PLATON

Alternatives to CCS in the Norwegian cement industry

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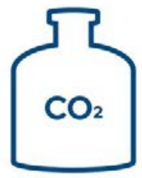

The investment decision by the Norwegian Government laid the foundation for CCS as a GHG mitigation measure in Norway. However, political and technological uncertainty may still require us to explore other GHG mitigation measures in e.g. the cement industry.

Alternatives to CCS in the Norwegian cement industry[2]

Introduction

After the end of World War II, cement production begun accelerating rapidly, increasing more than 30-times over since 1950 and almost 4-times over since 1990 (Andrew, 2019). With an increasing global population, development of new infrastructure may consume as much as 35-60% of the remaining carbon budget for limiting the global temperature increase to 2°C (Churkina et al., 2020).

Cement represents the largest share of emissions from concrete, the world's most used material (Ellis et al., 2019), and is estimated to be responsible for 4-8% of the global CO_{2e} emissions (Friedlingstein et al., 2019; Ellis et al., 2019; Summerbell Barlow and Cullen, 2016). Cement manufacturing in Norway is done in two cement plants (Norcem Brevik and Norcem Kjøpsvik), both of which are covered by the European Union Emission Trading System (EU ETS). In 2017, cement attributed CO_{2e} emissions accounted for 2% of national GHG emissions. Since 1990, the process-related emissions have increased by 20.7% due to increased production of clinker (see section 4.2.3), and between 2016 and

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2017 total emissions increased by 11.9% (Norwegian Environment Agency, 2019a; Norwegian Environment Agency, n.d.).

Norway has committed to reduce its GHG emissions by 50-55% by 2030 compared to 1990 levels in line with the Paris Agreement (Ministry of Climate and Environment, 2020) and further to be a low-emission society by 2050 (Norwegian Environment Agency, 2019). A low-emission society is defined in §4 in Norway's Climate Change Act:

> *«A low-emission society means one where greenhouse gas emissions, on the basis of the best available scientific knowledge, global emission trends and national circumstances, have been reduced in order to avert adverse impacts of global warming, as described in Article 2 1.(a) of the Paris Agreement of 12 December 2015.» (Lovdata, 2018)*

The act also stipulates that Norway shall achieve between 80-95% reduction of GHG emissions compared to the baseline of 1990, and that the effects of participating in the EU ETS shall be considered when assessing the progress (Lovdata, 2018). Reducing emissions from energy- and process-related industries, such as cement, is therefore important for Norway to become a low-emission society.

Carbon Capture and Storage (CCS) is a measure that is often mentioned in the literature (Atkins and Oslo Economics, 2016; Swedish Government, 2020) and by the industry itself (Fossil Free Sweden, 2018; Bjerge and Brevik, 2014) as an important solution to GHG mitigation in the cement sector. CCS as a technology has existed since 1996 in industrial scale. In 2016, 12 out of the 15 existing full-scale CCS systems were being used for enhanced oil recovery (EOR), and the three remaining in power generation (Atkins and Oslo Economics, 2016). It is as such a novel technology for use in land-based industrial applications and only exist in pilot plant-scale.

As the price of emitting GHG is far lower than the cost of implementing CCS, private companies have few economic incentives to invest in it at this point, leading to very few projects being planned globally (Atkins and Oslo Economics, 2016). This opens for questions on what alternatives there are to reduce GHG emissions from the cement sector aside from CCS?

Research Question

The primary research question that this study aim to answer is:

What potential is there to mitigate GHG emissions in the Norwegian cement sector and how do the different mitigation options compare to CCS in terms of marginal abatement cost?

To address the overarching research question, four secondary questions are used as facilitators:

- Do the cement sector face different challenges, either economical or technological, in implementing CCS compared to other CO_2 intensive sectors in the Norwegian context?
- Are there options to reduce the demand for cement through substitution and what are their GHG mitigation potential and associated marginal abatement costs?

- What measures can be considered to mitigate GHG emissions from cement manufacturing and what are their mitigation potential and associated marginal abatement costs?
- How do the identified measures compare to CCS in terms of marginal abatement cost and how may they be combined in order to mitigate the maximum amount of GHGs at minimised marginal abatement cost?

Scope and limitations

This study approaches GHG mitigation and the research questions holistically, by not solely focusing on the cement manufacturing industry. The stakeholders included are both conventional cement manufacturers, such as Norcem, and stakeholders further downstream in the value-chain, such as construction firms.

The identified measures within the scope of this thesis is presented in figure 1 and can be categorised either as improvement measures or substitution measures.

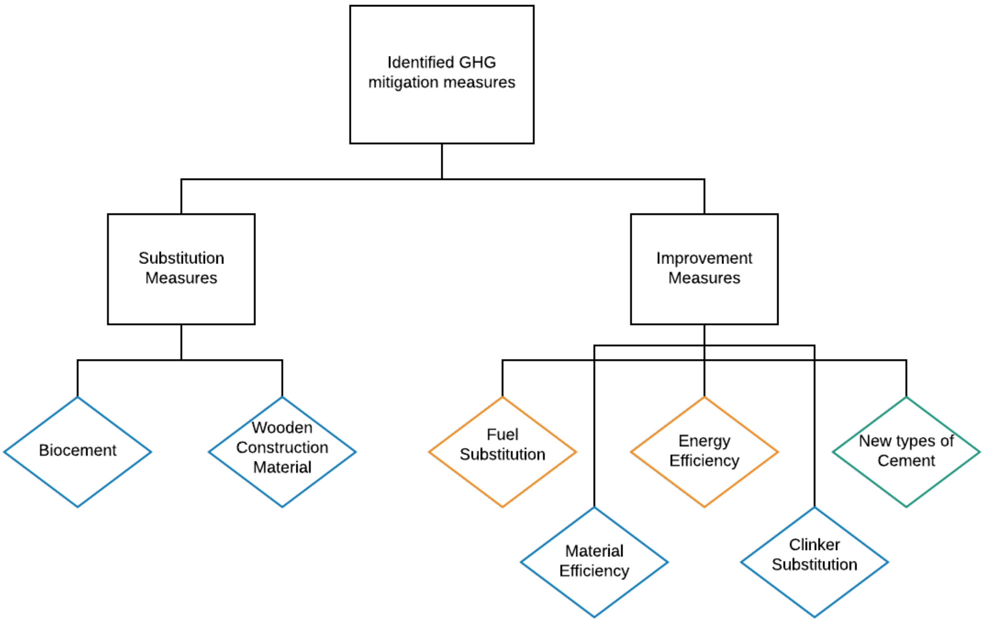

Figure 1 Identified GHG mitigation measures for the Norwegian cement industry

Improvement measures focus on developing and improving the current practice of cement as a material and does not foresee the entry of new materials in building practices. The measures include energy efficiency, fuel substitution, new types of cement, material efficiency and clinker substitution. Energy efficiency and fuel substitution only influence the energy-related emissions whilst new types of cement primarily reduce the process-related emissions. They are the measures related to the third secondary research question.

Substitution measures on the other hand relate to the second secondary research question and does not focus on improving the quality or environmental performance of cement, but instead focus on replacing it with other material that potentially could have a lower carbon footprint than cement manufacturing.

In 2016, 1.745 Mt of cement was produced at the two plants in Brevik and Kjøpsvik, most of which to be used in Norway. This accounts to a market share of 75% (Multiconsult 2019). The remainder, (0.6 Mt in 2016) of the cement was imported into Norway, primarily from Germany, Denmark, Sweden and the Netherlands (Statistics Norway, 2019).

With a very local demand for cement products, it is possible to mitigate GHG emissions from Norwegian cement production by reducing the amount of cement manufactured. Thus, it is possible to substitute it for other, less GHG intensive, materials. As cement has multiple application areas, it may not necessarily be possible to use substitution materials in every case and this will be investigated and included in the assessment.

Literature Review

To analyse the topic and answer the research questions, it is important with some context as to how the manufacturing process is designed and what the different application areas of cement are. As such, this study will present a literature review of the subject and collate some key facts and concepts before presenting the methodology.

The manufacturing process of cement

Cement is a collective term that applies to all binder materials, but the most common type is OPC. An irregular mixture of iron (Fe), aluminium (Al), silicon (Si) and calcium (Ca) is produced in the process, called clinkers. The four main compounds of OPC clinkers are:

- Alite (Ca_3SiO_5)
- Belite (Ca_2SiO_4)
- Aluminate ($Ca_3Al_2O_6$) and
- Ferrite (Ca_2AlFeO_5) (Gagg, 2014)

In Norway, the company Norcem is the sole supplier of cement, with one cement manufacturing plant in Brevik (Vestfold og Telemark county) and one in Kjøpsvik (Nordland county) (Norcem, n.d.-c). Norcem is part of the HeidelbergCement Group, with headquarters in Heidelberg, Germany (HeidelbergCement Group, n.d.-b).

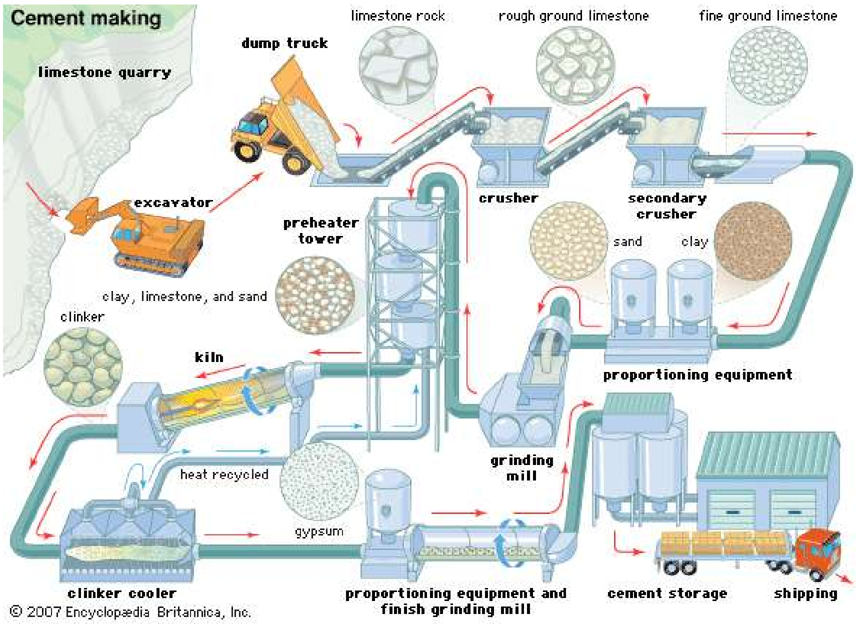

Figure 2 Manufacturing process of cement (Encyclopædia Britannica, 2019)

The manufacturing process is illustrated, by Encyclopædia Britannica (2019), in figure 2 and originates from the primary raw material limestone. Limestone can in Norway be found in the Oslo Rift and along the coast of the counties Vestland, Møre og Romsdal, Trøndelag, Nordland and Troms og Finnmark (Store Norske Leksikon, 2019). It is quarried locally in an open cast for manufacturing at Kjøpsvik and from mines locally in Brevik together with additional material from two open casts, one in Bjørntvet and one in Verdal (Norcem, n.d.-a; Norcem, n.d.-b). After the quarrying, the limestone and marlstone are crushed on-site and transported to the cement plant. The different raw materials are mixed and finely ground to particles smaller than 0.09mm, increasing the homogeneity of the raw mix and preparing it for the heating process (Cementa, n.d.).

Next, the material goes through a heat exchanger for preheating the raw meal. Hot exhaust gases from the kiln, an insulated chamber or oven used later in the process, passes the raw meal in opposite direction, transferring thermal energy to the raw meal. At the final stage of the preheater, calcium carbonate ($CaCO_3$) is separated into calcium oxide (CaO) and carbon dioxide (CO_2) in a combustion chamber (Cementa, 2018). During this chemical process (calcination), the so-called process-emissions from cement manufacturing occurs. These process emissions typically represent 60-65% of total emissions from cement manufacturing (Habert, 2014). The material enters the kiln, in which fuel is fired directly to reach temperatures at around 1450°C, which rotates and cause the material to slide through hotter zones, melting the material into clinker. The clinker is then discharged and air-cooled before entering the final step of the process, milling. Here, the clinker is ground together with gypsum, and sometimes different additives, to create the final product to be stored before shipping (Cementa, n.d.; Habert, 2014).

The majority of the process-related emissions (95%) occurs in the calcination process after the preheating process at 900°C, but due to problems with higher temperatures, 5% of the calcium carbonate remains to be processed in the kiln (Cementa, 2018).

What is cement used for?

The primarily application of cement is as a binder in concrete, which in turn is used in a wide variety of constructions such as residential buildings, roads, commercial buildings and bridges (Cembureau, 2018b).

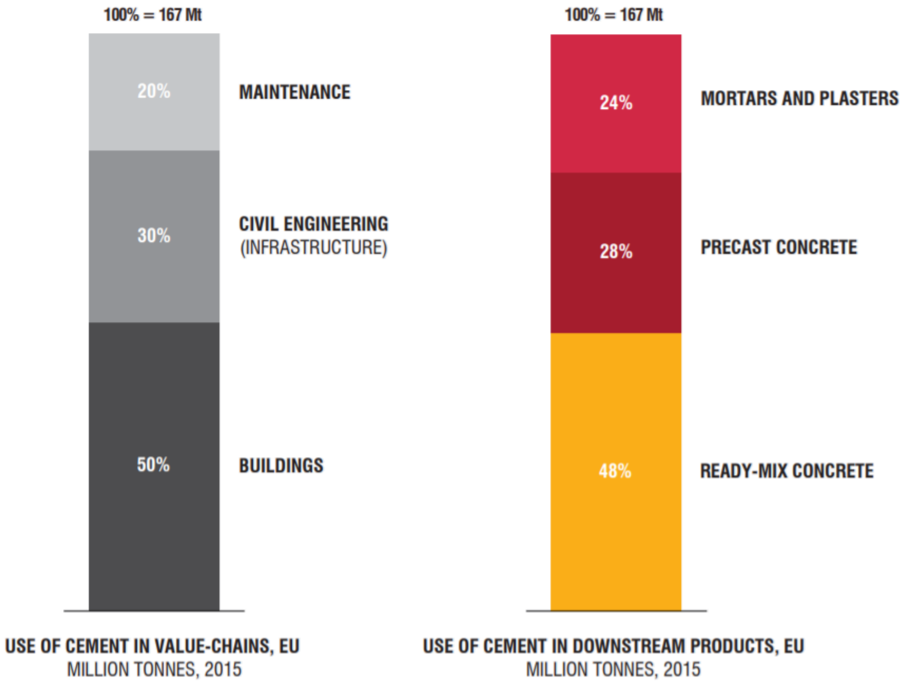

Figure 3 Cement downstream products and use in value-chains (Material Economics, 2019)

167 Mt cement was manufactured within the EU in 2015, out of which almost half (48%) was ready-mix concrete, followed by precast concrete (28%) and mortars and plasters (24%). Both the sub-products that cement is used in and the type of structures or value-chains that it consequently ends up in, is presented in figure 3 for an easy overview. The primary final product is buildings, where half of the EU-wide manufactured cement is used. Infrastructure (30%) and maintenance (20%) are the subsequent associated value-chains (Material Economics, 2019).

Carbonation

Carbonation is a chemical reaction that occurs when concrete structures react with airborne CO_2, which causes the concrete to absorb the atmospheric CO_2. In a study by Engelsen, Justnes and Rønning (2016), it was estimated that carbonation concrete structures in Norway absorbed 165,000 tonnes of CO_2 in 2011, assuming a service life of 100 years. Although the CO_2 uptake vary with carbonation depth, it was found that an average of 111 kg CO_2/t cement, whereof 94 kg CO_2 were from the service life, was absorbed. In a similar study by Xi et al. (2016), it was estimated that global carbonation of cement materials in the period from 1930 to 2013 had offset 43% of the cumulative process-related emissions[3] of CO_2 in the same period.

On the contrary, a study by Collins (2010), argue that the uptake from carbonation in concrete's primary life is less than 2% of the production emission and almost negligible. However, the study also stated that after the concrete have been crushed, significantly increasing the surface area, up to 41% of the production emission could be absorbed, depending on the application of the recycled aggregates. Souto-Martinez, Arehard and Srubar (2018) have investigated the initial CO_2 emissions from OPC versus in situ CO_2 sequestration and mention at one point that while some studies have concluded that long-term CO_2 sequestration is negligible in a Life Cycle Assessment (LCA), others do not. Their conclusion is that there is not yet any consensus of this in the cement and concrete community. Furthermore, the methods and guidelines for quantifying CO_2 emissions during the cement production process by the Intergovernmental Panel on Climate Change (IPCC) does not consider the offset CO_2 emissions by carbonation (Xi et al., 2016). Although often a local product, difficulties in allocating the emission offset arise when considering that cement is at times produced in one country and then used in another. It is also worth to note that it is desirable to minimise the carbonation rate in some concrete application areas as it limits the concrete's ability to protect embedded steel reinforcement against corrosion (Gartner and Sui, 2018). As the United Nations Framework Convention on Climate Change (UNFCCC) requires Annex I Parties to use the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (UNFCCC, 2020b), carbonation cannot at this point be included as an offset mechanism for the cement industry to reduce its reported CO_2 emissions. This might be subject to change as guidelines develop and will also be important to compare to other types of CO_2 sequestration.

Energy use and emissions from the cement industry

In a baseline scenario by Material Economics (2019), the manufacturing volume of cement in the EU is expected to increase by 10% until 2050 while emission intensity decreases from today's average 659 to 590 kg CO_2/t cement produces, resulting in no changes in the total emissions from EU-produced cement.

Table 1

Materials and emissions for Norcem Brevik and Norcem Kjøpsvik 2016 (Norcem, n.d.-b; n.d.-a)

	Norcem Brevik	Norcem Kjøpsvik	Total
Manufactured volume (clinker)	954 kt	354 kt	1,308 kt
Manufactured volume (cement)	1,284 kt	461 kt	1,745 kt
Clinker-to-cement ratio	0.74	0.76	0.75

[3] It should be noted that this is process-related emissions only, which only account for 60% of total emissions globally (Habert, 2014)

Total fuel use for process-heat	188 kt	51 kt	240 kt
Fuel use by type (%)			
- Waste	43 %	19 %	38 %
- Biofuels	25 %	12 %	22 %
- Fossil fuels	33 %	69 %	41 %
Power Consumption	182 GWh	63 GWh	245 GWh
CO_{2e} emissions	742 kt	289 kt	1,031 kt
Process / energy emission ratio	-	-	66/34
Emission intensity	578 kg CO_{2e}/ton cement	626 kg CO_{2e}/ton cement	591 kg CO_{2e}/ton cement

Table 1 presents key facts for the manufacturing of cement the two plants in Brevik and Kjøpsvik and the combined totals. The table presents an overview of the manufacturing volumes of both clinker and cement, the different types of fuel used to produce heat in the process as well as electricity consumption and associated CO_{2e} emissions.

In total between the two plants, fossil fuels is still the most used fuel for heating, although the use of waste is more common in Brevik (Norcem, n.d.-a; Norcem, n.d.-b). CO_{2e} emissions from the two cement plants were 1.03 Mt of CO_{2e} in 2016 and increased to 1.17 Mt of CO_{2e} in 2017 (Norwegian Environment Agency, n.d.). The process-related emissions are presented separately from energy-related emissions in the National Inventory Report of 2019, with 0.68 Mt and 0.77 Mt CO_{2e} in 2016 and 2017 respectively (Norwegian Environment Agency, 2019). The process-related emissions can then be subtracted from the total emissions, resulting in the energy-related emissions and the ratio between the two.

With the reported direct GHG emissions and production volume of the two plants, it is possible to establish the baseline according to the methodology in section 3 as the total emission divided by the total manufacturing volume, resulting in a baseline of 591 kg CO_{2e} emitted per ton cement produced. This is 10% lower than the baseline scenario reported by Material Economics (2019) and indicate that the Norwegian cement manufacturing process is highly developed in a European context.

The clinker-to-cement ratio describes the usage of alternative materials in relation to pure clinker. OPC can contain as much as 95% clinker and 5% gypsum, but the average in the EU is 73.7% clinker. A lower clinker-to-cement ratio (higher use of other constituents) result in lower emissions and lower energy use, but also affect other properties such as hardening time, early and late strength and resistance to salty conditions (Cembureau, 2018a). In composite cements, alternative raw materials such as fly ash, ground slag or limestone is the replacement material to the clinkers (HeidelbergCement Group, n.d.-a).

Measures to mitigate GHG emissions from cement industries

The measures considered within the scope of this study can be seen in figure 1 and include the two categories, substitution measures and improvement measures.

Wooden construction materials

Forests are natural carbon sinks that absorb CO_2 over its lifetime until it is released again when combusted or by decay (Organschi et al., 2016). Timber materials are often considered carbon neutral, although widely debated in LCA studies. If biogenic CO_2 is released before the newly planted carbon pool manage to sequester it, the atmospheric concentration of CO_2 will have increased (net positive emissions). Similarly, if additional CO_2 is sequestered from timber harvesting before the release, the atmospheric concentration will have decreased (net negative emissions) (Skullestad, Bohne and Lohne, 2016).

Churkina et al. (2020) show that global construction of timber buildings for new urban dwellers could store as much as 0.68 GtC per year (in a scenario where 90% of new constructions are built in timber) by utilising bio-based material in mid-rise (4-12 storeys) engineered timber structures. This would transfer stored carbon from forests into cities, possibly limiting the risk of natural depletion of forests by increasing temperatures and other natural disturbances.

Replacing concrete with materials made from wood may reduce the amount cement manufactured, which in turn would mitigate GHG emissions.

Biocement

Another replacement material with potential to reduce the environmental impact and the CO_2 emissions from cement production is the cementitious material called biocement. Compared to OPC, biocement has the advantages of being produced at ambient temperatures of 20-40°C, thus being far less energy-intensive. It also has much smaller particle size, allowing for biogrout to seal finer fissures in cracks than Portland cement grout (Gyu, Chu, Brown, Wang and Wen, 2017).

The biomineralization process MICP allows to produce minerals via metabolic activity in bacteria (Lee, Lee and Kim, 2018). Biocement is made from calcium salt (Ca^{2+}), urea ($CO(NH_2)_2$) and urease-producing bacteria (UPB) through the following chemical reactions:

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH^{4+} + CO_3^{2-}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

where urea is decomposed with UPB as a catalyst, forming carbonate (CO_3^{2-}). The carbonate then reacts with calcium ions to form calcium carbonate (Gyu et al., 2017).

The conventional source of calcium in MICP is from calcium chloride ($CaCl_2$), which is both expensive and environmentally harmful. The feasibility of alternative approaches such as enzymatically induced precipitation (EICP) is investigated as a way of producing biocement with cheap and globally abundant calcium carbonate, the same material that is decomposed at high temperatures in conventional cement production (Phua and Røyne, 2018).

Energy efficiency

One of the often perceived easiest GHG mitigation measures is to reduce the energy-related emissions through energy efficiency. A more energy efficient process will require fewer heating fuels and electrical power, consequently reducing the GHG emissions from combustion. Domestic electrical power is however to 97.4% generated from hydro- and wind power (Norwegian Water Resources and Energy Directorate, 2020) and although the Norwegian electricity system is interconnected with its neighbouring countries, it will be assumed that no emissions arise from electrical consumption. It will be presented for its illustrative purpose, nonetheless.

When assessing the energy efficiency, the two cement plants will not be considered separately despite that technological practices and advancements might differ, due to the lack of data. Energy will be divided into electrical power and heating fuels. Applying the power consumption and fuel consumed per tonnes of produced cement will result in an indicator for the energy efficiency in the two plants.

Table 2

Energy efficiency data Norcem 2016

	Norcem Brevik	Norcem Kjøpsvik
Cement produced	1,284 kt	461 kt
Power consumption	182 GWh	63 GWh
Fuel consumption	188 kt	51 kt
Electrical efficiency	141.7 kWh/ton cement	136 kWh/ton cement
Fuel efficiency	146 kg fuel/ton cement	111 kg fuel/ton cement

Alternative fuels

Typical fuels used for heating in the cement manufacturing process are fossil fuels such as coal, coke and natural gas, but due to increasing fossil fuel prices and environmental concern, the use of alternative fuels have increased (Rahman et al., 2013). The most common alternative fuel in the EU-28 was plastic (37.1%) followed by mixed industrial waste (17.7%) and tyres (14.9%), according to IFC (2017). The number vary between different large cement groups and for HeidelbergCement, the three most used alternative fuels were plastic (26.4%), wood chip and other biomass (24.5%) and other alternative fuel (14.6%). Comparing these numbers with table 1 shows that Norcem is above average with 22% of the total fuels being biomass (36.6% of alternative fuels). HeidelbergCement have reported in their 2030 sustainability commitments, that by 2030, they will increase the amount of alternative fuels to 30% (HeidelbergCement n.d.-b) up from 21.7% in 2018 (HeidelbergCement Group, 2019).

Clinker substitution

The GHG emissions in cement production stems, as described in the manufacturing process, from the clinker production and reducing the share of clinker to other material in cement can thus be an effective measure. The replacement material is often referred to as Supplementary Cementite Materials (SCMs), which often require no heating or processing beside grinding (Material Economics, 2019). Substituting clinker for SCMs is an established practice and the clinker share in Norway is 75%, as listed in table 1. Most common is inert limestone filler, but other SCMs such as Granulated Blast Furnace Slag (GBFS), fly ash, natural pozzolans, burnt shale and calcined clays can also be identified in the literature (Scrivener, John and Gartner, 2018; Favier, Wolf, Scrivener and Guillaume, 2018).

In its sustainability report of 2018, the most common cement type of HeidelbergCement Group is OPC (39%) followed by multi-component cement (18.5%), limestone cement (18%), slag cement (12.1%) and Pozzolana/fly ash cement (9.2%) (HeidelbergCement Group, 2019).

Material efficiency

Concrete typically constitutes of 7-20% cement by mass, resulting in a density of approximately 300 kg/m^3 for compressive strengths of 30-40 MegaPascal (MPa). This has been the practice to ensure e.g. concrete strength and corrosion resistance. The global average binder intensity is an indicator of how much cement is needed per unit of concrete to achieve a certain compressive strength, (kg cement/ m^3 of concrete and MPa compressive strength). The global average practice is 12 kg/m^3 MPa and the minimum practice is 8. As cement is the source of 95% of total CO_2 emissions in concrete, reducing the amount of cement in concrete can significantly reduce the CO_2 emissions of concrete (Material Economics, 2019).

Utilising limestone for partial replacement of clinker or other reactive have been practised since the 1980s and the CO_2 emission reduction is almost proportional to the replacement rate (John, Damineli, Quattrone and Pileggi, 2018).

Fillers come in many variations and are available everywhere in more or less unlimited quantities. They may be defined according to John et al. (2018), as:

> *«Fine particulate materials that are inert or almost chemically inert when mixed with cement, produced by grinding with or without surface treatment. »*

Mixing fillers in cement, simply put, reduce the concentration of reactive material in cement. Although this increases the porosity of the system (decreasing its strength), it can be compensated for by grinding the filler finer or a lower water/cement ratio (John et al., 2018).

Alternative types of cement

There exist a large number of different production technologies for cement, at different levels of maturity. Some technologies have been around for as long as OPC, whilst others are in not yet past research-stage and not commercialised. This section will explore a few of those alternatives which have been found to have potential to reduce GHG emissions without changing the application area.

Reactive Belite-rich Portland Cement (RBPC) clinkers

RPBC is similar to OPC in terms of mineralogy and are also known as high belite cements (HBC). The difference lies in the ratio of belite to alite in the clinker composition. In RBPC, belite is the most abundant phase (>40%) as opposed to OPC where alite is most abundant. RBPC has successfully been used in the third phase of the Three Gorges Hydropower project in China and meets the Chinese standards for Portland Cements. It is in many aspects considered to be more durable than OPC and can be produced in conventional OPC manufacturing plants without major changes to the operation (Gartner and Sui, 2018).

Belity-Ye'elimite-Ferrite (BYF) clinkers

BYF clinkers primarily differs from OPC in the proportions of raw materials that is fed into the kiln. BYF requires 20-30% less limestone than OPC, consequently reducing the calcination that creates the process-related emissions. The production also requires less energy due to lower operating temperatures (1250-1350°C) and smaller volumes of limestone to calcinate, but otherwise follows the same process as for OPC.

Carbonatable Calcium Silicate Clinkers (CCSC)

As opposed to conventional concrete, where so called hydraulic binders (e.g. OPC, RBPC and BYF) harden due to the reaction between the clinker and water, CCSC instead utilise the fact that calcium silicates can harden by carbonation. Understanding how to accelerate the hardening process in an industrial context while also keeping a low energy consumption will be central to this technology. A problem with carbonation hardening is that it occurs from the outside by diffusion and reaction, leading to an inhomogeneous hardening profile, making it disadvantageous for concrete with large cross sections. Such concrete also do not protect mild steel against corrosion in the presence of high humidity and low quantities of chloride or sulfate (Gartner and Sui, 2018).

Manufacturing of CCSC has been demonstrated in conventional OPC plants, with similar raw materials required. The manufacturing process of CCSC concrete is on the other hand vastly different to that of OPC, RBPC and BYF as it must be cured in a CO_2 rich atmosphere as well as good control of the gas composition, gas circulation, temperature and relative humidity. Specially adapted concrete curing chambers are therefore needed, posing additional capital costs for concrete manufacturers. This will likely limit the application area to factory-made concrete articles. From similar thermodynamic calculations as for RBPC and BYF and the fact that all the process-related emissions could be reabsorbed during the carbonation-hardening, the critical factor is the kiln energy consumption. This is possibly less than half of typical OPC clinkers and an easier technological challenge to solve as opposed to process-related emissions (Gartner and Sui, 2018).

Magnesium Oxides derived from Magnesium Silicates (MOMS)

Magnesium oxide (MgO) can be formed by calcining natural magnesite rock and then mixed with magnesium salts to form cement with good binding properties. Calcining magnesite rock releases large amounts of process-related emissions, similar to limestone calcination. However, similar to CCSC, magnesium oxide can be hardened by direct carbonation, i.e. by absorbing CO_2. In theory, a MOMS approach with energy-efficient production could result in cement with negative net-zero CO_2 emissions (Gartner and Sui, 2018).

Carbon Capture and Storage (CCS)

As mentioned in the introduction, CCS is one of the primary measures to combat the emissions of cement manufacturing, being strongly favored by the industry itself (Bjerge and Brevik, 2014). A full-scale CCS project at Norcem Brevik may be the first project in the cement sector on a global basis (Gassnova, 2020a) with a technical capacity of capturing 400,000 tonnes of CO_2 per year, which corresponds to about 50% of the emissions at Norcem Brevik (Gassnova, 2020b). The CCS project at Norcem Brevik have been designed for cost-benefit optimality, and as a result no additional heat or fuel is required to operate the CCS process. The plant utilises waste heat recovery for thermal energy production (Norcem, 2019). With external thermal energy sources, the potential CO_2 capture (mitigation) for could approach the technical capture efficiency at 90% (Gardarsdòttir, Normann, Skagestad and Johnsson, 2018).

There exist multiple types of CCS technologies that could be integrated in the cement production process. The literature is weighted towards retrofitting amine-based CO_2 capture processes, but studies have looked at other technologies such as calcium-based looping systems (CaL), oxyfuel combustion technologies, chilled ammonia processes (CAP) and membrane-assisted CO_2 liquefaction (MAL) (Gardarsdòttir et al., 2019).

Post-combustion capture

The most realistic post-combustion capture category is chemical absorption, with Mono-ethanol amine (MEA)-based absorption being the most common (IEAGHG, 2018). The flue gas from the production process is cooled in a direct contact cooler where water and SO_x is removed by scrubbing. CO_2 is then absorbed from the flue gas by contact with the MEA solvent. Additional heat is required to regenerate the solvent and power is required to operate the fans and pumps in the absorption and compression process (Voldsund et al., 2019).

Another post-combustion process is the chilled ammonia process with similar structure as MEA-based absorption, but with chilled ammonia as the solvent instead of MEA. The ammonia needs to be cooled in the process, requiring additional power (Voldsund et al., 2019).

Membrane-assisted CO_2 liquefaction is a third post-combustion process, that only requires electric power as additional input to the process. For the MAL technology, the flue gas is cooled and removed of water in a direct contact cooler before CO_2 is separated through a polymeric membrane. After the initial separation in the membrane, CO_2 is liquified to form high purity CO_2 (Voldsund et al., 2019).

Oxyfuel process

The oxyfuel process requires modification of the cement kiln as the gas atmosphere need to be different. Combustion occurs in an oxidizer to produce a CO_2 dense flue gas, allowing for easier purification in the CO_2 purification unit. Similar to MEA-based absorption, additional power is required to operate an air separation unit (Voldsund et al., 2019).

Calcium Looping

Calcium looping is based on the reversible carbonation process that is central to cement manufacturing and can be applied either in a tail-end or integrated configuration. In the tail-end configuration, flue gas is sent to a carbonator that utilise the carbonation process to remove CO_2 by reaction with CaO. Coal is burnt under oxyfuel conditions in a separate calciner, which is the sent to the cement kiln as a constituent of the raw meal. In the integrated configuration on the other hand, the same calciner is used in the capture process as during cement production. Both processes require additional fuel and power for an air separator unit, a CO_2 purification unit and fans (Voldsund et al., 2019).

Table 3

Summary of total plant costs and economic KPIs for the reference cement plant and the CO2 capture technologies (Adopted from Gardarsdòttir et al. (2019))

	Ref cement plant	MEA	Oxyfuel	CAP	MAL	CaL-Tail-End	CaL-Integrated
TPC, cement plant + CO_2 capture plant (MNOK)	2,069	2,839	3,367	3,580	4,563	4,117	4,300
TPC, CO_2 capture plant (MNOK)	-	771	1,298	1,511	2,505	2,048	2,231
Annual OPEX (MNOK	416	770	588	669	720	598	619
Cost of clinker (NOK/t)	635	1,089	943	1,064	1,217	1,073	1,119
Cost of CO_2 avoided (NOK/tCO_2)	-	813	430	671	847	531	594

The cost of different CCS technologies are analysed by Gardarsdòttir et al. (2019) in comparison with a best available technologies cement plant with 1 Mt annual clinker production, similarly to that of Norcem Brevik, with results presented in table 3. The cost of CO_2 avoidance is found to be lowest for the oxyfuel technology at 430 NOK/tCO_2 (42.4 €[4]/tCO_2) followed by tail-end CaL at 531 NOK/tCO_2 (52.4 €/tCO_2). As several studies, with various assumptions and methodologies, have reported costs for MEA-based CO_2 capture, a large cost range, 761-1,724 NOK/tCO_2 (75-170 €/tCO_2) can be found in the literature (Gardarsdòttir et al., 2019).

Due to high concentrations of CO_2 in the flue gas (15-22 vol%), post-combustion is favourable for the cement industry, but it comes with the drawback of requiring additional energy. As there is usually no power plant at a cement production site, this might pose a significant challenge. However, clinker substitution for fly ashes can enable the extraction of excess energy from the process to cover part of the energy demand for CO_2 capture technologies (Onarheim, Mathisen and Arasto, 2015).

In addition to the CCS technologies covered by Gardarsdòttir et al. (2019), some more novel CCS technologies exist as innovation projects.

Direct Separation

The Low Emission Intensity Lime and Cement (LEILAC) project is a novel carbon and capture technology designed specifically to capture process emissions from limestone calcination, developed by a consortium in a five-year Horizon 2020 project with a pilot plant being built in Lixhe, Belgium by HeidelbergCement. The technology allows for capture of CO_2 without it being in contact with air or combustion gases, preventing the

[4] Currency conversion is based on XE (2020) from 6 February 2020, where 1 EUR = 10.141 NOK, 1 SEK = 0.959 NOK and 1 USD = 9.238 NOK.

need for separation and imposing no additional energy or capital costs. For the direct separation concept, a Direct Separation Reactor (DSR) replaces the calciner in a conventional cement plant, within which the raw meal is being heated by both conductive and radiative heat transfer from the reactor wall. At the end of the calciner, the solid clinkers and the CO_2 gases are separated. As the separated CO_2 has not been in contact with air, no additional step of separating the CO_2 from the air before transport and storage is necessary (Hills, Sceats, Rennie and Fennell, 2017).

The technology itself only relates to the process-related emissions and hence has a maximum potential mitigating two thirds of the total emissions. However, it is claimed to be compatible with capture technologies for energy-related emissions, increasing the maximum potential to 85% (Hills et al., 2017). Most of the costs for the technology in addition to an unabated cement plant, is expected from the CO_2 compressing unit. LEILAC is therefore expected to be significantly cheaper than other CCS technologies (Hills et al., 2017), but cost estimates are still considered unknown (Hills, Lesson, Florin and Fennell, 2016), making it difficult to compare the technology to other GHG mitigation measures.

CemZero

In a joint project, Norcem's sister company in Sweden, Cementa, and Swedish state owned power company Vattenfall, conducted a feasibility study (Cementa and Vattenfall, 2018) on the possibility of reducing GHG emissions by supplying the heat needed in the kiln from electricity as opposed to the conventional use of burning fuels. The project, CemZero, within which the feasibility study was part, mapped different heat transferring technologies and associated process layouts. The conclusion of the study was that the concept of plasma generators in a preheater and precalciner kiln system was the, at the time, most relevant technology path.

From the economic analysis of the study, it was shown that the production cost of such a system including CCS was about twice the production cost of a reference plant without CCS. The study also included a comparative scenario with post-combustion amine-based carbon capture, the most mature carbon capture technology and utilised in the Norcem Brevik pilot plant. The results showed that electrification of the cement manufacturing came at a lower cost and with a lower energy demand compared to post-combustion amine-based carbon capture, indicating that the conceptual design could be competitive with other CCS technologies. CO_2 avoidance cost were 890 NOK/tCO_2 for amine-based capture (towards the lower end of the cost range by Gardarsdòttir et al. (2019)) and 777 NOK/tCO_2 for the CemZero concept. It should be noted however, that many assumptions led up to the calculations, which is subject to uncertainties and can be viewed in the original study.

Methodology

The intent of the study is to collate and summarise multiple data sources on the different measures that could mitigate greenhouse gases and their marginal abatement cost. The results are applied in a Norwegian context and provides answer to the primary research question. Answering this research question provides an accessible overview for further studies conducted within the PLATON project. Sought data points are the maximum potential of emissions that each measure can accomplish if implemented to its maximum limit and the measures' associated costs. This includes not only improvements to the manufacturing process and cement plant upgrades, but also downstream improvements in different value-chains. This provides a basis for comparison with the performance of CCS.

Literature Review

The three first secondary research questions will primarily be answered through a literature review, where the first part has been presented in the literature review, identifying the measures that will be considered in this study. The literature review is narrative in its nature in the sense that it provides a comprehensive overview of a subject or topic of research and has less stringent criteria for literature selection compared to a systematic literature review (Griffith University, 2020). The studied literature is primarily accessed through the databases included in KTH Primo[5] for academic articles and books. In addition, several websites were used to fill in specific details, such as that of companies within HeidelbergCement Group for specific country and group-level information.

From the literature review, the maximum potential mitigation for each measure is identified as well as its marginal abatement cost in comparison to conventional cement manufacturing practices. The potential mitigation is evaluated against an emission intensity baseline, presented below, in order to illustrate the results as percentual GHG mitigation.

This study will be limited to only assess GHG emissions from cement manufacturing that contributes to global warming. It will not consider any type of local emissions such as particulate matter (PM). Global Warming Potential (GWP) is a term used to compare different greenhouse gases' warming potential in a harmonised way. 1 GWP correspond to the warming potential of 1 unit of CO_2 over 20, 50 or 100 years (UNFCCC, 2020a). This study will base the assessment on a 100-year period, with the commonly used term of CO_2-equivalents.

Emission intensity baseline

The emission intensity baseline of the cement manufacturing process is developed from the emission intensity presented in table 1. Although emission levels for both cement plants are available up until 2018, data of manufacturing volumes of cement and clinkers are not complete after 2016. As such, the year for baseline comparison will be 2016. Without specific information beyond what is presented in table 1, it is difficult to assess the two plants individually. Therefore, the resulting baseline of emission is the average 591 kg CO_{2e}/t cement of the two plants.

As cement is not the final product used in buildings, but rather act as a binder in concrete, it is not possible to straight up compare the GHG emissions from cement with wooden construction materials. LCAs may be performed at the product- or building level, as set out in the standards EN15804 and EN15978 (Gervasio and Dimova, 2018). The manufacturing level measures are included in the product stage (A1-A3). In addition, there may be environmental impact during the transportation of material to the construction area (A4) as well as during the construction process (A5). The second module includes environmental impact during the use stage (B1-B7), where the choice of building material may for example influence the building envelope and resulting operational energy use for heating. In addition, the deconstruction, demolition, and

[5] The database of KTH Royal Institute of Technology in Stockholm, Sweden.

transportation of material at the end-of-life stage of a building is included in modules C1-C4.

This study did not intend to conduct an LCA of its own, but instead rely on the results of previous studies. LCAs may be strongly influenced by the studied system and building can be designed in a great range leading to different results (Rønning, Prestrud, Saxegård, Haave and Lysberg, 2019). The study therefore identified four different studies from the Nordic region with the intent to apply the average result for the analysis. However, as is mentioned in the section for wooden construction materials, two of the identified LCA studies did not recommend generalising results, and as such there are no results for wooden construction materials. This will be further analysed in the discussion.

The measures presented in the literature review have been identified through an iterative process of database searches and subsequent review of the sources of those articles. An important piece of literature has been the special issue of Cement and Concrete Research (volume 114) which includes a series of white papers and review of low-CO_2 eco-efficient cement based materials by a working group of the United Nations Environment Program Sustainable Building and Climate Inititative (UNEP-SBCI).

Evaluating marginal abatement cost

Answering the fourth secondary research question is done based on the data derived from the literature review on GHG mitigation measures and comparing it with the marginal abatement cost of CCS. However, since it is possible to combine several of the GHG mitigation measures identified in the literature review, three different combination or scenarios of combinations will be used to analyse the effectiveness of the measures compared to CCS.

To assess the cost of the measures, this study will utilise the concept of marginal abatement cost. Abatement cost is the cost associated with mitigating pollution (in this study, CO_{2e}) (Investopedia, 2020). Marginal abatement cost is then the cost of mitigating one additional unit of pollution over a set baseline (Oxford Reference, 2020). The marginal abatement cost is identified in existing literature and converted to Norwegian currency (NOK/t CO_{2e}). As this study is heavily reliant on secondary data from previous studies, there is therefore a risk that the methodology of the different studies assessed is not consistent. This is a weakness of the study which will be further addressed in the further work section

The price of EU ETS allowances for CO_2-emissions or other carbon taxation is not considered in the cost assessment, but will be included as a reference in the combinations

From the literature review, different CCS technologies were presented. The lowest cost of CO_2 avoidance was reported for the oxyfuel technology at 430 NOK/tCO_2. However, as integrating oxyfuel into the manufacturing process requires modification of the cement kiln, it is not a relevant design for retrofit in existing cement plants in Norway. As MEA-based absorption is the technology that is being pursued for the full-scale project at Norcem Brevik (Gassnova, 2020b), it makes sense to use that as a basis for comparison in a Norwegian context. The CO_2 avoidance cost (890NOK/tCO_{2e}) for MEA-based capture reported by Cementa and Vattenfall (2018) will be used as the reference value as it is a study by Norcem's sister company in Sweden.

Marginal Abatement Cost Curves (MACC)

The MACC allows for analysis and visual representation of the last abated unit of CO_{2e}. It is produced against a baseline scenario without CO_{2e} constraints against which the marginal abatement cost is evaluated. MAC curves are used to easily see the marginal abatement cost related to a certain measure responsible for the reduction of CO_2 emissions. MAC curves are typically either expert-based (histogram) or model-derived (Kesicki and Ekins, 2012).

This study will use expert-based MAC curves to illustrate different pathways towards mitigated GHG emissions from the Norwegian cement industry. When assessing the different combinations of measures to mitigate GHG emissions, it is important to acknowledge that some measures reduce the effectiveness of other measures and the values in the graphs over different combinations will not necessarily correspond to those presented in table 10 and 11. To understand the alterations and synergies between the different measures, the following subsection will present the assessed combinations and which measures are included. The CO_{2e}-intensities presented in the tables are cumulative and not only based on that measure.

Description of assessed combinations

Combination 1 - The industry's pathway to fossil-free competitiveness

The first illustrated combination of measures is based on the measures identified by the Norwegian cement industry itself (Norcem, n.d.-d) and includes energy efficiency, fossil fuel substitution, new types of cement and CCS. However, energy efficiency and fuel substitution can only replace the energy-related emissions, totalling 33%, as have been identified in table 1. Switching to BYF clinkers can then reduce the process-related emissions by an additional 16 percentage points, with the last emissions for fossil-free cement to be reduced through CCS. However, since the efficiency of replacing OPC with BYF clinkers is reduced when it only improves the process-related emissions, the marginal abatement cost needs to be adjusted. With 44% of the mitigated emissions from BYF clinkers being energy-related, the marginal abatement cost is increased by a factor 1.8 and results in 53 NOK/tCO_{2e}.

Table 4

Evaluation of measures for combination 1

	Reduced CO_2-intensity	New CO_2-intensity	Mitigation vs baseline	Cumulative abatement
Baseline		591 kg CO_{2e}		
Energy efficiency	18 kg CO2e	573 kg CO_{2e}	3%	3%
BYF clinkers	94 kg CO2e	479 kg CO_{2e}	16%	19%
Fuel substitution	177 kg CO2e	302 kg CO_{2e}	30%	49%

Combination 2 - Reduced clinker volumes

The second combination assessed included energy efficiency, fossil-fuel substitution for biofuels, material efficiency, clinkers substitution and CCS.

Combining demand reducing measures with improvement to the manufacturing process largely affect the effectiveness of the measures. Material efficiency and clinker substitution can bring down the clinker manufacturing by 66% without affecting the CO_{2e}-intensity of the manufacturing process. Energy efficiency and fuel substitution can then reduce the CO_{2e} intensity by 3 respectively 30%, but only results in a total reduction of 1 and 10% respectively compared to the baseline as it is only applied to one third of the manufactured volume. These four very cost-effective measures can thus mitigate as much as 77% of the GHG emissions.

Table 5

Evaluation of measures for combination 2

	Reduced CO_2-intensity	New CO_2-intensity	Cumulative clinker manufacturing	Mitigation vs baseline	Cumulative abatement
Baseline		591 kg CO_{2e}	100%		
Material efficiency		591 kg CO_{2e}	50%	50%	50%
Clinker substitution		591 kg CO_{2e}	33%	33%	66%
Energy efficiency	18 kg CO_{2e}	573 kg CO_{2e}	33%	1%	67%
Fuel substitution	177 kg CO_{2e}	396 kg CO_{2e}	33%	10%	77%

Combination 3 – BYF Clinkers and Material Efficiency

Combination 3 includes the same measures as combination 2, except that clinker substitution is swapped for the change from OPC to BYF clinker. With fossil-fuel substitution and energy efficiency, BYF clinkers will only reduce the process-related emissions (56% of the emission-reduction as was mentioned in the literature review).This results in 16% emissions reduction by BYF-clinkers, which is then halved by the reduced clinker manufacturing. The marginal abatement cost for BYF clinker is the same as for combination 1. Even though the total mitigation potential is reduced by the inclusion of material efficiency, it does not increase the cost per manufactured ton clinker.

Table 6

Evaluation of measures for combination 3

	Reduced CO_2-intensity	New CO_2-intensity	Cumulative clinker manufacturing	Mitigation vs baseline	Cumulative abatement
Baseline		591 kg CO_{2e}	100%		
Material efficiency		591 kg CO_{2e}	50%	50%	50%

Energy efficiency	18 kg CO_{2e}	573 kg CO_{2e}	50%	1.5%	51.5%
BYF clinkers	93 kg CO_{2e}	480 kg CO_{2e}	50%	8%	59.5%
Fuel substitution	177 kg CO_{2e}	303 kg CO_{2e}	50%	15%	74.5%

GHG mitigation potential and marginal abatement cost

In this section, the identified GHG mitigation potential and marginal abatement cost of the different measures are presented. The findings are based on the literature review.

Substitution measures

Wooden Construction Materials

Saade, Guest and Amor (2020) have through a systematic literature review investigated whether the literature supports that the environmental performance of wood framed buildings is superior to that of steel and concrete framed buildings, on the basis of LCAs.

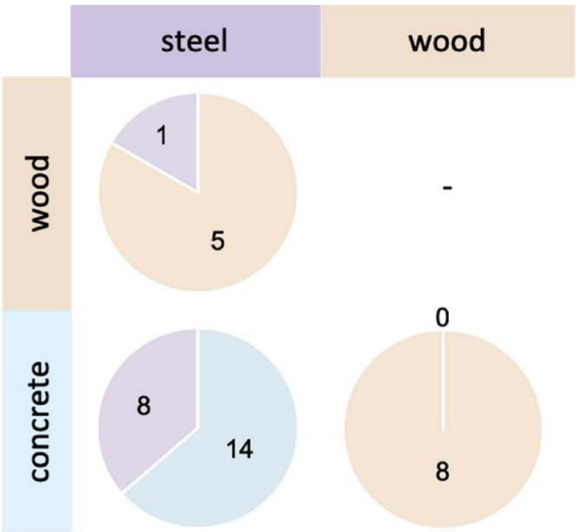

Figure 4 Outline of case studies comparing wood, concrete and steel frames in terms of their GWP throughout the building's life cycle (Saade, Guest and Amor 2020).

The results, seen in figure 4, showed that wood framed buildings performed better than concrete buildings in terms of global warming potential (GWP) in all comparisons reviewed. In one of the comparisons, a steel framed building outperformed the wood framed building. The results for primary energy demand were much more spread out and did not indicate that any building material is superior to another.

As building conditions (heat load, availability of materials, building practice et. cetera) vary largely by location, focus is moved from a global perspective to a Norwegian or Nordic context where the results are a little bit more representative.

Table 6

Four identified LCAs with geographical relevance

	Peñaloza, Norén and Eriksson (2013)	Kurkinen et al. (2015)	Skullestad, Bohne and Lohne (2016) [6]	Strekerud (2017)
LCA system boundary	A1-A5, B1, B2, B6, C1-C4, D	A1-A5, B2, B4, B6, C1-C4	A1-A3, D	A1-A5, B1-B7, C1-C3
Studied country	Sweden	Sweden	United States and Norway	Norway
Carbon Storage	Carbonation	None	Carbonation and wood	Wood, in one of the scenarios
Result wood	657 kg CO_2/m^2	280-340 kg CO_2/m^2	-235 - 140 kg CO_2/m^2	43-230 kg CO_2/m^2
Result concrete	833 kg CO_2/m^2	320-325 kg CO_2/m^2	386 - 399 kg CO_2/m^2	702.6 kg CO_2/m^2
Comment		Range of two scenarios for both wood and concrete	Only approach 3 is considered in this study	

As outlined in the methodology, four different Norwegian or Swedish studies have been selected to conclude on the potential GHG mitigation from wooden construction materials. The results of the studies identified in table 6 show very different values for both wood and concrete, but seem to indicate that wood in general perform better than concrete. The average emission reduction between the four studies is 334 kg CO_2 for wooden construction materials.

The variation between the different studies is likely partly due to the different modules of the LCA that have been included, as outlined in the first row. It was not possible to identify four studies with identical LCA system boundary within a Scandinavian context. Secondly, the studies assess buildings of different size, location and climatic conditions which will affect the results.

However, Rønning and Tellnes (2018) advocates against drawing general conclusion in the discussion on wooden construction materials versus concrete as it is heavily context dependent. Skullestad, Bohne and Lohne (2016) comment on their own results in a similar fashion by saying that the results of an LCA is not representative in all situations (see the discussion for elaboration).

[6] The negative value is a result of the study using a negative GWP factor for the storage of carbon in wood have been included.

Although there are many LCAs comparing concrete/cement and wooden construction materials, there appears to be a gap in cost comparisons between the options. Zacharias and Fougberg (2018) present a cost comparison between utilising concrete and cross-laminated timber (CLT) for the frame of 4-8 story residential buildings, based on interviews with 5 Swedish experts. The results indicate an increase by 5-15% (on top of 4,780 NOK/m^2 gross floor area) for CLT but that it can vary between projects. Although a bachelor thesis relying on a small number of interviews, the study gives an initial approximation of the difference in costs between the materials.

Combining a price increase of 10% for wooden construction materials with the average CO_2 reduction from table 6 would result in a marginal abatement cost of 1,435 NOK/tCO_2.

In this part, substituting cement for wooden construction materials has only been applied to buildings and not infrastructure such as bridges. Only half of all cement produced is used in buildings (see figure 3), and the substitution potential is therefore only 50% of the total Norwegian cement emissions. Furthermore, it is neither technically nor economically viable to utilise 100% wooden construction materials and the substitution factor is more likely to be around 50% for apartment buildings and 35% for commercial buildings (Brege, Nord and Stehn, 2017)

As indicated by the literature, there appears to be GHG reduction possibilities by substituting cement and concrete for wooden construction materials, but also uncertainties as to how forest management practices play into the results of the substitution. With varying practices between countries, it is important with make well-grounded assumptions and create a regional model. Cost projections of substituting cement for wooden construction materials are rare and the ones that exist are themselves rough estimations and only indicative.

Biocement

Within the Norwegian research project BioZement 2.0, the GWP of MICP biocement is found to be 70-83% lower than conventional concrete (Myhr et al., 2019), results similar to Iezzi, Brady, Sardag, Eu and Skerlos (2019), whose findings showed that biological concrete masonry units (bioCMU) had 66% less GWP than that of conventional CMU. The main source of GWP in biocement production were ammonia (NH^{4+}) emissions, stemming from the hydrolysis of urea.

Gyu et al. (2017) states that the number of applications for biocement is limited to increase the shear strength of soil and also to repair cracks in concrete, but that it is not viable as an complete substitution material as a hydraulic binder. With a low pH of around 8.6, biocement also make a poor material for reinforced concrete as it causes the steel to corrode (Phua and Røyne, 2018). Lee et al. (2018) increased the applications for biocement to also include acting as a building skin that increase the habitat of wild bees in urban environments but does not consider it as a full substitution to conventional cement. Jian et al. (2011) mention that the scale of annual production and consumption could be several million tons for e.g. formation of grout curtains, fixation of leakages but even if the production globally would reach hundred million tons, it would still be less than 1% of the 30 billion tons annually conventionally produced cement (Fossil Free Sweden, 2018).

Myhr et al. (2019) state that the price of material is about 10% higher for biocement compared to conventional OPC-based concrete. Translating (precise details can be found in appendix B) this to marginal abatement cost result in 679 NOK/tCO_{2e}.

Based on the limited application areas and challenges with biocement production mentioned, it is unlikely that biocement will be able to compete as a full substitution material to cement in the short future, but could potentially decrease the demand for OPC. The large cost increase of the input material result in a significant cost of abatement at 679 NOK/tCO_{2e} and although prices might decrease with economies of scale, a significant price drop would be necessary.

Cement improving measures

Energy Efficiency

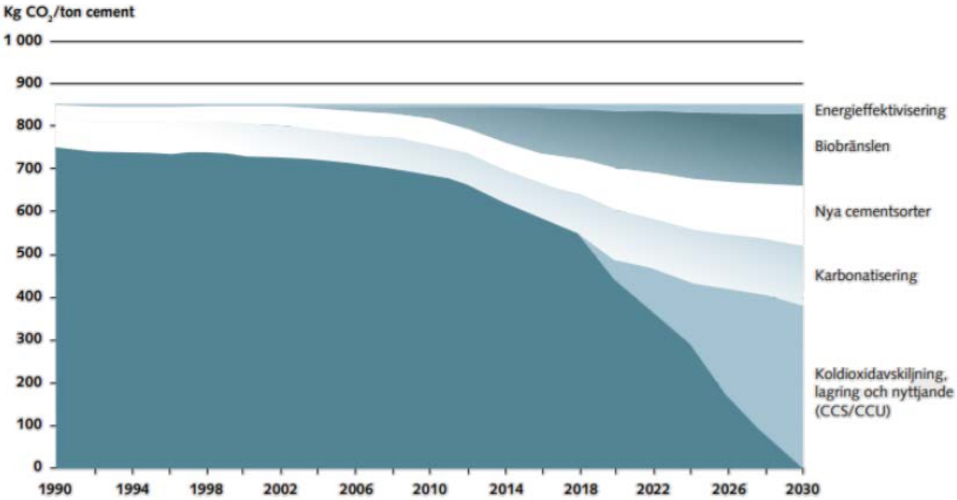

Figure 5 Vision zero of Cementa and Norcem for CO_2 emissions (Fossil Free Sweden, 2018; Norcem, n.d.-c)[7]

With limited data available on the how close to state-of-the-art the industrial process is, it is difficult to accurately assess the energy efficiency potential. Representatives of Norcem stated in 2014 that most modern plants are close to the theoretical limits of efficiency (Bjerge and Brevik, 2014) and Scrivener et al. (2018) state that state-of-the-art dry kilns are unlikely to become much more energy efficient. As indicated in figure 5, in their shared vision zero both Norcem and sister company Cementa is suggesting that energy efficiency will play a minor role (approximately by 25 kg CO_2/t cement) in their transition to emission free cement production by 2030 (Fossil Free Sweden, 2018; Norcem, n.d.-d). It is likely that energy efficiency only will improve when it is economically viable and the payback period is short enough (Scrivener et al. (2018). In this study, based on the information from Bjerge and Brevik (2014), Scrivener et al. (2018) and Norcem, (n.d.-d), the potential for mitigation is evaluated to be 25 kg CO_{2e}/ton cement (3%) at no marginal cost compared to the baseline scenario.

Alternative Fuels

There are reports of 100% substitution rates of alternative fuels, but more often there are limitations due to environmental, social and product quality issues. Alternative fuels may come with different characteristics compared to fossil fuels, heat distribution might be poorer, emissions of SO_2, NO_x and CO_2 might be higher and the final clinker composition

[7] Translation of the Swedish words in figure 5:
Energieffektivisering = Energy efficiency, Biobränslen = Biofuels, Nya cementsorter = New cement types, Karbonatisering = Carbonation, Koldioxidavskiljning, lagring och nyttjande = Carbon capture, storage and use

may be affected by the incorporation of combustion by-products (Rahman et al., 2013). Switching from fossil-based heating fuels could theoretically remove all combustion-related emissions from the cement manufacturing process. As these account for one third of the total emissions in Norwegian cement manufacturing, the potential mitigation is 33%.

For this study, four different data sources have been identified on the cost of alternative fuels in the cement industry.

In 2010, the Norwegian Climate and Pollution Agency[8] released a report (Norwegian Climate and Pollution Agency, 2010) stating that there was potential to mitigate 25 ktCO_{2e} at the price of 87 NOK/ton CO_{2e}. Further mitigation would result in a greater marginal cost, 778 NOK/ton CO_{2e} per ton.

McKinsey & Company (2009) estimated the fuel cost for waste to be 50.7 NOK/t CO_{2e} (5€/ton) and the cost for biomass to be 202.8 NOK/t CO_{2e} (20€/ton). Multiplying these values with the total amount of fossil fuel to replace in table 1 would result in 5 MNOK (492,000€) for waste and 20 MNOK (1,968,000€) for biofuels. Under the assumption that both fuels are CO_{2e} neutral (as is done in the study by McKinsey & Company (2009)), the marginal abatement cost would be acquired by dividing with the energy-related emissions. This would result in 56.8 NOK/tCO_{2e}(5.6€/tCO_{2e}) for biofuels and 14.2 NOK/tCO_{2e} (1.4€/tCO_{2e}) for waste.

Table 7

Global commodity price assumptions in 2018 (Adopted from McKinsey and Company (2018))

Product	Price (NOK/GJ)
Natural gas	64.6
Coking coal	27.7
Coal	18.5
Solid biomass	27.7
Biogas	129.3

A more recent data source from McKinsey & Company (2018) presents the global average commodity prices for selected fuels as in table 7.

The marginal abatement cost for biofuels can then be calculated according to appendix C and results in 137 NOK/tCO_{2e}.

Finally, the European Cement Research Academy (ECRA) estimated in a study European Cement Research Academy (2017) that switching from coal/coke to oil/gas/pure biomass would come at a operational cost increase of 81-162 NOK/t cement while a switch to alternative fuels (including biomass) would come at a cost decrease of 20-25 NOK/t clinker. The marginal abatement cost is calculated in appendix C, resulting in -84 NOK/tCO_{2e} for waste fuels and 604 NOK/tCO_{2e} for biofuels.

[8] The Climate and Pollution no longer exist and has instead been replaced by The Norwegian Environment Agency

Table 8

Summary of alternative fuel costs from the literature review

	McKinsey and Company (2009)	McKinsey and Company (2018)	European Cement Research Academy (2017)	Norwegian Climate and Pollution Agency (2010)
Marginal abatement cost biofuels	57 NOK/tCO_{2e}	137 NOK/tCO_{2e}	604 NOK/tCO_{2e}	87-778 NOK/tCO_{2e}
Marginal abatement cost waste fuels	14 NOK/tCO_{2e}	-	-84 NOK/tCO_{2e}	-

The price for biofuels in Norway is relatively high, compared to other European countries (Trømborg, 2015) and as such, this study will utilise the cost presented in the most recent of the articles by McKinsey & Company (2018), as an approximation for biofuels.

The results of the study by European Cement Research Academy (2017) appears a bit extreme for biofuels and as such, the more conservative marginal abatement cost of the study by McKinsey & Company (2009) will be used.

Clinker Substitution for Supplementary Cementitious Materials

GBFS can be used to substitute as much as 70%, but has decreased in availability between 1980 and 2014, which is only expected to further diminish. To generate GBFS, blast-furnace slag is quenched in a granulator, which requires capital investment. Therefore, GBFS should not be considered as a waste material and are often more expensive than the production cost of OPC. In addition, more than 90% of the available blast furnace slag is used as SCM and there is little additional potential for GHG mitigation (Scrivener et al., 2018).

Fly ash is a waste product from coal combustion and is available in greater amounts than GBFS, varying by region. In many regions the material is scarce and present little potential as a replacement material for clinker (Scrivener et al., 2018). As coal is not used for power generation in Norway, the availability of the material would be from energy-intensive industrial processes where coal is combusted to produce high temperatures. There is likely limited potential for additional substitution in Norway.

New discoveries points toward that calcined clays in combination with ground limestone is capable of replacing as much as 50% of the clinker without affecting the performance. This combination is inexpensive and widely available (Scrivener et al., 2018), but is yet to be deployed in large-scale in Europe. This is largely because of it not being economically competitive to GBFS and fly ash (Faviet et al., 2018). In a study by Berriel et al. (2016) of the environmental and economic potential of limestone calcined clays for cement manufacturing in Cuba, it is concluded that in a combination consisting of 50% clinker, 15% unburned limestone and 30% calcined clay, there was significant savings both in environmental impact and investment costs.

However, since the clinker-to-cement ratio already is 0.75, the additional improvement of acquiring a clinker-to-cement ratio of 0.5 would be an improvement of 33%.

Material Efficiency

New research by John et al. (2018) show that as much as 70% of the binder may be replaced by filler materials without affecting the mechanical strength, by decreased water usage. High-filler cement development requires optimised clinker particle size distribution, a dilution filler of the same size of the clinker, a performance filler as well as a dispersant to prevent particle agglomeration. For a more detailed technical explanation of the concept, the original research of John et al. (2018) should be consulted.

Utilising fillers may result in binder intensities at around 4-5 kg/m^3 MPa for 30 MPa concretes and CO_2 intensities of 2-3 kg CO_2/m^3 MPa compared to 4-7 kg CO_2/m^3 MPa, indicating an emission saving potential of around 50%. Although this is not a new technology per se, it is novel within the OPC field with limited amount of research (Scrivener et al., 2018).

No investments in the production process or the kiln is necessary for increased filler content and the thermal energy consumption is expected to decrease with filler content. However, electricity consumption will likely increase by the more sophisticated grinding required (John et al., 2018).

Filler material might originate from other agents in the market (Scrivener et al., 2018). Costs are expected to be lower than that of OPC and John et al. (2018) state that filler production cost is approximately 37% lower than the cost of OPC. As such, it should be safe to conclude that high-filler cement does not increase production costs.

With a very low electricity emission factor in Norway, the increased electricity consumption does not risk counteracting the established reduction presented above.

There are few practical limitations to using fillers, but the construction sector is considered to be a highly standardised, low-tech and conservative sector, which pose a challenge for the market penetration of high-filler cements (John et al., 2018).

Alternative Types of Cement

Due to the lack of available published LCAs of alternative clinker technologies, Gartner and Sui (2018) have done theoretical thermodynamic assessments of potential for CO_2 mitigation and primary energy consumption.

Reactive Belite-rich Portland Cement (RBPC)

The calculations indicate that it is theoretically possible to reduce emissions by approximately 10%, both by reduced fuel use and from material composition. The Cost for RBPC clinkers is expected to be comparable to OPC as it can be produced in conventional cement plants and have similar raw material.

Belite-Ye'elimite-Ferrite (BYF) clinkers

BYF clinkers requires more aluminium than OPC that need to be brought in through aluminium-rich raw material. As cement plants usually are located close to the raw material needed for OPC, the increased requirement for aluminium represents an additional cost (Gartner and Sui, 2018). The European Cement Research Academy

(ECRA) reported that the increased operational cost for BYF clinkers is between NOK 20.3-38.5 (€2-3.8) (European Cement Research Academy, 2017).

As BYF binders are not in commercial production, little data has been published on the performance and durability in comparison to OPC. However, in the EU-supported Project Aether, ran by a consortium lead by Lafarge, industrial trials indicate that the compressive strength is equivalent to OPC as well as resistance to external chemical attacks and dimensional stability (Project Aether, n.d.).

As for application areas, BYF binders are in theory suitable for a wide range of applications but have so far only been demonstrated in a limited number of applications. The reduced calcination and lowered energy demand indicate a CO_2 emission reduction of about 28%, similar to the 25-30% observed during trials. 56% of the emission saving is process-related and 44% is energy-related (Gartner and Sui, 2018).

Carbonatable Calcium Silicate Clinkers (CCSC)

Costs for CCSC is likely higher than OPC as additional investment is needed in a carbonation chamber and the purchasing of CO_2, but no explicit value is given by Gartner and Sui (2018).

Magnesium Oxides derived from Magnesium Silicates (MOMS)

Magnesium oxide (MgO) can be manufactured by calcining natural magnesite rock and then mixed with magnesium salts to form cement with good binding properties. Calcining magnesite rock releases large amounts of process-related emissions, like limestone calcination. However, like CCSC, magnesium oxide can be hardened by direct carbonation, i.e. by absorbing CO_2. In theory, a MOMS approach with energy-efficient production could result in cement with negative net-zero CO_2 emissions (Gartner and Sui, 2018).

The production process would be completely different from conventional cement plants, making it difficult to hypothesize around the costs. Research on MOMS was being pursued in the UK in 2008 but did not achieve sufficient funding and was discontinued in 2012. No current research is known to exist, but the approach could still be relevant in a long-term perspective (Gartner and Sui, 2018).

Table 9

Summary of alternative types of cement

	RBPC	BYF	CCSC	MOMS
Additional cost of production [NOK/tCO_{2e}]	0	29.4	Unknown	Unknown
Potential CO_2 emission mitigation compared to OPC	10%	28%	66%	100%

A comparison of the four identified novel types of cement is seen in table 9 and indicates that although CCSC and MOMS may achieve significant mitigation improvement, little is known of the associated costs as they are both in a fairly early research stage.

Due to that, the most realistic alternative is RBPC and BYF clinkers, but additional research should be done to provide better estimations on the associated cost.

Summary of measures

From the results of the review of measures, this section provides an overview of the different measures' potential GHG mitigation and associated costs. Both measures of substitution and cement improvement is presented.

Table 10

Estimated mitigation potential and marginal abatement cost for substitution measures

	Wooden construction materials	Biocement
Total potential mitigation		66%
Marginal abatement cost [NOK/tCO_2]		679

Table 11

Estimated mitigation potential and marginal abatement cost for cement improving measures

	Energy efficiency	Fuel substitution (biofuels)	Fuel substitution (waste)	Clinker substitution	Material efficiency	RBPC clinkerse	BYF clinkers
Total potential mitigation	4%	33%	33%	33%	50%	10%	28%
Marginal abatement cost [NOK/tCO_2]	0	137	14	0	0	0	29.4

The results of the literature review is summarised in table 10 (presenting substitution measures) and table 11 (presenting measures to improve cement production).

Wooden Construction Materials

Most of the literature is suggesting that there is significant GHG mitigation potential by substituting concrete for wooden construction materials. The resulting emissions from different LCA studies ranged between 36-192% in comparison to similar building structures, mainly made of concrete, depending on the system boundary and treatment of carbon storage. However, with such a large spread of the results and very uncertain cost estimates there is a significant difficulty in quantify the marginal abatement cost. Two Norwegian studies specifically mentioned that the results were not representative as a general model, but only for the studied building model (Skullestad et al., 2016; Rønning and Tellnes, 2018). As such, this study will not attempt to quantify the data for wooden construction materials. A qualitative discussion is instead presented in the discussion on the role of wooden construction materials.

Biocement

Biocement is a biological substitution material that has been researched due to its potential to reduce the GHG emissions from cement, and the most common mechanism is MICP.

LCAs done of biocement indicate the possibility of mitigating two thirds of the GHG emissions by producing biological concrete masonry units (bioCMUs) instead of conventional CMUs. However, the costs of input material needed for the production are still high, resulting in a marginal abatement cost in the range 679 NOK/tCO_{2e}. One of the major challenges is to identify a low-cost calcium source and to further scale up the production.

Material Efficiency

The use of filler material in concrete mixtures instead of cement shows potential to reduce CO_{2e} emissions and energy use over the life cycle of cement. The GHG mitigation potential is approximately 50% at no increased production costs and potentially even decreased costs.

Energy Efficiency

Energy efficiency is often perceived as one of the most cost-efficient mitigation measures in many sectors as the reduced energy demand that come with an investment result in lower energy consumption and lower expenses. However, Norcem's two cement production facilities are likely operating with close to best available technology and further energy efficiency may be costly and hard to assess.

To obtain more precise results, collaboration with Norcem would be necessary. The potential to reduce emissions is small (~3%) and the results would strongly depend on the assumptions made.

Alternative Fuels

The potential to substitute fossil fuels used in the kiln for alternative fuels could technically be as much as 100%, removing all the energy-related emissions (33% of total emissions). The emission reduction is highly depending on what fuel would be used as a replacement to fossil fuels.

The cost of alternative fuels varies depending on the type of fuel and regional availability. The marginal cost of biofuels has been estimated at 137 NOK/tCO_2.

Clinker Substitution

The largest source of emissions in the cement production process is from calcination during the production of clinker. Substituting clinker for other SCMs in the final cement product may thus reduce the CO_{2e}-intensity in cement.

Due to the regional availability of material, neither blast furnace slags nor fly ashes are likely to have additional potential to substitute clinkers. Instead, recent discoveries point towards a combination of calcined clay and limestone that could substitute as much as 50% of the clinker, reducing the CO_{2e} emissions by 33%.

Alternative Types of Cement

The most realistic alternative to OPC is ones that may be retrofitted into the existing manufacturing process, RBCP and BYF clinkers, which could reduce emissions by 10 respectively 28% for a small increased costs from the raw material needed. It is possible to produce in conventional cement plants and only require modification in the raw material input, where lower limestone content in the clinker reduce the emission from the calcination process.

Combined Marginal Abatement Cost of measures in comparison with CCS

In this section, the economic analysis is carried out by assessing the marginal abatement cost and maximum GHG mitigation of the measures against CCS. The details of the combinations have been described in the methodology.

Combination 1 – The industry's pathway to fossil-free competitiveness

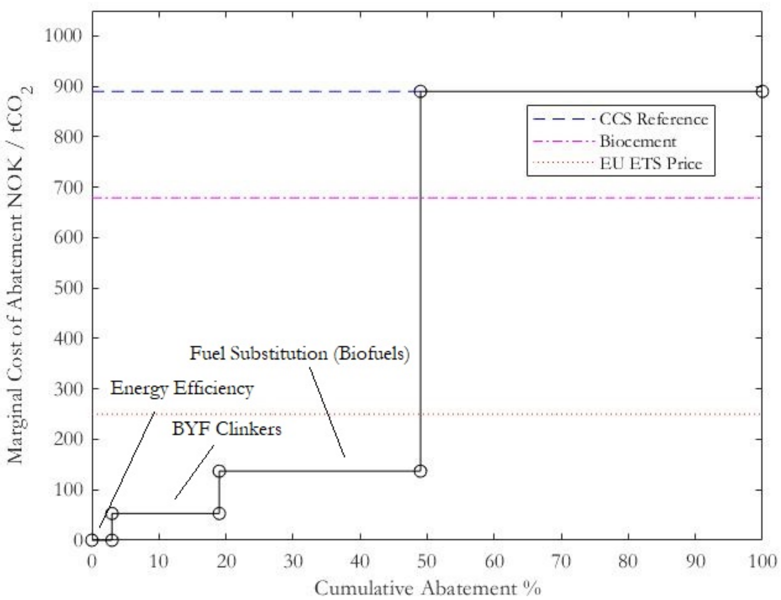

Figure 6 Combination 1 – The industry's pathway towards fossil-free competitiveness

The first combination of measures are described in table 4 and include energy efficiency, BYF clinkers and fuel substitution, based on the industry's envisioned pathway towards fossil-free competitiveness. Figure 6 illustrates the different levels of mitigation and their associated marginal abatement cost, where the lowest MAC is that of energy efficiency, followed by BYF clinkers and fuel substitution. The resulting 49% cumulative abatement is similar to the vision of Norcem (see figure 5).

Combination 2 – Reduced clinker volumes

The second combination assessed included energy efficiency, fossil-fuel substitution for biofuels, material efficiency, clinkers substitution as described in table 5.

The decreased manufacturing volume of clinker through the measures of material efficiency and clinker substitution greatly decrease the efficiency of the energy efficiency and fuel substitution.

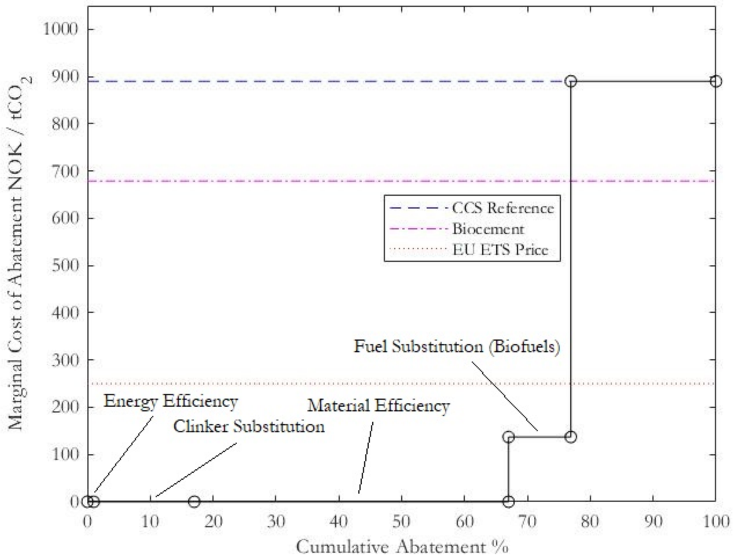

Figure 7 Combination 2 – Reduced clinker volumes

Despite the reduced efficiency of the measures, almost 67% of cumulative abatement can be achieved without imposing any additional cost in the manufacturing process. The fuel substitution then bring the final cumulative abatement to almost 77%.

Combination 3 – BYF Clinkers and Material Efficiency

Combination 3 includes the same measures as combination 2, besides that clinker substitution is exchanged for changing to BYF clinkers. The fuel substitution and energy efficiency will together remove the energy-related emissions. As such, only the process-related emissions remain to be reduced by BYF clinkers. Similarly to combination 1, the MAC of BYF clinkers have been increased from what was presented in table 11 due to it no longer affecting the energy-related emissions.

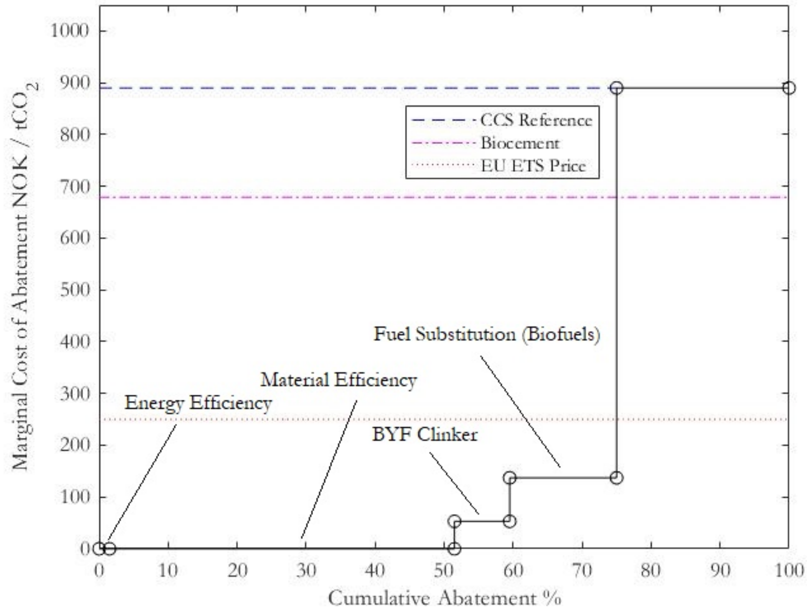

Figure 8 Combination 3 - BYF clinkers and material efficiency

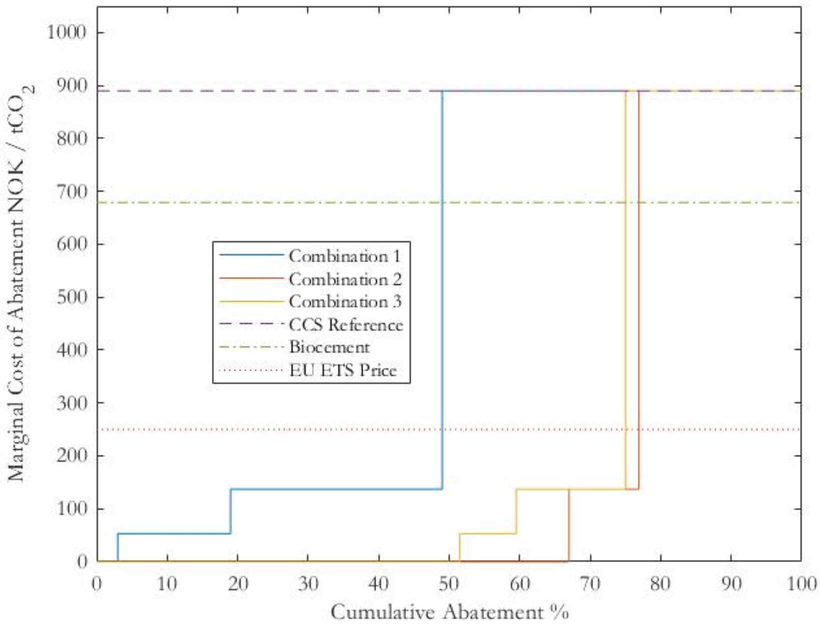

Figure 9 All combinations next to each other

In order to compare the different measures, it is useful to plot the three combinations next to each other, as have been done in figure 9. From the figure, it is easy to see which combination is the most cost-efficient measure based on a certain desired abatement. However, as can be seen in the figure, for all levels of abatement, combination 2 present the low marginal abatement cost (although the same as combination 3 at certain levels).

Discussion

The Norwegian cement industry have already presented their conceived pathway towards zero CO_{2e} emissions by 2030, with the by far largest emphasis being put on CCS. Norcem may host the first full-scale CCS project in the cement sector on a global basis, but it is only estimated to cover 50% of the emissions from the plant in Brevik (36% of total emissions in 2018) (Gassnova, 2020a; Gassnova, 2020b). Committing to CCS may be a successful GHG mitigation strategy, but there is also uncertainty involved. Public acceptance towards CCS could constrain the development, limiting the possibility of implementation (Fais, Keppo, Zeyringer, Usher and Daly, 2016).

Norcem have concluded that the implementation of CCS will increase the production cost of cement by 100%, proposing a risk for carbon leakage through increased import of cement in the event of no governmental incentives or financial support for cement CCS throughout the supply-chain (Norcem, 2019).

With high concentrations of CO_2 in the flue gas from cement manufacturing (Onarheim et al., 2015), post-combustion CCS does not seem to face additional challenges compared to other CO_2-intenstive sectors in Norway. Multiple different technologies are possible to implement in the cement industry, with varying cost of CO_2 avoidance (Gardarsdòttir et al.,2019).

Multiple studies have concluded that it is possible to achieve high rates of GHG mitigation without committing to CCS (Favier et al., 2018; Scrivener et al., 2018; John et al., 2018), by instead focusing primarily on the use of substitution of clinker for other SCMs and material efficiency by the use of high-filler cements.

Substitution measures appear to have a limited possibility to replace conventional OPC, and it is especially unlikely that Biocement will be able to compete with cement for large market shares in a near future, as it is still in an early phase of its development. Increased use of wooden construction materials on the other hand show more potential as a GHG mitigation measure but also comes with inconsistencies and difficulty to assess. Although Saade, Guest and Amor (2020) found support in the literature for lower environmental impact by wooden construction materials, the selection of Nordic studies in table 6 showed a spread in the results. It is therefore difficult and not without issues to try to generalise and quantify the GHG mitigation potential, as both Skullestad et al. (2016) and Rønning and Tellnes (2018) mentioned. Similar challenges exist for cost estimation, which combined present a significant barrier. Results are perceived to be context dependent and consequently no real attempt to quantify the marginal abatement cost have been done in this study.

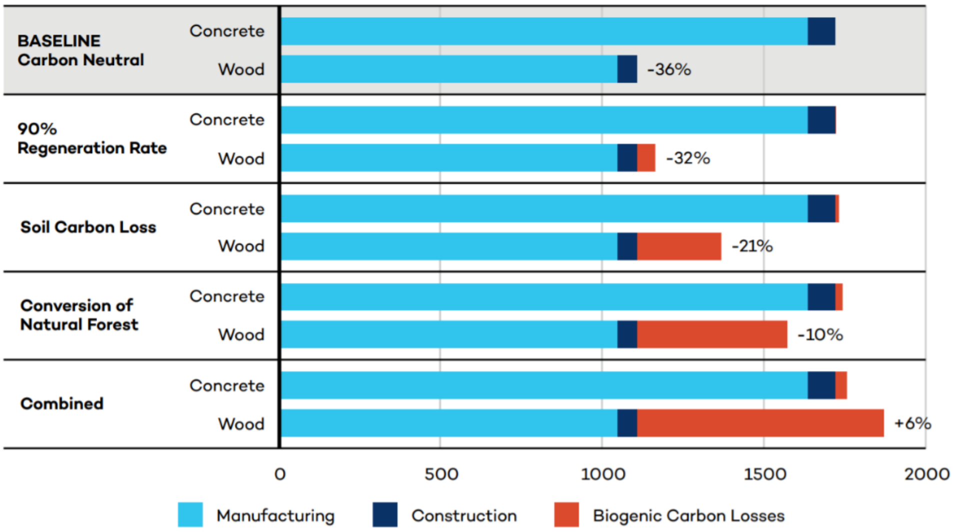

Figure 10 Whole-building cradle-to-gate life cycle GHG emissions: Four different forest management scenarios (Stiebert et al. 2019)

Additionally, complications arise when the dimension of stored carbon is included. LCA studies comparing building materials have been challenged for assuming forests to be carbon neutral and not incorporate silvicultural success rates (regeneration rate), emissions from soil disturbance and the conversion of old-growth primary forests to young-growth forests. The incorporation of these three factors and the impact compared to a baseline assessment, where wood is considered carbon neutral, is shown in figure 10. The inclusion of the three factors have a large impact on the result, where wooden construction materials move from having 36% less GHG emissions over its lifetime to even exceed that of concrete by 6% (Stiebert et al., 2019).

Looking beyond the GHG emissions arising from the different construction materials, both cement and wood products continue to sequester CO_2 after being harvested/produced (Churkina et al., 2020; Organschi et al., 2016). Applying the average CO_2 sequestration per ton cement by Engelsen et al. (2016) and carbon concentration in wood by Martin, Doraisami and Thomas (2018) to material intensity in buildings provided by Churkina et al. (2020) result in 63 kg CO_2/m^2 and 337 kg CO_2/m^2 for cement and timber constructions respectively (precise calculations can be found in appendix A).

Furthermore, none of the LCAs analysed buildings which were built entirely in wood, but rather only certain parts were substituted with wooden construction materials. The foundation in multi-storey buildings often need to be in concrete to be able to support the weight of the building. A substitution factor of 50% for apartment buildings have been mentioned by Brege et al. (2017) and gives an indication on how much of apartment buildings that can be built in wooden construction material. A 100% substitution factor is technically infeasible in some constructions and as such, the substitution into wooden construction materials is not a measure which may be considered a complete solution. Although no general conclusion was drawn, the literature review indicate that increased wooden construction materials may be a helpful tool towards GHG mitigation in the cement sector. The topic requires further scientific attention and the development of simple models that can be used for specific building projects.

Although potential exist for substitution of cement, it appears to be unfavourable compared to measures that improve the environmental performance of cement. Several measures with significant potential to mitigate GHG exist (clinker substitution, material efficiency and BYF clinkers) at associated marginal abatement cost below that of retrofit MEA-based absorption CCS.

Most interesting is substituting clinker for a combination of calcined clays and ground limestone as well as increased use of fillers in concrete, partially replacing clinker.

It may appear confusing that significant reduction is possible, at a cost that is lower than the price of purchasing emissions allowances within the EU-ETS of ~250 NOK/tCO_2 (before the steep price reduction that occurred as a result of the economic shutdown following COVID-19 (Carbon Market Watch, 2020)). A reason to why these measures have not diffused may be that the construction industry is conservative and characterised of standardised products (John et al., 2018). Additionally, the idea that the construction phase adds little to the environmental impact over a building's lifetime and the fact that regulations are centered around the use phase (Royal Swedish Academy of Engineering Sciences, 2014) may counteract the diffusion of e.g. clinker substitution. John et al. (2018) mention that a progressive work of standardisation for high-filler cements may improve public confidence and tackle sceptical stakeholders within the technical community.

Collectively for the substitution measures is that the stakeholders interested in the increased market penetration are vastly different than traditional cement manufacturers. Norcem has little incentive to promote other materials than their own products. As such, the information available on measures to tackle GHG emissions from the cement industry is likely to be weighted towards improvements in the cement manufacturing process.

As mentioned already in the methodology, one of the greatest weaknesses of this study is the potential inaccuracy of certain data due to potentially differing methodology between the studies assessed and insufficient information on specific data for the two Norwegian cement plants. However, despite the weakness, the results show clear indication that there exist alternatives to CCS with less uncertainties in terms of technological development and costs.

From the economic analysis of the three combinations of measures, it became apparent that high rates of decarbonisation is possible, but to a maximum of 77%. From figure 9 it was possible to identify combination 2 as the most cost-efficient combination at any given level of abatement.

Further Work and Limitations

Much of the data in this study relies on approximations of the cost of measures, which include significant uncertainties. It was not possible to solely rely on Norwegian data source and at times it is gathered on an international level and may not necessarily be representative for the Norwegian setting. Attempts have been made to close the gap. The scientific community would benefit from a larger study that is developed in close collaboration with Norwegian cement manufacturer Norcem and other relevant stakeholders. This would allow for more accurate estimations of country specific data. With more information, it would also be possible to conclude on a more precise marginal abatement cost and related marginal costs curves, production functions and cost functions.

With the identification of promising measures within the cement sector, there emerge a need for studies on the local availability of calcined clay and filler material in Norway to further examine the feasibility of clinker substitution and high-filler cements as measures in a Norwegian context.

Additionally, the study is limited to only assessing the GWP of cement manufacturing and alternative substitution measures. Including the local emissions of e.g. PM could give different results.

Conclusion

This study concludes, similarly to other studies on the global level, that CCS is not the only solution to GHG mitigation in the Norwegian cement industry. The industry is well suited for CCS with high concentrations of CO_2 in the flue gases and multiple feasible technologies that could be implemented.

Utilising a larger amount of wooden construction materials may help mitigate GHG emissions, although it is not possible to conclude on a general cost level for the substitution. With increased knowledge of this, building-specific modelling and studies may help distinguish the marginal abatement cost for individual construction projects. The other identified substitution measures, Biocement, is still in such an early development stage that it is unlikely to have a significant impact on the cement market within a near future. As such, the measure will likely play a small role in the possible GHG mitigation.

The improvement measures in the cement manufacturing process are more numerous and come with significant potential. Energy efficiency is seen as a cheap measure but provides little mitigation as cement kilns are already very energy efficient. Switching from fossil-fuels to alternative fuels such as waste and biofuels for the heating process could theoretically eliminate all of the energy-related emissions. However, biofuel is a limited resource that may be very important in other sectors' pathways towards reduced GHG emissions and waste is to a large extent used for district heating, creating competition for the resources. The two novel cement types (RBPC and BYF) are both possible to produce in a conventional manufacturing layout, only requiring adjustments to the raw material used. There seems to be a limited amount of assessments of the potential of these new cement types, but the ones that exist show promising results.

However, the greatest potential outside of CCS appears to be with clinker substitution and material efficiency through high-filler cements. These two measures may combined mitigate as much as 66%, by reducing the amount clinker manufacturing to 33%. It is possible to do so without significantly increasing the cost of cement and/or concrete. High-filler cements may even come at a negative cost, as the material is reported to be readily available and inexpensive.

In the economic analysis, three different combination of measures were identified and evaluated in order to assess how to achieve different level of abatement at a minimised cost. From the results it was shown that combination 2, which included energy efficiency, fuel substitution, clinker substitution and material efficiency, had the lowest marginal abatement cost at any given abatement level. However, neither of the combination of measures managed to achieve more than 77% of cumulative abatement without the use of CCS. As such, it is clear that if the cement sector wishes to achieve carbon neutrality, investing in CCS may be necessary and in fact a cost-effective measure. With that being said, pursuing alternative measures such as high-filler cements and clinker substitution may still be important to reduce the amount of CO_2 that need to be captured, transported and stored.

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Appendices

A. Calculations of CO2 sequestered in building materials

Sequestered CO_2 in concrete

$$503.83 \text{ kg concrete}/m^2 * 0.111 \text{ kg } CO_2/\text{kg concrete} = 55.93 \text{ kg } CO_2/m^2$$

where 503.83 is the material intensity (amount of material per m^2 in residential buildings) of concrete in a residential building (Supplementary material (Churkina et al., 2020)) and 0.111 is the average kg CO_2 sequested in a kg of concrete (Engelsen et al., 2016).

Sequestered CO_2 in timber

$$0.476\ kg\ C/kg\ timber\ *\ 193\ kg\ timber/m^2\ *\ 3.67\ kg\ CO_2/kg\ C\ =\ 337.16\ kg\ CO_2/m^2$$

where 0.476 is the global average carbon concentration in wood (Martin et al., 2018), 193 is the material intensity (amount of material per m^2 in residential buildings) of timber in residential buildings (Supplementary material (Churkina et al., 2020)) and 3.67 is the molecular carbon to CO_2 ratio.

B. BioZEment Cost Calculations

Table 12

Material Assumptions BioZEment (Adopted by Myhr et al. (2019))

Material	Amount	Cost per unit	Total cost
Limestone	140 kg/ton	0.38 NOK/kg	53.2 NOK
Urea	3.4 kg/ton	2.1 NOK7kg	7.14 NOK
Glucose	1.4 kg/ton	3.5 NOK/kg	4.9 NOK
Yeast extract	0.045 kg/ton	1400 NOK/kg	63 NOK
Peptone	0.13 kg/ton	2000 NOK/kg	260 NOK
Salt	0.13 kg/ton	0.336 NOK/kg	0.044 NOK
Bacterial mass	0.003 kg/ton	5000 NOK/kg	15 NOK
Electricity	5 kWh/ton	1 NOK/kWh	5 NOK
Oil	0.05 l/ton	500 NOK/l	25 NOK
Cleaner Fluid	0.01 l/ton	30 NOK/l	0.3 NOK

From table 12 the total material cost of BioZEment is 433 NOK/ton. The cost of materials is reported to be 10% more than for OPC-based concrete, meaning that the cost for OPC-based concrete is 433 divided by 1.1, resulting in 394 NOK/ton. The additional cost of BioZEment material is consequently 39 NOK.

Myhr et al. (2019) also specifies that the GWP of BioZEment is between 12.5 to 22.6 kg CO_{2e}/ton compared to 75.6 kg CO_{2e}/ton for OPC based concrete. Dividing the additional cost by the CO_{2e} mitigation results in a marginal abatement cost of 679 NOK/tCO_{2e}

C. Fuel cost calculations

In this appendix, the different fuel cost calculations for section 4.2.2 is calculated. The different references are presented in table 7.

European Cement Research Academy (2017)

The additional operational cost of switching to gas/oil/biomass was estimated to increase by 81-162 NOK/t cement and decrease by 20-25 NOK/t clinker for waste fuels (including biomass).

The average of the specified values can be multiplied with the manufacturing volumes from table 1 in order to acquire the additional cost.

$$\frac{(81+162)\ NOK/t\ cement}{2} * 1.745\ Mt\ cement\ =\ 212.017\ MNOK$$

and

$$\frac{(20+25)\ NOK/t\ clinker}{2} * 1.308\ Mt\ clinker\ =\ 29.430\ MNOK$$

In order to acquire the marginal abatement cost, the costs may be divided by the energy-related emissions:

$$\frac{212.017\ MNOK}{0.34\ *\ 1.031\ Mt\ CO_{2e}}\ =\ 604\ NOK/tCO_{2e}$$

And

$$\frac{29.430\ MNOK}{0.34\ *\ 1.031\ Mt\ CO_{2e}}\ =\ 84\ NOK/tCO_{2e}$$

where 0.34 is the share of energy-related emissions specified in table 1.

This results in a marginal abatement cost of -84[9] and 604 NOK/tCO_{2e}.

McKinsey and Company (2018)

In order to calculate the marginal cost of using solid biomass in McKinsey and Company (2018) as fuel compared to using coal, the first step is to calculate the price difference of coal and solid biomass according to table 7:

$$27.7\ NOK/GJ\ -\ 18.4\ NOK/GJ\ =\ 12.2\ NOK/GJ$$

The results are then to be multiplied by the specific thermal energy requried in precalciner kilns and dry porcess rotary kilns equipped with multi-stage cyclone preheaters according to Tokheim and Brevik (2007) and Favier et al. (2018).

$$12.2\ NOK/GJ\ *\ 3\ GJ/t\ clinker\ =\ 36.6\ NOK/t\ clinker$$

The cost is then converted to be per tonne cement by multiplying with the average clinker-to-cement ration from table 1:

[9] A negative is acquired as there is a cost decrese (savings) with waste fuel.

$$36.6\ NOK/t\ clinker\ *\ 0.75\ t\ clinker/t\ cement\ =\ 27.45\ NOK/t\ cement$$

The total marginal cost of using biofuels instead of coal is then acquired by multiplying the per tonne cement value with the total manufacturing volume:

$$27.45\ NOK/t\ cement\ *\ 1{,}745{,}000\ t\ cement\ =\ 47.9\ MNOK$$

The total energy-related emissions are acquired by multiplying the ration of energy-related emissions with the total emissions, also from table 1.

$$1.031\ Mt\ CO_{2e}\ *\ 0.34\ =\ 350{,}540\ tCO_{2e}$$

with which we can calculate the marginal abatement cost as

$$\frac{47.9\ MNOK}{350{,}540\ tCO_{2e}}\ =\ 137\ NOK/tCO_{2e}$$

D. MATLAB code for MAC curves and marginal cost curves

```
clear all, clc, close all

Energy_Efficiency = [3; 0];
BYF_Clinker = [28; 29.4];
Clinker_Substitution = [33; 0];
Material_Efficiency = [50; 0];
Fuel_Substitution_Biofuels = [33; 137];
CCS = [100; 890];
Biocement = [66; 679];

% Add additional measures to the list manually.
Measures = [Energy_Efficiency BYF_Clinker Clinker_Substitution ...
    Material_Efficiency Fuel_Substitution_Biofuels Biocement];

x = [0];
y = [];

% Picks out the x-values twice from every measure.
for i = 1:2:2*length(Measures)
    a = Measures(i) + x(i);
    x = [x a a];
end

% Picks out the y-values twice from every measure.
for i = 2:2:2*length(Measures)
    b = Measures(i);
    y = [y b b];
end

Biocementx = 0:100;
Biocementy = [];

for k = 1:length(Biocementx)
    p = Biocement(2);
    Biocementy = [Biocementy; p];
end

Carbon_Costx = 0:100;
Carbon_Costy = [];

for j = 1:length(Carbon_Costx)
    w = 250;
    Carbon_Costy = [Carbon_Costy; w];
end

% Adds an additional y-data point at zero to finish the graph.
y = [y 0];

CCSx_ref = 0:100;
CCSy_ref = [];
```

```
for j = 1:length(CCSx_ref)
    a = CCS(2);
    CCSy_ref = [CCSy_ref; a];
end
```

```
Fuel_Substitution_Biofuels(1) = 30;
BYF_Clinker(1) = 16;
BYF_Clinker(2) = 53;

CCS(1) = 100 - Energy_Efficiency(1) - Fuel_Substitution_Biofuels(1)...
    - BYF_Clinker(1);
Combination_1 = [Energy_Efficiency BYF_Clinker Fuel_Substitution_Biofuels...
    CCS];

x1 = [0];
y1 = [];

% Picks out the x-values twice from every measure.
for i = 1:2:2*length(Combination_1)
    a = Combination_1(i) + x1(i);
    x1 = [x1 a a];
end

% Picks out the y-values twice from every measure.
for i = 2:2:2*length(Combination_1)
    b = Combination_1(i);
    y1 = [y1 b b];
end

% Remove last x-data point to finish the graph.
x1(end) = [];

figure(1)
plot(CCSx_ref,CCSy_ref,'b--',Biocementx,Biocementy,'m-.',...
    Carbon_Costx,Carbon_Costy,'r:',x1,y1,'ko-')
set(gca,'FontName','garamond')
legend('CCS Reference','Biocement','EU ETS Price')
xlabel('Cumulative Abatement %')
ylabel('Marginal Cost of Abatement NOK / tCO_2')
axis([0 100 0 1050])
```

```
Energy_Efficiency = [3; 0];
BYF_Clinker = [28; 29.4];
Clinker_Substitution = [33; 0];
Material_Efficiency = [50; 0];
Fuel_Substitution_Biofuels = [33; 137];
CCS = [100; 890];
Biocement = [66; 679];

Energy_Efficiency(1) = 1;
Fuel_Substitution_Biofuels(1) = 9.9;
```

```
Clinker_Substitution(1) = 16;
CCS(1) = 100 - Clinker_Substitution(1) - Material_Efficiency(1)...
    - Energy_Efficiency(1) - Fuel_Substitution_Biofuels(1);

Combination_2 = [Energy_Efficiency Clinker_Substitution...
    Material_Efficiency Fuel_Substitution_Biofuels CCS];

x2 = [0];
y2 = [];

% Picks out the x-values twice from every measure.
for i = 1:2:2*length(Combination_2)
    a = Combination_2(i) + x2(i);
    x2 = [x2 a a];
end

% Picks out the y-values twice from every measure.
for i = 2:2:2*length(Combination_2)
    b = Combination_2(i);
    y2 = [y2 b b];
end

% Remove last x-data point to finish the graph.
x2(end) = [];

figure(2)
plot(CCSx_ref,CCSy_ref,'b--',Biocementx,Biocementy,'m-.',...
    Carbon_Costx,Carbon_Costy,'r:',x2,y2,'ko-')
set(gca,'FontName','garamond')
xlabel('Cumulative Abatement %')
ylabel('Marginal Cost of Abatement NOK / tCO_2')
legend('CCS Reference','Biocement','EU ETS Price')
axis([0 100 0 1050])
```

```
Energy_Efficiency(1) = 1.5;
Fuel_Substitution_Biofuels(1) = 15.5;
BYF_Clinker(1) = 8;
BYF_Clinker(2) = 53;
CCS(1) = 100 - BYF_Clinker(1) - Material_Efficiency(1)...
    - Energy_Efficiency(1) - Fuel_Substitution_Biofuels(1);

Combination_3 = [Energy_Efficiency Material_Efficiency ...
    BYF_Clinker Fuel_Substitution_Biofuels CCS];

x3 = [0];
y3 = [];

% Picks out the x-values twice from every measure.
for i = 1:2:2*length(Combination_3)
    a = Combination_3(i) + x3(i);
    x3 = [x3 a a];
```

```
end

% Picks out the y-values twice from every measure.
for i = 2:2:2*length(Combination_3)
    b = Combination_3(i);
    y3 = [y3 b b];
end

% Remove last x-data point to finish the graph.
x3(end) = [];

figure(3)
plot(CCSx_ref,CCSy_ref,'b--',Biocementx,Biocementy,'m-.',...
    Carbon_Costx,Carbon_Costy,'r:',x3,y3,'ko-')
set(gca,'FontName','garamond')
legend('CCS Reference','Biocement','EU ETS Price')
axis([0 100 0 1050])
xlabel('Cumulative Abatement %')
ylabel('Marginal Cost of Abatement NOK / tCO_2')

figure(4)
plot(x1,y1,x2,y2,x3,y3,CCSx_ref,CCSy_ref,'--',Biocementx,Biocementy,'-.',...
    Carbon_Costx,Carbon_Costy,'r:')
set(gca,'FontName','garamond')
xlabel('Cumulative Abatement %')
axis([0 100 0 1050])
ylabel('Marginal Cost of Abatement NOK / tCO_2')
legend('Combination 1', 'Combination 2', 'Combination 3',...
    'CCS Reference','Biocement','EU ETS Price','fontname','garamond')
```