and refund

Alternative forms of carbon leakage mitigation

A number of policies could be designed to mitigate carbon leakage while incentivizing or mandating emission reductions:

1. Standards and regulations: As mentioned previously, obligatory standards could be applied to cement producers or purchasers obliging them to meet certain decarbonization requirements. Extending standards from targeting domestic producers to importers ensures that these imports also meet local requirements aligned with national net-zero pathways. This may provide an incentive against CO2 leakage by creating an equal level playing field in the domestic market. A potential challenge of this approach, as in the case on CBAM, is the need for a CO2 tracking and monitoring system associated with high administrative efforts. In addition, this policy could be subject to criticism similar to CBAM (e.g., barriers to international trade). Setting procurement standards is a similar approach, yet still would face similar challenges regarding CO2 data collection and monitoring [80].
2. Pricing mechanisms: Free allocation of allowances under the ETS is the key policy instrument through which carbon leakage is addressed today in Switzerland and the EU. Nevertheless, this option may hinder innovation and decarbonization efforts depending on the selected benchmarks and the extent to which the CO2 price is internalized [80]. Another instrument to minimize competitiveness impacts may be the use of CO2 price exemptions and rebates (e.g., Switzerland exempts operators participating in the ETS from the CO2 levy [86]). Offering companies either direct or indirect reimbursement for CO2 prices paid could effectively put these companies back into a competitive position vis-à-vis their foreign competitors. Yet, as in the case of free allocations, depending on the extent of the rebate, this approach could neutralize the efforts to internalize the cost of pollution [179][174]. CBAM on the other hand, could provide the opportunity for carbon leakage protection while exposing local producers to a CO2 price and incentivizing decarbonization.
3. Subsidies and incentivizes: Lastly, subsidies and incentives could financially support local producers with decarbonization costs so that they are not put at a disadvantage. Direct funding, in addition to solutions such as CCfD, could subsidize the cost of producing low-carbon cement, keeping prices competitive not only with local CO2-intenisve cement but also with cheaper imports [160]. Rather than a standalone policy, subsidies are considered to be seen as complimentary policies to introduce with other instruments to sufficiently address carbon leakage [80].

Green Lead Markets

Lead markets are markets that first adopt innovations and lead the international diffusion, setting a global standard [180]. Green lead markets are thus those markets that involve green and circular industrial products in early development phases. There are two approaches to the development of green lead markets; their validity is yet to be confirmed (see footnote 64):

The first approach is establishing green lead markets through other climate policies such as public procurement, CCfDs, CBAM and others [181]. Such policies could play a role in hedging additional decarbonization costs and minimizing risk, creating an initial supply and reference for low-carbon cement while triggering a green lead market.

The second approach proposed by think tank Agora Energiewende and confirmed via interview with their policy experts, is the establishment of green lead markets through the sale of low-carbon cement at its true cost (i.e., including the additional decarbonization cost) [182]. In their assessment of current regulation, products funded by the state are banned from being marketed as low-carbon or "green" in the EU [182][68].

In this approach, if, for instance, CCfDs were employed to cover the additional cost of CCS, this would leave a cement producer with two options when selling the decarbonized cement:

(1) sell the low-carbon cement in the same way as conventional cement at a competitive subsidized price without marketing it as a low-carbon product (referring to Figure 48, this would be at a price of 75 $CHF/ton_{clinker}$);

(2) market the cement as low-carbon and pass on the additional CO2 abatement cost to the end customer through a climate surcharge which some market participants might be willing to pay (referring to Figure 48, this would be at a price of 191 $CHF/ton_{clinker}$).

If the second option is chosen, the cement company has the freedom to charge a price higher than 191 $CHF/ton_{clinker}$, rendering the cement more profitable than just receiving the CCfD premium from the state. In principle, this could position the use of the proposed green lead market approach as attractive vis-à-vis a pure CCfD approach. In this case, the quantities of cement sold via green lead markets shall be deducted from the CCfD reducing the burden on state budget [182].

Our calculations show that the increased price of clinker due to CCS would have a marginal impact on the total cost of a building (~1% added cost). Thus, building owners may be willing to pay the true costs and market their building as using low-carbon cement giving them a competitive advantage and allowing them to potentially increase the market value of their building (and increase rent).

13.4 Carbon levy on end products

Category: Pricing instrument

Value chain impact: Upstream – midstream – downstream

MRV: Mandatory (If a levy is imposed on CO2 content, MRV is required) – Not necessary (If a levy is imposed on weight, MRV is not required)

Status: Currently not considered

Potential complimentary policies: direct funding, ETS, free allocations, CCfDs, climate and innovation fund etc.

Background

Multiple countries have relied on carbon pricing and particularly taxation as a tool to drive national emission reductions. Sweden, Norway, France and Chile are examples of nations with a fossil fuel CO2 tax [125][69]. However, manufacturing and heavy industry are very often exempt from these schemes either due to their

[68] It was not possible for us to validate this assessment in detail. A further legal analysis beyond the scope of this project is required to determine whether products receiving state aid are indeed prohibited to be marketed as "green".
[69] Throughout this section we use the terms tax, levy and surcharge interchangeably.

participation in other pricing mechanisms such as ETS and/or for competitiveness reasons as we will discuss in this section.

When designing a carbon levy, policymakers may want to consider some key design elements [183]. The scope will depend on the ambition of the policy and the realms to be covered: a levy could apply to fossil fuels (as already done in Switzerland), total embodied carbon of a product, embodied carbon above a certain cap etc. The point of taxation along the value chain is another design element that can impact the administrative complexity and public acceptance of the policy instrument; for example, an upstream taxation on fuels and raw material, a midstream surcharge on emissions from cement production or, lastly, a downstream consumption surcharge on the final products [78][80].

Climate surcharges ultimately aim to internalize negative externalities of CO2 emissions by pricing emissions. As opposed to cap-and-trade systems, this instrument does not provide certainty regarding the emission reduction that will be achieved but does offer price certainty which may provide better long-term investment security for low-carbon technologies [172]. Setting appropriate tax levels and pre-defining price trajectories are two relevant policy design aspects that could send strong signals to the industry and trigger investments [179]. As in the case of the Swiss fossil fuel levy, the pre-announced price trajectory can be seen to offer the industry the opportunity for long-term planning.

When discussing carbon taxation, it is not uncommon for concerns around social welfare unfavorable public opinion to be raised [184]. To address this, an assessment of the distributional effects of a climate levy could provide clarity to understand the impact of such a mechanism on lower-income and at-risk members of the society, as well as other economic or social trade-offs [185]. It is possible that public acceptance may hinge on how the instrument`s revenues are used. Today, in Switzerland, the CO2 levy revenues are distributed back to the society and economy, in addition to funding a subsidy program for renewable energy-based building systems [120]. Overall, possible spending options for carbon revenue include the financing of other climate policies or programs, supporting households and businesses deal with the impacts of carbon pricing through direct or indirect financial support, reducing the impacts of carbon pricing on the competitiveness of affected domestic industries, reforming existing distortionary taxes and more [185].

In applying a carbon tax on basic material such as cement or concrete, competitiveness issues could arise not only in an international context but also locally in relation to alternative materials. One potential option to ensure an equal international level playing field is to expose imports to the same levy [79]. During the stakeholder workshops, Swiss cement manufacturers highlighted the perceived inconsistency of applying a CO2 levy on the embodied CO2 of concrete while exempting other building materials. This brings along the complexity of factoring in other building material performance aspects such as durability, lifetime, insulation value and more. Voluntary labels could provide some insights into how to account for these non-CO2 metrics but further research is needed to understand the potential implications of establishing mechanisms for this.

To avoid double charging, industries subject to a climate charge could be exempt from other CO2 pricing mechanisms such as the ETS [78]. As cement installations covered by the ETS today receive free allocations, this minimizes the impact of double charging. Yet, with the EU's plan to phase out free allocations, this issue requires further considerations. Switzerland has the flexibility to implement such a measure on top of the ETS, however, such an approach could potentially face opposition due to competitiveness issues and the level playing field vis-à-vis EU competitors. We later highlight the example of the CO2 levy in the Netherlands (see box below).

Potential setups

In this section, we discuss two possible setups for a consumption-based CO2 charge. The first is a climate surcharge on the final product based on weight and an average CO2 baseline (see Figure 54). The second is a CO2 price that is also levied on the final product but is dependent on the CO2 intensity rather than its weight (see Figure 55). Both approaches tax the material at the point of consumption as opposed to the ETS which is applied on the cement producer level.

In the first potential setup shown in Figure 54, a climate surcharge is applied to concrete based on the weight of cement in the structure. This means that carbon intensive and low-carbon cement are priced equally regardless of their embodied emissions. This approach could create an incentive to reduce the consumption of cement and possibly shift to alternative materials. The revenue from the climate surcharge could be funneled to cover the additional cost of low-carbon cement production through a subsidy mechanism. The possible advantage of this approach is that CO2 tracking is deemed unnecessary for both domestic and imported products, which are also subject to the surcharge to protect local production from CO2 leakage [78]. This could facilitate implementation and reduce the administrative burden. Additionally, exports could be decided to be exempt from the surcharge. To ensure WTO compatibility, domestic and imported good shall be subject to the same rates [186].

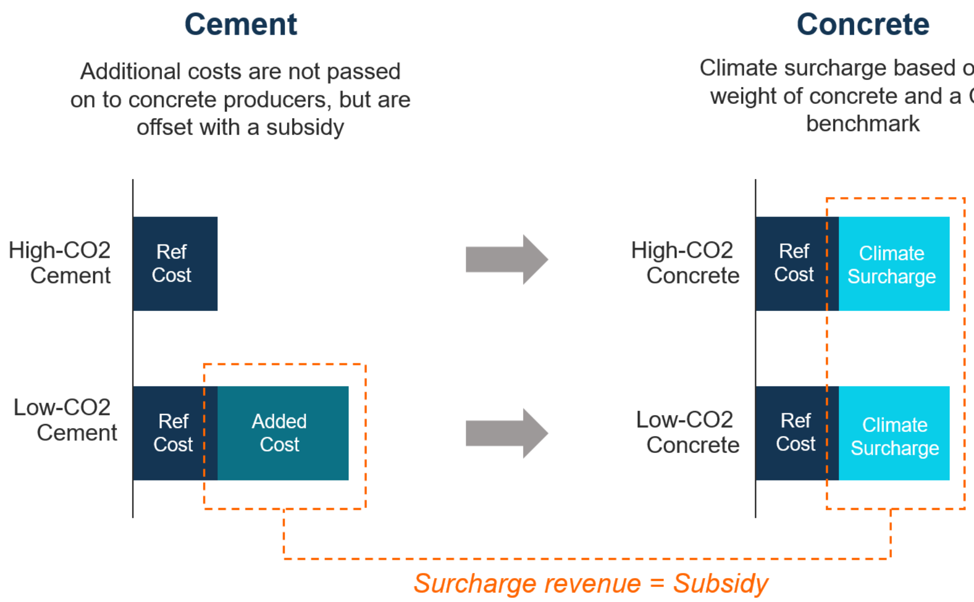

Figure 54: Climate surcharge levied on final products based on weight

In the second setup shown in Figure 55, a CO2 price is levied on the embodied emissions of cement at the point of consumption. This differs from the climate surcharge in that it is based on the actual emissions resulting from the production of the cement rather than just the weight. It also differs from carbon pricing that targets midstream and cement producers such as in the ETS. In this case, the level of the CO2 price to be paid by the customer could be based on the CO2 intensity of the cement. Therefore, high-CO2 cement would be exposed to a high CO2 price, whereas low-CO2 cement would not be charged, ultimately causing the additional costs of decarbonization to be passed on the to the customer[70] [78]. Depending on the CO2 price, this could render both high- and low-CO2 cement at similar price levels. It is also possible that the CO2 price exceeds the additional cost of low-carbon production, potentially further incentivizing investments in decarbonization technology. As in the previous case, and to avoid CO2 leakage, imports could also be subject to this levy with exports being exempt. One possible significant barrier to this approach is the need for CO2 monitoring and disclosure for domestic and imported products. As we saw in the previous section on CBAM, CO2 tracking is a complex undertaking especially with regards to imported goods.

[70] This is a simplification as low-CO2 cement will still have a small fraction of associated CO2 emissions.

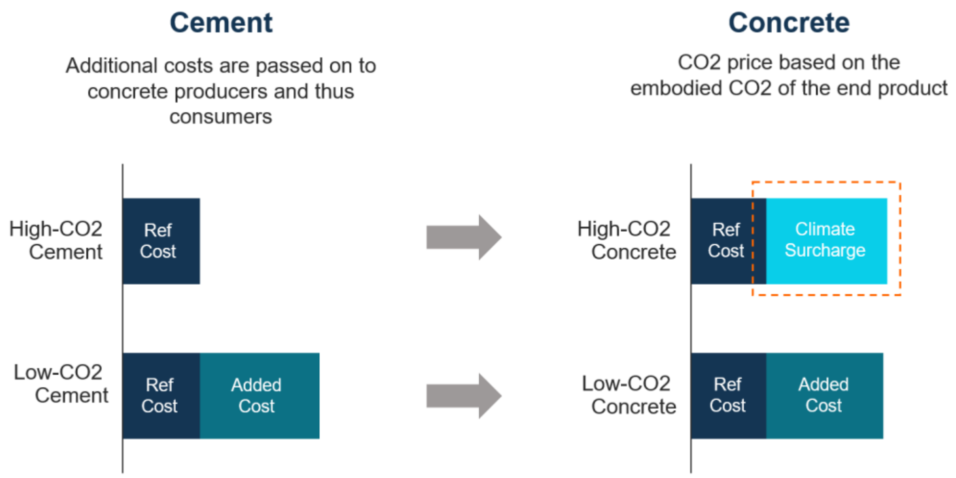

Figure 55: CO_2 price levied on final products based on embodied emissions

EXAMPLE: Netherlands: Industry Carbon Tax Act [Wet CO_2-heffing industrie]

Another approach, compared to the two discussed above, involves a levy imposed on production emissions. In 2021, the Dutch government introduced a CO2 levy on industrial emissions with a pre-defined price trajectory starting at 30EUR/ton$_{CO2}$ in 2021 and gradually increasing to 125EUR/ton$_{CO2}$ by 2030 [135]. The final price paid by the targeted industries is the difference between the national CO2 price of that year and the EU ETS price. In essence, the levy is designed to be a floating contribution on top of the EU ETS, yielding a fixed price on local emissions and providing industry with price certainty and hedging the risk of ETS price volatility [179].

To avoid the immediate threat of climate leakage, operators will not pay for most of their emissions due to the allocation of "dispensation rights" (similar to free allocations under the ETS). The dispensation rights are based on the actual production of an installation and a 10% industry benchmark as with the EU ETS (phase 4 benchmarks). The effective tax rate (difference between tax level and ETS price) is levied on the amount of CO2 emitted minus the dispensation rights. Unused dispensation rights in one year can be sold to other entities subject to the same instrument for compliance in that same year. The dispensation rights can only be sold within the closed market of players subject to the tax bill and limited to intra-year bilateral trading - lesson learned from the EU ETS [135]. The dispensation rights will decrease annually according to a reduction factor to reach 0.69 after 2030 [187]. Effectively, this approach acts as a form of CO2 floor price.

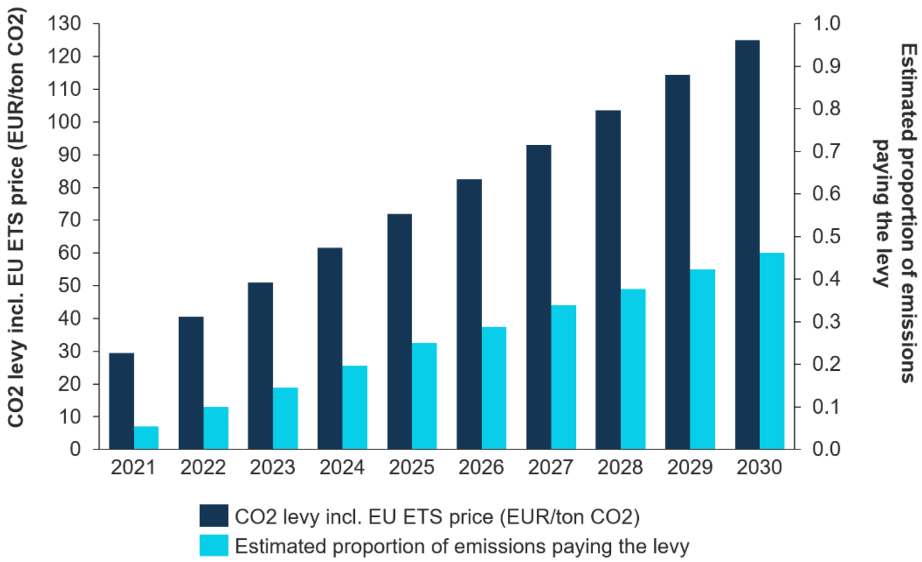

Figure 56: Netherlands CO2 levy and the estimated proportion of emissions paying the levy [156]

14 Insights to policymaking in manufacturing industries

The success or failure of policies regarding the mitigation of CO2 emissions does not solely depend on the instruments themselves but also on the timing and phasing in of each policy with respect to the existing policy landscape [80]. In this context, it has been proposed that subsidies and incentives in the near-term could focus on piloting these technologies and gathering data on their performance while driving down costs [80][188]. At this stage, policies are suggested to be technology-specific and not to aim for emission reductions but rather on proving technical viability and establishing the required boundary conditions to ensure success if the technology is deployed at scale. Once the technology is validated, proposed policies could aim at achieving CO2 abatement at the lowest possible cost, which can be achieved through technology-agnostic instruments allowing the market to select the best option [188]. In the early stages, capital markets might be hesitant to provide capital for technologies such as CCS and the associated infrastructure as they potentially face technological risk, unstable CO2 prices, an unclear regulatory landscape and no clear business case. Here, governments could support capital deployment and operational costs of these technologies through direct funding [188]. At later stages, once the technology is proven on a commercial scale, public support could shift to supporting only the operational costs as they are still likely to be higher than the conventional production depending on the CO2 price. Simultaneously, a shift of shared risk between public and private to more private could be aimed for at later maturity levels [188].

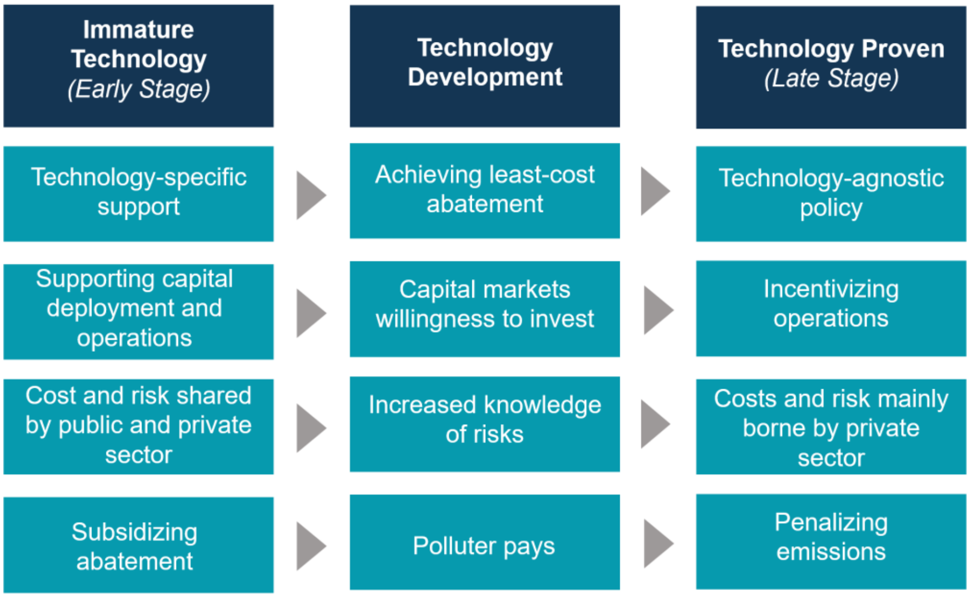

Figure 57: Progress and focus of climate policies for low-carbon technologies [188]

A transition from supportive subsidies in the near-term to overcome technical, financial, commercial and legal uncertainties to mandatory standards in the long-term applied to domestic and imported products could be advantageous, all the while keeping in mind the administrative complexity of the instruments, their implementation timelines and interdependencies [188]. An illustration of a possible policy roadmap can be found in Figure 58.

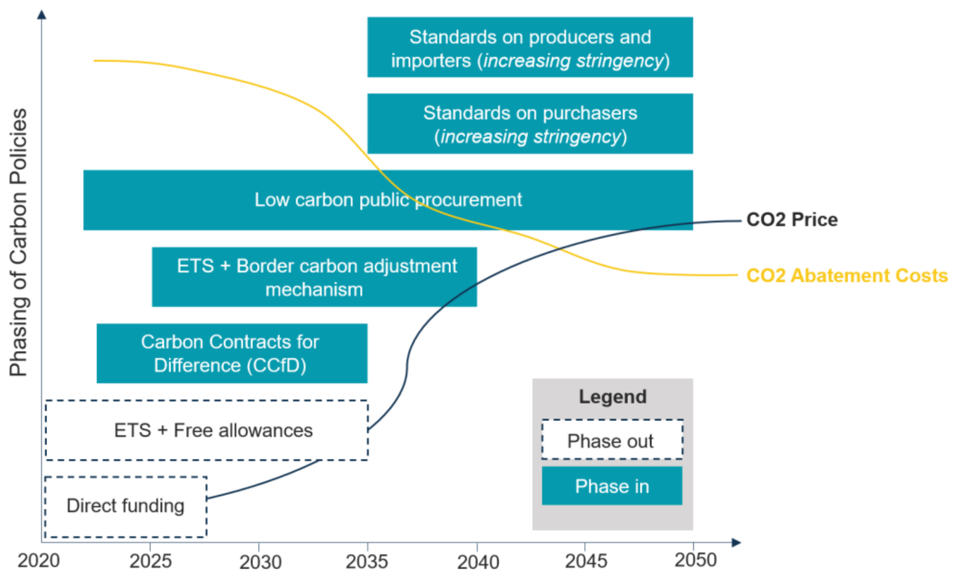

Figure 58: An illustrative example of phasing of carbon policies for industry in line with net-zero [80][188]

In the near term, the existing policy measures could continue to provide security (direct funding and ETS system). Then, it is suggested that these could be gradually replaced by CCfDs or adjusted, as in the case of an ETS system with CBAM [78][80]. These new measures, together with low carbon public procurement may provide security and lower the risk for private industries. However, as carbon prices likely rise, capturing CO2 becomes commercially viable and more stringent emission targets are set internationally, trade exposed sectors are thought to require less protection. Thus, the costs and risks may gradually transition to the private sector. Slowly, the market may define which fraction of the decarbonization costs could be passed on to the consumer leading to the most efficient cost structure [188]. Standards imposed in the long-term could ensure net-zero compatibility across all sectors while mitigating the impact on competitiveness. The standards themselves could be set up with flexible compliance (e.g., tradable performance standards) and gradually increase in stringency [80].

15 Conclusion

This report suggests that there is a pathway for the Swiss cement industry to achieve net-zero emissions by 2050. Depending on the CO2 mitigation pathway, even negative emissions are possible. However, our analysis shows that with the mitigation options available today, this will require the deployment of carbon capture.

The decarbonization technologies and approaches assessed in Part I of this study are at different stages of commercialization and development. Energy efficiency, clinker substitution and alternative fuels are already common practice in the European cement industry while alternative clinkers and carbon capture are novel solutions. The latter are associated with higher investment costs and risks than the established decarbonization measures; yet, their potential climate impact is comparably higher. Our analysis finds that on an absolute cost basis, the least cost pathway to net-zero is through a diversified portfolio of solutions, i.e. a combination of energy efficiency, clinker substitution, alternative fuels and carbon capture and storage (CCS). Based on our assumptions and analysis, this pathway yields an overall CO2 abatement cost of 113 CHF/ton_{CO2}, leading to modelled annual decarbonization cost of around 300 million CHF for the Swiss cement industry.

The most relevant technological lever for decarbonization is CCS. CCS is also the most complex to implement as it not only requires the installation of a new, albeit mature technology but also the appropriate boundary conditions beyond the cement plant, including long-term access to clean energy and alternative fuels such as biomass and CO2 transport infrastructure, among others. Additionally, current Swiss regulations prohibit the accounting for captured CO2 as part of the ETS which poses a barrier to the deployment of this technology, which the Federal Government has already proposed to address in the revision of the CO2 law [89].

Given the importance of CCS in the presented pathways to net-zero, it needs to be highlighted that the industry-wide deployment of carbon capture relies on appropriate CO2 transport infrastructure and frameworks to be in place. For pilot plant installations, alternative means of transport are possible, but at-scale widespread adoption requires the existence of a CO2 pipeline network in and beyond Switzerland. A shared cross-border European CO2 infrastructure would allow emitters across the continent to connect to permanent geological storage.

Part II of this report establishes that similar to CCS, the other decarbonization technologies also face barriers to deployment. EU and Swiss policy could help in overcoming these barriers. While there are few cement-specific policies in place globally already, a number of existing and discussed policy options from other contexts and industries could be considered. Some technology-specific barriers appear to call for tailored policy solutions: Clinker substitution barriers, for instance, could be addressed by a shift from the prescriptive Swiss concrete code to a performance-based approach, allowing for the overall reduction in clinker and cement production; alternative clinker adoption as another example could be facilitated by specific public procurement requirements.

To address the high CO2 abatement costs of solutions such as CCS, a range of policy instruments are being developed and discussed for the medium term, covering subsidies, incentives and pricing mechanisms. These include, for instance, Carbon Contracts for Difference (CCfD) to cover the additional costs of CO2 abatement, the phase out of free allocations and the Carbon Border Adjustment Mechanism (CBAM) to create a level playing field with imports and avoid carbon leakage. Their design and coordination with other climate policies require further research, however. In the long run, CCS may prospectively move towards commercial viability and trade exposed sectors could potentially require less protection. In this way, it may be an option to let the costs and risks gradually transition to the private sector. While policy research and design is ongoing, in order to parallelize and thus accelerate, the cement producers could engage in plant-level analyses and pilot decarbonization projects in line of numerous other similar activities in the European and global cement industry.

Lastly, although not touched upon in this analysis in detail, we would like to emphasize the importance of reducing cement production as a key and cost-effective approach to reducing emissions from the cement industry. This could be achieved through multiple levers including: use of alternative construction material, increasing concrete recycling quotas, optimizing structure dimensioning, avoiding overspecification, increasing the demand for highly blended cement, among others [25][155].

16 Outlook and Future Implementation

Our study has provided a techno-economic assessment of CO2 mitigation technologies for the cement industry in Switzerland. We have demonstrated that there are multiple CO2 mitigation pathways that enable the industry to fully decarbonization by 2050. Given the different stages of development, some technologies can be directly implemented such as changes to the fuel mix, whereas others require further technical feasibility studies and depend on future infrastructure. Feasibility studies on a cement plant level, could quantify the viability and business case of CCS further (similar to the study performed by waste incineration plant KVA Linth [189]). In addition, a national dialogue between the cement industry, other heavy emitters, cantons, the Federal State and other key stakeholder on the topic of CCS could facilitate and accelerate the rollout of the required CO2 infrastructure. Our study has also revealed the need for further research in a number of areas, both on a decarbonization technology level (e.g. on the integration of different capture technologies and their energy demands in the broader energy system) and with regards to policy (e.g. on the detailed design of and coordination with other climate policies).

With the Swiss and EU policy landscape currently in transition, it is relevant to observe the ongoing discussions and outcomes as they may significantly impact the financial viability and deployment of the technologies discussed. This is especially true with regards to the possible phase-out of free allocations on the EU level and accounting of captured emissions in the Swiss ETS, as these two policy modifications affect the business case of CCS. The ETS carbon price is another key element that should be accounted for especially in connection to the policy transition. Throughout this report we use a price of 86 CHF/ton_{CO2}, as this was the approximate price throughout the end of the project.

17 Communication

Throughout the project, the team has continuously communicated the findings with the project stakeholders (cemsuisse, FOEN, and SFOE) through meetings and workshops. This also allowed us to collect and integrate feedback. We have also reached out to various technical and policy experts for input regarding the latest updates in the industry and political landscape. Their insights have been incorporated into multiple sections of this report.

Our results will be further disseminated via public presentations and a detailed presentation deck available on the sus.lab website.

18 Publication

In addition to this publicly available report, the results of this study will be published in the form of a detailed presentation on the sus.lab website (www.suslab.ch).

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20 Appendix

Appendix A – Emissions model

Table 24: Fuel consumption and corresponding emissions

	Fuel Consumption 2019 [3]	Fossil Fuel Emission Factor [3]	Biogenic Emission Factor [3]	Fossil Fuel CO2 Emissions	Biogenic CO2 Emissions
Unit	TJ	tCO2/TJ	tCO2/TJ	ktCO2	ktCO2
Primary Fossil Fuels	**3,736**			**348**	
Gas oil	106	74		8	
Residual fuel oil	63	77		5	
Petroleum coke	552	91		50	
Other bituminous coal	831	93		77	
Lignite	2,120	96		204	
Natural gas	65	56		4	
Secondary Fossil Fuels	**5,805**			**376**	**75**
Waste oil	1,466	68	5	100	8
Waste coke from coke filters	48	97	NA	5	-
Mixed industrial waste	-	74	NA	-	-
Other fossil waste fuels	-	97	NA	-	-
Solvents and residues from distillation	1,623	63	7	103	12
Waste tires and rubber	1,041	61	23	64	24
Plastics	1,627	65	20	105	32
Biomass	**1,937**			**2**	**183**
Mix of special waste with saw dust (CSS)	58	30	82	2	5
Sewage sludge (dried)	512	NA	95		48
Wood waste	861	NA	100		86
Animal meal	475	NA	87		41
Sawdust	31	NA	100		3
Agricultural waste / other biomass	-	NA	110		-
TOTAL	**11,478**			**725**	**259**

Appendix B – Swiss cement composition

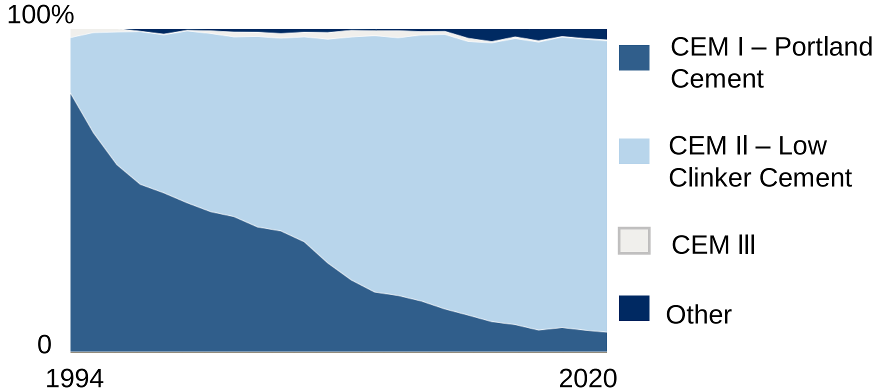
Average composition of cements produced in CH in 2015 (Percentage by mass) [42]–[44]

CEM I - 0.6781 kg_{CO2eq}/kg_{cement}	
Clinker	90.5 %
Limestone	4.64 %
Gypsum	4.93 %

CEM II/A - 0.589 kg_{CO2eq}/kg_{cement}	
Clinker	78.8 %
Limestone	16.8 %
Blast furnace slag	0.02526%
Silica fume	0.0916%
Gypsum	4.5%

CEM II/B - 0.557 kg_{CO2eq}/kg_{cement}	
Clinker	67.2 %
Limestone	18.7 %
Burnt Shale Oil	10.9 %
Blast furnace slag	0.669 %
Fly ash	0.0000992 %
Gypsum	2.46 %

Cement delivered according to type (%):



Appendix C – Alternative clinkers

Table 25: Data on enthalpy of formation, process emissions and composition of binder systems

Clinker Phase	Enthalpy of formation GJ/ton$_{clinker}$	Process emissions kg$_{CO2}$/ton$_{clinker}$	Composition of binder systems **OPC**	**RBPC**	**CSA**	**BYF** *High-ye'elimite*	**BYF** *Low-ye'elimite*	**CCSC**	**HMC** *Forsterite Olivine*	**HMC** *Magnesite rock*
Alite (C3S)	1.82	579	63%	16%						
Belite (C2S)	1.30	512	15%	62%	23%	46%	60%			
Aluminate (C3A)	2.01	489	8%	8%						
Ferrite (C.iAF)	1.36	362	9%	9%	15%	17%	17%			
Quicklime (CaO)	3.20	786								
Wollastonite (CS)	0.77	379						100%		
Ye'elimite (C4A3$)[71] [from CaSO4]	0.77	*216*			62%	35%	20%			
Periclase (MgO) [from MgCO3]	2.90	1100								100%
Reactive Periclase (MgO) [from Mg2SiO4]	0.86	0	5%	5%					100%	
Process emissions (kg$_{CO2}$/ton$_{clinker}$)			513	482	306	373	412	379	0	1100
Difference to OPC				- 6%	- 40%	- 27%	- 20%	- 26%	- 100%	+ 114%
Enthalpy of formation / fuel consumption (GJ/ton$_{clinker}$)			1.67	1.42	0.98	1.10	1.17	0.77	0.86	2.90
Difference to OPC				- 15%	- 41%	- 34%	- 30%	- 54%	- 48%	+ 74%

[71] The $ sign is sulphate (SO3/SO4) in the cement notation.

Table 26: Details on alternative clinkers [6][41]

Clinker System	Raw Meal	Binder Manufacturing	Concrete Processing and Applications	Cost	Environmental Performance	Performance and Durability	Standards	TRL
RBPC	High availability of raw material - same raw material, different mix (higher belite content as opposed to OPC which has a higher alite content) Low grade limestone sufficient	Can be produced in conventional cement plants Lower fuel demand, higher production rates Harder to grind, may require additional grinding capacity Lower clinkering temperature 1,350°C	No processing issues Hydraulic curing Lower early stage hydration, not suitable for pre-cast at ambient temperature, suitable for mass and heavy strength concrete Precast products, ready-mixed concrete applications, and site-mixed concretes	Similar investment cost for additional clinker and cement Retrofit cost ~ 0-12 mio EUR Slight increase in OPEX ~2-3.8 EUR/t cement	9% less CO_2 emissions Lower NO_x and SO_x due to lower burning temperatures 5% electricity penalty to grind to fineness of OPC (greater hardness of belite vs. alite)	Similar setting time, lower H_2O demand, lower heat evolution, early strength gain but higher later age strength, lower drying shrinkage. Advantage over OPC in mass concrete and high strength concrete, and in hot climates.	Meets Chinese standards for Portland cements	Commercialized

CSA	Same raw material, mix changes Less limestone, more aluminum Limited high aluminum sources e.g., bauxite	Can be produced in conventional cement plants Lower clinkering temperature	Precast products, ready-mixed concrete applications, and site-mixed concretes	Higher raw material cost	41% less CO2 NOx emissions lower due to lower temperature 30-50% less grinding energy	Similar performance feasible Less carbonation and chloride migration resistance Rapid strength gain and shorter curing time	EU law being drafted, some compositions covered by Chinese CSA standard	Commercialized
BYF	Same raw material, mix changes Three essential phases: Belite> Ye'elimite>Ferrite 20-30% less limestone, more aluminum that can be sourced from clays and coal (lower content vs. CSA)	Can be produced in conventional cement plants Lower clinkering temperature 1250-1350°C	Shorter setting and hardening times (e.g., pre-cast) but can be controlled for other applications using chemical admixtures Sensitivity to temperature thus workability will require worker training Precast products, ready-mixed concrete applications, and site-mixed concretes	Similar investment cost for additional clinker and cement Higher material cost but less than CSA due to cheaper aluminum source	23% less CO2 emissions NOx emissions lower due to lower temperature 30-50% less grinding energy	Set rather rapidly Could in principle replace OPC in many applications Gain strength at similar rates over a wide range of temperatures, and give acceptable durability in many standard tests Relatively insensitive to excess water	EU law being drafted, some compositions covered by Chinese CSA standard	Demonstration E.g., Aether

CCSC	Raw material mainly mineral wollastonite ($CaSiO_3$) or other low-lime calcium silicates CO_2 supply	Conventional OPC plant Low fuel sulfur contents, waste fuels may be inappropriate	Adapted curing chambers for careful control of gas composition and circulation, temperature, and humidity Pure CO_2 stream to cure elements in industrially-acceptable timeframe (~24hrs) Mixed and placed with little water in a CO_2-rich environment till sufficient strength is reached Precast products (5% CH market), not applicable to mass concrete applications	Similar investment cost for additional clinker and cement Can be produced in conventional plant Similar raw material cost (raw meal) Additional capital cost for curing chambers Additional cost for purchasing and transporting the CO_2	34% less CO_2 emissions; 86% less CO_2 emissions after 100% carbonation Theoretically, all process emissions can be reabsorbed Mix water is captured and can be recycled, i.e., water neutral	Not capable of protecting steel reinforcement against corrosion, so best suited to non-reinforced applications	Precast concretes can be sold under local technical approvals	Pilot E.g., Solidia

HMC	MgO source is usually mineral natural magnesite rock ($MgCO_3$) – contains carbon Alternative MgO source is basic magnesium silicate rocks e.g., pure forsterite olivine (Mg_2SiO_4) – no carbon Global reserves of basic magnesium silicates are sufficient but much less distributed than limestones	Different manufacturing process, new plant required No established manufacturing process Location near basic magnesium silicates deposits	Too early to disclose of practical limitations	Too early to disclose of costs Most likely more expensive $MgCO_3$ is very scarce mineral compared to limestone Mg_2SiO_4 commonly found at or near to the Earth's surface	More sequestration of CO_2 than emitted in manufacturing phase 100% more CO_2 emissions when using $MgCO_3$, but can all be reabsorbed 85% less emissions when using Mg_2SiO_4, the remaining and more can be absorbed. Potential for negative-emissions	Magnesium carbonate, calcium silicate hydrate and calcium hydroxide matrix results in an enhanced compressive strength Concerns regarding the stability of magnesium carbonate at high temperatures Too early to assess true durability	N/A	Research E.g., Novacem

Appendix D – Details on the CCS model

Table 27: Parameters and assumptions for the CCS model adaptation to Switzerland

Model Input	Unit	Value
Emission Factors [3][190]		
Cement Production Fuel	kgCO2/GJ	63
Coal	kgCO2/GJ	92.7
Natural Gas	kgCO2/GJ	56.4
Electricity	kgCO2/MWh	128
Utility and Consumables Price		**2015**
Raw Meal Price	EUR/t clinker	5
Coal Price	CHF/GJ_{LHV}	4.2
Natural Gas Price	CHF/GJ_{LHV}	7.5
Electricity Price	CHF/MWh	90
Cement Production Fuel[72]	EUR/GJ	3.14
Annual Average Salary		
	CHF/Pers	100,000
CO2 Transport and Storage Cost[73]		
Transport	CHF/t CO2	45
Storage	CHF/t CO2	23
Assumptions for the cement production fuel cost[74]	**Share**	**CHF/GJ**
Primary Fossil Fuels	33%	4.2
Alternative Fuels		
Other fossil fuels (waste)	50%	3
Biomass	17%	1.47
Average		**3.14**

[72] Calculated at the lower end of the table.
[73] Extracted from the findings of feasibility and cost study of a CO2 collection network in Switzerland [58].
[74] Cost of fuels is provided by cement industry expert.

Table 28: Assumptions for the economic cost performance of the CO2 capture technologies

Fixed OPEX [11]	**Unit**	**Value**
Overhead (Insurance, taxes, regulatory, etc.)	%/TPC	2
Maintenance (incl. Maintenance labor)	%/TPC	2.5
Maintenance Labor	% total maintenance	40
Labor		
Operation Labor		
Ref. Plant	people	100
CO2 capture plant	people	20
Salary	CHF/pers	100,000
Support and admin	% O&M labor	30
Variable OPEX [11]		
Cement Production Fuel	CHF/GJ	3.14
Raw meal price	$CHF/ton_{clinker}$	5.35
Coal price[75]	CHF/GJ_{LHV}	4.20
Natural gas price	$CHF\ /GJ_{LHV}$	7.50
Electricity price	CHF/MWh	90.00
Cost of steam from NG boiler	CHF/MWh	31.7
Cost of steam from cement waste heat	CHF/MWh	10.6
Cooling water cost	EUR/m3	0.39
Process water cost	EUR/m3	6.65
Ammonia solution price for NOX removal	EUR/ton	130
MEA solvent	EUR/ton	1450
Ammonia solvent	EUR/ton	406
Sulfuric acid	EUR/ton	46
Sodium hydroxide for flue gas SOX	EUR/ton	370
Membrane material replacement	EUR/m^2	7.87
Miscellaneous variable O&M	$CHF/ton_{clinker}$	1.1
CO2 transport and storage [58]		
CO2 Transport	CHF/ton_{CO2}	44.6
CO2 Storage	CHF/ton_{CO2}	23
Economic Parameters [11]		

[75] The fuel costs (coal, natural gas and electricity) are the costs in Switzerland as provided by experts.

Capacity factor	%	91.3
Economic lifetime	Years	25
Construction time - cement plant	Years	2
Allocation of cement plant construction costs by year	%	50/50
Construction time - CO2 capture	Years	3
Allocation of CO2 capture construction costs by year	%	40/30/30
Discount rate	%	8
Annuality factor		0.094
Clinker production	$ton_{clinker}$/hour	120.6
	$ton_{clinker}$/year	952,432
Exchange rate [191]	EUR	CHF
2015	1	1.07

Appendix E – Swiss concrete code overview

There are 27 standardized cements in the EU cement standard EN 197-1 [38]. The standard states the constituents of the different cements, proportioning and the physical, chemical and mechanical properties of the cement and its constituents. There are 5 categories of cement, grouped according to the constituents other than cement. CEM I is OPC, whereas all others are categorized as blended cements, and which were developed in Europe mainly due to cost and environmental considerations [192]. Blended cements need to have favorable properties in terms of workability, strength development and durability to be used in the market. The opportunity of using blended cements, in addition to CO2 abatement and resource efficiency, is the ability to combine the advantages of all different constituents into an optimized and robust cement for varying applications.

The European concrete standard EN 206-1 is a non-harmonized EN-standard, meaning that it has the status of a framework document requiring the introduction of national specifications known as National Application Documents (NAD) in each country [192]. The standard aims to ensure the durability of concrete subject to varying environmental exposures (e.g., stress, weather conditions etc.). This is achieved through a descriptive/prescriptive approach in EN 2016-1, whereby exposure classes that cover the possible environmental exposures such as carbonation, de-icing salt, chloride from sea water etc. are listed with their associated technology measures such as concrete composition, max water-cement ratio, minimum cement content etc. EN 206-1 contains recommendations for limiting values, and these can be changed when implementing the final NAD requirements. As an alternative to the prescriptive approach, the EN 206-1 offers a performance-based option referred to as Equivalent Concrete Performance Concept (ECPC). Here a concrete mixture may be used if it does not comply with the prescriptive specifications if the performance of the new mix is equivalent to the standardized concrete for the relevant exposure class [193]. The performance is quantified using certain durability indicators and tests corresponding to the exposure class.

All cements listed in the European Cement Standard EN 2197-1 may be used in the manufacturing of concretes in accordance with the European Concrete Standard EN 206-1. However, due to durability considerations in certain applications and the lack of local experience, the use of some of the listed cements are restricted from use for certain exposure classes in some countries. Additionally, countries have set different limitations regarding concrete technology measures as can be seen in Figure 59 below [192]. The figure shows the limits for a vertical surface with no significant exposure to chloride. There are varying limitations to compressive strength, maximum w/c ratio and minimum cement content, in addition to restrictions on the types of cement that can be used. When the national standards set prescriptive limitations such as these, not only do they inhibit the use of certain blended cements, thus inhibiting the decrease in clinker-cement ratio, but they also prevent concrete producers in minimizing cement content within the concrete mix.

Country	Exposure class	min f_c	max $(w/c)_{eq}$	min c kg/m³	CEM I	CEM II																		CEM III			CEM IV		CEM V	
						S		D	P/Q		V		W		T		LL		L		M									
						A	B	A	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	C	A	B	A	B
Austria	XC1+XF1	--	0.55	300	x	x	x	x			x	x	(x) 2)						x	(x) 2)		(x) 2)	x	(x) 2)					
Belgium	EE3 (XC4+XF1)	C30/37	0.50	320	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				
Czech Republic	XC1 to XC4 or XF1	C30/37	0.50 or 0.55	300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					
Denmark	(XC2, XC3, XC4, XF1, XA1)	C25/30	0.55	150 3)	(x) 4)						(x) 4)	(x) 4)					(x) 4)			(x) 4)									
Finland	XC3 or XC4, XF1	C25/30	0.60	250 5)	x	x	(x) 6)	x			x	(x) 6)					x 6)				x	(x) 6)							
Germany	XC4 + XF1	C25/30	0.60	280	x	x	x	x	x	x	x	x	O	O	x	x	x	O	O	O	(x) 7)	(x) 7)	x	x	O	O	(x) 8)	(x) 9)	(x) 9)
Ireland	XC2 or XC4 + XF1	C30/37 if XC4 + XF1	0.55	320	x												x		x										
Italy	XC1	C25/30	0.60	300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	XC2 + XF1	C32/40	0.50	320	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Luxembourg	XC4 + XF1	C25/30	0.60	280	x	x	x	x		x					x		x				(x) 10)		x	x					
Netherlands	XC3	--	0.55	280	x	x	x				x	x			x	x							x	x					
	XC4 + XF1	--	0.50	300	x	x	x				x	x			x	x							x	x					
Norway	XC4 + XF1	--	0.60	250	x	x		x			x						x		x										
Portugal	XC4 + XF1 11)	C30/37	0.60	280	x	x		x	x		x		x		x		x		x		x								
			0.55	300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	(x) 12)			(x) 12)	(x) 12)	(x) 12)	
Sweden	XC4, XF1	--	0.55	300	x 4)	x 4)		x 4)			x 4)						x 4)				(x) 4)		x 3)	x 3)					
Switzerland	XC4 + XF1	--	0.50	300	x	x		x									x				(x) 4, 13)								
United Kingdom	XC3/4 + XF1	C28/35	0.60	280	x	x	x	x		x	x						x	x	x	x			x	x					

x	allowed
(x)	allowed with restrictions
	not mentioned
O	not allowed

Sources: [2, 9, 10]

1) Due to the complexity of the national annexes, this compilation is not exhaustive and the accurate repetition of all specifications cannot be guaranteed.
2) Cements need testing
3) min filler: 375 kg/m³
4) Minimum strength class 42,5
5) min c = 270 kg/m³ for XC4
6) Cement not approved for XC4)
7) Only CEM II/A-M (S-D; S-T; S-LL; D-T; D-LL; T-LL; S-P; S-V; D-P; D-V; P-V; P-T; P-LL; V-T; V-LL) and CEM II/B-M (S-D; S-T; D-T; S-P; D-P; P-T; S-V; D-V P-V; V-T)
8) Only CEM IV/B (P) and valid only for trass according to DIN 51043, used as a main constituent up to a maximum content of 40 % (m/m)
9) Only CEM V/A (S-P) and CEM V/B (S-P) and valid only for trass according to DIN 51043
10) Only CEM II/A-M (S-D; S-T; S-LL; S-V)
11) Assumption
12) Not less than 50 mass% clinker
13) Only CEM II/A-M (D-LL)

Figure 59: Extraction from EN 206-1 national annexes of different countries for an exposed vertical surface of inland concrete with no significant levels of external chlorides [192]

The Swiss and other European standards on cement types and minimum cement content per m3 of concrete are too restrictive and do not allow the CO2 reductions that would otherwise be possible [25]. In Figure 59, it can be observed that countries such as Italy permit the use of all cement types, whereas in Switzerland this is restricted to CEMI and CEMII for the application at hand[76]. Furthermore, whereas the minimum cement content ranges between 150 and 320 kg/m³, Switzerland lies on the upper limit of the spectrum with 300 kg/m[77] whereas Denmark is on the lower end at 150kg/m³.

In Switzerland`s code SIA 262, the national appendix of EN 206-1, defines requirements for common types of concrete used in building construction and civil engineering [85]. Each concrete type satisfies certain exposure classes, a compressive strength class and other composition requirements as per

[76] The referenced paper was written in 2011 [192].Since then the list of cements allowed in Switzerland has expanded and can be found in the SIA registry (Liste der frei gegebenen Zemente ww.sia.ch/register) or Table NA.5, page 15 in SIA262.

[77] This still applies today as can be seen in Table NA.6, page 16 in SIA262. The minimum cement content in Switzerland ranges from 280 to 320 kg/m³ concrete.

Table NA.5, page 15 in SIA262. The Swiss standard limits the reduction of clinker-cement ratio and the overall reduction of cement consumption in the following ways:

Cement level:

1) Cement type: SIA 262 lists the types of cements that can be used per concrete type in Switzerland (Table NA.1, page 7 in SIA262). Some of the cements permitted in the European EN 197-1 are not listed in the Swiss standard, prohibiting their use. For example, CEM III/C which according to EN 197-1 allows for a clinker replacement with GBFS up to 95% is not permitted for use in Switzerland. The use of calcined clay for LC3 is permitted in EN 197-1 and SIA 262 under CEM II/B-Q with a minimum clinker content of 65%. The LC3 formula with 50% clinker has been in the European standard revision process and was thought to enter into force in 2021 as CEM II/C-Q [45]. The question remains whether SIA will include the new CEM II/C-Q in the Swiss standard. This will enable cement companies to produce LC3 eventually driving down the clinker-cement ratio.
2) Cement quantity: SIA 262 defines limits for the minimum quantity of cement that must be used in the concrete mix (Table NA.6, page 16 in SIA262). As mentioned above, the minimum cement content ranges between 150 and 320 kg/m^3 in Switzerland, comparably high in relation to other European countries like Norway, Finland and Denmark (see Figure 59). This limitation does not restrict the reduction of clinker-cement ratio but inhibits the overall reduction in cement consumption.

Concrete level:

Additive quantity: SIA 262 permits the use of additives to the concrete mix such as fly ash and silica fumes. Adding these “Type II”[78] additives to the concrete mix reduces the amount of cement required. The k-value concept is used to determine the maximum amount of Type II additives that can be included in the concrete mix (Table NA.3, page 12 in SIA262) and thus the maximum amount of cement reduction granted due to the addition of these additives (Sections NA.5.2.5.2.2, NA.5.2.5.2.3 and NA.5.2.5.2.4, page 10 and Table NA.2, page 11 in SIA262). Hence, the k-factor allows concrete producers to calculate the new and reduced limit for minimum cement content. For example, when using CEM I, the minimum cement content shall not be reduced by more than k x (minimum cement content – 200) kg/m3 and the amount of (cement + Type II additive) shall not be less than the minimum cement content required. Calculating this for concrete type A and for the use of fly ash as an additive: k-value for fly ash in combination with CEM I is 0.4, the minimum cement content of type A concrete is 280 kg/m^3 concrete. The calculation is as follows: maximum cement reduction 0.4 x (280-200) = 32 kg/m^3 so cement content is 280-32 = 248 kg/m^3.

[78] Pozzolanic or latent hydraulic additions. Type I includes inert additions.

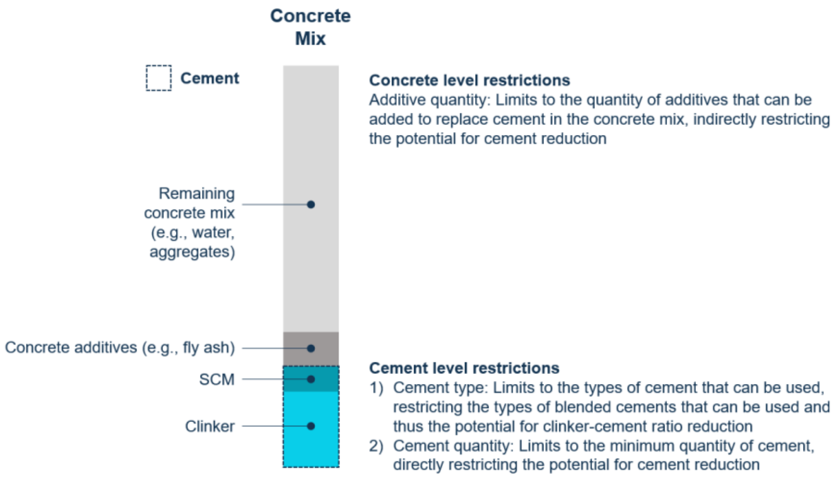


Figure 60: Swiss standard limits the reduction in clinker-cement ratio and overall cement consumption

The prescriptive approach of SIA 262 allows concrete producers to deliver concretes that fulfil the performance requirements by respecting the choice of cement, minimum cement quantities and w/c ratio limits without the need for continuous testing. Industry experts have referred to this as the fixed concrete recipe that "guarantees the high quality of Swiss concrete". SIA 262 denies the use of ECPC[79], the performance based approach permitted by EN 206-1.

[79] SIA 262 NA.5.2.5.3

Appendix F – Global cement carbon capture projects

Table 29: List of global cement carbon capture projects

Project Name	Location	Cement Company	Type	Project Duration	Capture Capacity	CCS/CCU	Cost[80]	Funding Source	Refer-ence
SkyMine beneficial CO2 use project	USA	Capitol Aggregate	Demonstration	Construction 2010-2015, operational since August 2015	77,000 ton_{CO2}/year	CCU (Production of chemicals)	125 million USD	Mostly private financing with public funding (US Department of Energy's National Energy Technology Laboratory)	[144] [145]
Norcem CO2 capture project	Norway	HeidelbergCement	Commercial capture facility	Testing 2013-2017 Expected operation 2023	400,000 ton_{CO2}/year	CCS	N/A[81]	Majority public funding with partial private financing	[146] [147]
ACCSESS	Poland	HeidelbergCement	Pilot	Project launched in 2021	N/A	CCUS	N/A	Mostly public funding (Horizon2020)	[92]
Baimashan Cement Plant CCU Demo	China	Anhui Conch	Demonstration	2018	50,000 ton_{CO2}/year	CCU	10 million USD	Private	[148] [149]
Dalmia Cement Project	India	Dalmia Cement	Commercial capture facility	Expected operation 2022	500,000 ton_{CO2}/year	CCU	N/A	N/A	[200]

[80] We refer to the project costs of installing the carbon capture for the respective cement plant. In case the cement capture project is a part of a larger project (e.g., Norcem CO2 capture project part of the Norwegian Longship project), we list the cement-related costs if available.
[81] N/A: No public information found.

Lafarge Holcim Cement Carbon Capture	USA	Lafarge Holcim	Study for the commercial capture facility	Expected operation mid-2020s	730'000 ton_{CO2}/year (long-term aim 1-2 million ton_{CO2}/year)	CCS or enhanced oil recovery (EOR) *(conflicting public information)*	N/A	Private financing with 45Q tax credit 35 USD/$ton_{CO2\text{-}EOR\text{-}stored}$ in the USA	[151] [152]
CO_2MENT	Canada	Lafarge Holcim	Demonstration	Capture in 2019-2021 CO2 utilization 2020-2023	200 ton_{CO2}/year	CCU	22 million USD (incl. efficiency improvements)	Privately financed with partial funding from the British Columbia Ministry of Environment and Climate Change Strategy	[203]
ITRI's Calcium Looping Pilot	Taiwan	Taiwan Cement Cooperation	Pilot and demonstration	Operational since 2013	1 ton_{CO2}/hour	CCU	N/A	N/A	[204]
CLEANKER	Italy	Buzzi Unicem,	Demonstration	Design and construction 2017-2021	N/A	CCUS	9.2 million EUR	Public funding (Horizon2020)	[63]
CEMCAP	Germany, Norway and Italy	HeidelbergCement, Norcem and Italcementi	Analysis and demonstration	Demonstration 2015-2018	N/A	Tested 5 capture technologies	10 million EUR	Majority publicly funded (Horizon2020) and partial Swiss public funding	[55]
LEILAC	Belgium	HeidelbergCement	Pilot and demonstration	Construction 2016-2020 Ongoing since	85 ton_{CO2}/day	CCS	12 million EUR	Public funding (Horizon2020)	[205]
LEILAC 2	Germany	HeidelbergCement	Demonstration (scale up of	Design phase 2021	100,000 ton_{CO2}/year	CCS	16 million EUR	Public funded (Horizon2020) with	[206]

			LEILAC 1 by 4 times)					additional industry funding	
Cemex Zement/Carbon Clean	Germany	Cemex Zement	Demonstration (scale up feasibility study commissioned)	Announced in 2021 Scale up 2026	Starting 100 ton_{CO2}/day, 300 ton_{CO2}/day by 2026 and 2,000 ton_{CO2}/day final goal	CCU	N/A	N/A	[157] [158]
Cemex USA	USA	Cemex	Demonstration	2009 - 2011	2,740 ton_{CO2}/day	CCS	1.1 million USD	Public funding (U.S. Department of Energy)	[209]
CEMEX Balcones	USA	Cemex	Design and development	Announced in 2021 Operation for 30 months	N/A	CCS	1.5 million USD	Public funding (U.S. Department of Energy)	[210]
Mitsubishi/Tokuyama Demonstration	Japan	Tokuyama	Pilot and demonstration	Start in 2022 Operation for 9 months	N/A	Capture	N/A	N/A	[211]
HyNet North West	UK	Hanson UK (Heidelberg Cement)	Commercial capture facility	Expected operation 2026	800,000 ton_{CO2}/year	CCS	N/A	Public funding (UK government)	[162] [163]
ECRA CCS Project	Italy and Austria	HeidelbergCement, LafargeHolcim	Demonstration (2 facilities)	Intended operation 2020 Status unknown	> 500 ton_{CO2}/day in Italy and 500,000 ton_{CO2}/year in Austria	CCS	80 million EUR for both plants	Seeking 50 million EUR in public funding, 30 million EUR funding from cement industry	[164] [165]

Fujiwara Pilot Capture Plant	Japan	Taiheiyo Cement	Pilot	Intended operation 2019 Status unknown	N/A	CCS	N/A	Working "in conjunction with the [Japanese] Ministry of Environment"	[216]