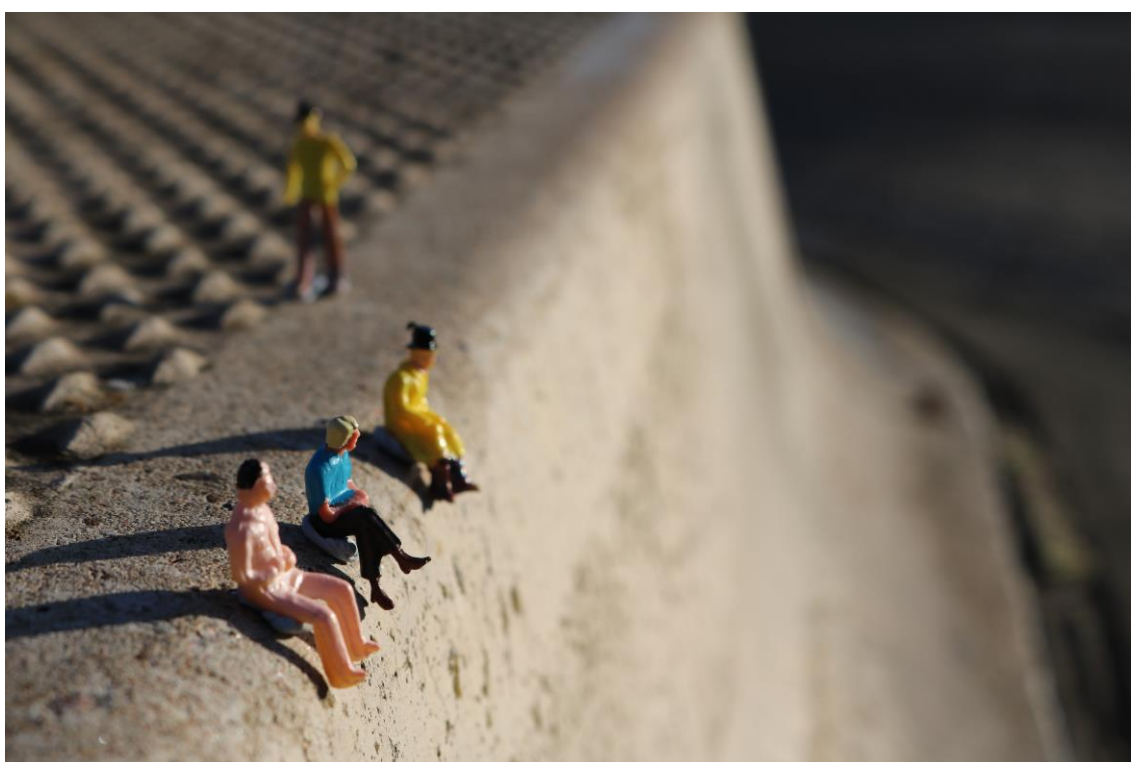




BUILT ENVIRONMENT SYSTEM TRANSITION AND SERVICE INNOVATION



Climate impact of BioZement in the construction of residential buildings in Norway

Olivia Cintas, Frida Røyne, Nadia Al-Ayish

RISE Report 2020:37

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Abstract

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The construction sector is a major contributor to global warming. One solution to the challenge is to develop new sustainable material alternatives. The BioZEment concept employs bio-catalytic dissolution and precipitation of calcium carbonate as a novel alternative to concrete. In this report, the reduction in global warming potential of using BioZEment is assessed with a building stock model, where the use of conventional concrete is compared to the use of BioZEment in Norwegian dwellings until 2100. The assessment is conducted with the assumption that BioZEment has expected material properties and is gradually penetrating the building stock until it reaches a full implementation by 2050.

Results indicate that the use of BioZEment has a higher potential of reducing global warming potential than conventional concrete, regardless of the development of the cement industry. BioZEment could decrease cumulative greenhouse gas emissions with ca 15 % by 2100 compared to using conventional concrete with a conservative development and slightly less if compared to using concrete with an optimistic development (including among other initiatives breakthrough technologies like carbon capture and storage, and carbon capture and utilization).

Results also indicate that, while BioZEment is not fully implemented in the entire building stock, using the optimistic development concrete instead of conservative concrete provides the lowest cumulative emissions by 2100. That means that including several migration strategies at the same time will reduce emissions further than taking one single action.

The building stock model provides interesting indications about the potential of BioZEment, which can guide further development. If Norway is to meet its ambitious goals of emission reductions and climate neutrality, it is important to design thought through and robust strategies for the construction sector.

Key words: building stock, life cycle assessment, concrete, cement, bacteria, climate

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Preface

The project BioZement 2.0 (Centre for Digital Life Norway 2020) was carried out 2017-2020. The ambition was to create a cementing material that is environmentally superior to conventional concrete, with the objective: “Through a transdisciplinary approach, build a sound scientific basis for the sustainable development of a next-generation bio-concrete, based on the dissolution and precipitation of CaCO_3 using bacterial metabolic processes”.

The 20 mill NOK budgeted project, funded by the Research Council of Norway, was led by the University of Oslo. The other project partners apart from RISE were all based in Norway: the Norwegian University of Science and Technology (NTNU), the research institute SINTEF, Consumption Research Norway (SIFO), and Pure Logic AS.

The role of RISE in the project was to provide support in assessing the environmental impact of the BioZement product, with the use of life cycle modelling and a building stock perspective.

Summary

Concrete, which mainly consists of cement, water and aggregates, is the second most consumed material in the world after water, and essential in the construction sector. Estimations show that cement production stands for 5 to 8 % of the total anthropogenic CO₂ emissions, due to the release of fossil CO₂ during de-carbonation (60%) and the burning of fossil fuels (40%) to produce energy for it. The currently massive environmental impact show that it is urgent to reduce emissions from the construction industry.

The aim of this report has been to strengthen the outlook of the BioZEment product, by assessing its environmental mitigation potential. This was done through assessing the global warming implications for the Norwegian building stock of a theoretical technology penetration of BioZEment within the next 100 years, with different projections. The investigated scenarios were (i) whether concrete (Baseline) or BioZEment (BioZEment) is being used in the new buildings, and (ii) whether a more conservative or optimistic (including carbon capture and storage) development of the cement industry is assumed with regard to abating GHG emissions.

Results indicate that the use of BioZEment has a higher potential of reducing global warming potential than conventional concrete, regardless of the development of the cement industry. BioZEment could decrease cumulative greenhouse gas emissions with ca 15 % by 2100 compared to using conventional concrete with a conservative development and slightly less (ca 13%) if compared to using concrete with an optimistic development (including among other initiatives breakthrough technologies like carbon capture and storage, and carbon capture and utilization). Results also indicate that, while BioZEment is not fully implemented in the entire building stock, using the optimistic development concrete instead of conservative concrete provides the lowest cumulative emissions by 2100. That means that including several migration strategies at the same time will reduce emissions further than taking one single action. The assessed advantage of BioZEment is dependent on the material having expected material properties, and on a full implementation in the new building stock by 2050.

The building stock model provides intriguing indications about the potential of BioZEment, which can guide further development. If Norway is to meet its ambitious goals of emission reductions and climate neutrality, it is important to design thought through and robust strategies for the construction sector.

1 Introduction

The critical state of global warming has made many countries realize that extensive efforts for reducing greenhouse gas emission are needed. Norway has the long-term and legally binding goal of becoming a “low carbon society” in 2050, described as achieving an 80-95 % reduction below 1990 levels. The mid-term target is to reduce emissions by at least 40 % by 2030 compared with the 1990 level. Norway also has the ambition of being climate neutral by 2030 (Nordic Energy Research, 2019). The construction sector is a major contributor to global warming, responsible for around 18 % of global greenhouse gas emissions (Edenhofer et al. 2014). It is therefore intriguing to explore how this sector can improve its climate footprint.

1.1 Concrete and the construction industry

Concrete, which mainly consists of cement, water and aggregates, is the second most consumed material in the world after water, with a global production of around 10 km³ of concrete every year (Gartner et al. 2011). The cement and concrete production reflect the demand of the society as it is an essential material for infrastructure and buildings. Some of the benefits of concrete is the high compressive strength, moldability and high durability. However, being the most consumed building material in the world and having a cement production technology which requires combustion results in a notable impact on the global warming. Estimations show that the cement production stands for 5 to 8 % of the total anthropogenic CO₂ emissions (IEA 2009, Olivier et al. 2016).

It should be noted that concrete is a material, like other materials, which serves a purpose. For that reason, it is important to consider the environmental impact of the finished product which fulfils a certain function; for example, a load bearing exterior wall which fulfils requirements of a specific U-value, fire class, sound insulation etc. In other words, reducing the environmental impact of concrete structures is important in order to reach the sustainability goals. Nevertheless, it is also important to search for environmentally more sustainable alternatives for the same application and function.

According to a study on CO₂ uptake in concrete by Pade et al. (2007) 3,2 million m³ of concrete was produced in Norway in 2003, 75 % of which is ready-mix concrete that is cast in situ. Table 1 shows volumes of concrete for different applications in the Nordic countries.

Table 1 Volumes of concrete for different applications, in the Nordic countries.

Concrete and construction type	Norway Volume [m3]	Denmark Volume [m3]	Sweden Volume [m3]	Iceland Volume [m3]
Ready-mix, of which;	2,400,000	2,200,000	3,200,000	250,000
-Indoor walls	485,000	476,000	683,000	54,000
-Indoor slabs	504,000	584,000	709,000	23,000
-Outdoor walls	224,000	376,000	363,000	37,000
-Foundation (buried)	180,000	88,000	189,000	20,000
-Other	1,007,000	676,000	1,256,000	116,000
Precast elements, of which;	297,000	392,000	559,000	19,000
-Hollow core slabs	196,000	132,000	176,000	10,000
-Indoor walls	35,000	109,000	151,000	4,000
-Facades	38,000	59,000	82,000	4,000
-Other	28,000	92,000	150,000	1,000
Precast products (not in buildings)	492,000	1,277,000	264,000	147,000
Total	3,189,000	3,869,000	4,023,000	416,000

1.2 The BioZEment concept

The BioZEment concept is to employ bio-catalytic dissolution and precipitation of calcium carbonate as a novel process for concrete production. The end-product of BioZEment is thus not cement, as the name might imply. The name refers to the innovative cementation process.

Whereas conventional concrete is a mixture of aggregates, water and cement, the BioZEment process creates the solid concrete product directly. The production of BioZEment takes place in two steps. In the first step, an acid producing strain that is adapted to high pH and ion concentrations produces organic acid in a suspension of crushed limestone. This induces dissolution of part of the limestone. In the second step, the dissolved limestone is introduced to a packing of sand together with urea and a strain of urease producing bacteria. Enzymatic hydrolysis of urea increases the pH of the system, which induces precipitation of the dissolved limestone. The dissolved material acts as a binder between the sand grains, forming a solid material.

2 Aim and approach

The ambition of the BioZement 2.0 project is to create a cementing material that is environmentally superior to conventional concrete, with the objective: “Through a transdisciplinary approach, build a sound scientific basis for the sustainable development of a next-generation bio-concrete, based on the dissolution and precipitation of CaCO_3 using bacterial metabolic processes”.

In order to assess the “sustainable development”- part of the objective, a work package focused on environmental aspects was set up. The aim of the work package was to strengthen the outlook of the BioZement product, by assessing its environmental mitigation potential. In the BioZement 1.0 project, the environmental impact of BioZement was evaluated from a product perspective: the BioZement material was compared with conventional concrete. In the follow up 2.0 project, the environmental performance is assessed from an additional perspective: From a residential building stock perspective. Here, the environmental implications for the Norwegian building stock of a theoretical technology penetration of BioZement within the next 100 years are assessed with different projections. We have excluded other concrete structures (like bridges etc) from the analysis, which means that the assessed potential is representative for approximately 70 % of the Norwegian concrete sector, as indicated by Pade et al. (2007).

Other areas explored in this report, as a consequence of the information generation for the environmental assessments, are the expected material properties and application prospects of BioZement, and the future physical market role and share of BioZement.

3 Concrete properties and applications

Today, concrete is produced by mixing cement, water, aggregates and usually admixtures. Depending on the proportions of these raw materials different properties can be achieved.

Concrete has a high compressive strength but a low tensile strength. For that reason, reinforcement is used to take the tensile forces. Reinforcement is usually made of steel but could also be made of carbon-, glass-, basalt- or aramid fibres depending on the purpose of use. It is the composite effect, i.e. the compressive strength of the concrete and tensile strength of the reinforcement that determines the load-bearing capacity.

When talking about durability of concrete, most of the damages is related to corrosion of steel bars. The reinforcement inside the concrete is protected by a thin passivating film that has been created due to the high alkalinity of the pore solution. Corrosion starts when the pH drops to lower than ca. 9 due to carbonation of concrete. Carbonation is the process when CO_2 is reacting to $\text{Ca}(\text{OH})_2$ and forms CaCO_3 which is the original state before concrete hydration. Another reason for corrosion is chloride ingress which through different mechanisms can break the passive layer. Durability may be increased by reducing the permeability of concrete, capturing the chloride ions in concrete or using non-corrosive reinforcement. Traditionally, reduction of concrete permeability, i.e. an increase in durability, is achieved through increasing the share of cement compared to water, i.e. decreasing the water-to-cement ratio. Nowadays, it is known that increase of concrete durability can also be achieved by adding supplementary cementitious materials which reduce permeability, have the ability to capture chloride ions and increase the strength of concrete over longer periods. Industrial waste products such as fly ash and ground-granulated blast furnace slag are examples of such materials, which are widely used in the concrete industry (Lagerblad 2005, Shi et al. 2012).

Other damage mechanisms of concrete include sulfate attack; expansive alkali silica reaction caused by an inappropriate use of type of aggregate with reactive silica in combination with a cement with high alkali content or external supply of alkali; freeze-thaw, which causes high stress on the pore structure; and damage caused by high acidic environment.

The effect of the environment has a big effect on the durability and depending on where the concrete will be used there are different requirements on the content. In EN 206:2013 “Concrete - specification, performance, production and conformity” and its specific national appendices the application of concrete is divided into five environments and 18 exposure classes related to those environments. Each exposure class defines which types of cement and supplementary cementitious material (binder) can be used and which maximum water-to-cement ratio and binder content is applicable. Additionally, the steel reinforcement is protected by the concrete cover, which is expressed as minimum cover thickness based on environment and concrete type.

In an indoor environment there is a minimal risk of corrosion due to the low humidity and the concrete may therefore have a very long service life. Because of low humidity, indoor concrete is not subjected either to alkali silica reaction, freeze-thaw attack. Additionally, indoor concrete is not subjected to acid attack.

In this project the following applications of concrete in buildings have been considered:

- Concrete for foundation
- Precast – indoor and outdoor
- Ready-mix concrete indoor and outdoor

The difference between these applications is the exposure environment and production technique. Precast concrete elements are produced at the factory with high control and time constraint. The precast concrete mixtures usually differ to those of a ready-mixed concrete. In foundations concrete is the dominant material, even for other building material frames. The foundation concrete may have a lower compressive strength. And, if only compression occurs then reinforcement is only necessary where concrete cracking may occur due to movements caused by heat development or water evaporation/loss.

3.1 Concrete and sustainability

The main sustainability issues for concrete are recycling of old concrete, resource use and global warming potential caused by greenhouse gas (GHG) emissions. In this report the focus is on the global warming potential.

There are several ways to reduce the GHG emissions from buildings. It involves the collaboration of all actors in the construction process and can be broken down in several steps. Firstly, to consider the whole building which is intended to be improved. How can it be designed in a way which leads to less use of resources? Second, is to consider the building frame and the building part. How can we minimize the resources while obtaining the function? Third, we go to the material level. How can the sustainability of the material in a given environment be improved? To be able to improve the sustainability a life cycle approach needs to be adopted where all the in- and outflows of resources and emissions from processes during the life cycle are investigated. In this report we focus on the material level and the effect of replacing one part concrete with one part BioZement.

The global warming potential of concrete is mainly due to the production of cement clinker, an intermediate step in cement production. Approximately 40 % of the GHG emissions are derived from the energy input. The rest are emitted during the calcination process when CO₂ is released (Favier et al. 2018). Generally, concrete contains about 80 % aggregates, 14 % cement and 6 % water, in weight. When considering material extraction, transport to concrete factory and energy use at concrete factory the GHG emissions are to 90 % from the use of cement. This means that optimizing the cement production at factory and reducing the cement clinker in concrete is an efficient way to reduce the global warming potential. In turn, the cement clinker may be reduced in different ways. One way to reduce it is by replacing part of the Portland cement (CEM I) with supplementary cementitious materials from industrial waste products such as fly ash and ground-granulated blast furnace slag. This can be done in either the cement mix or directly in the concrete mix. Additives and aggregate quality also play a role in reducing the cement clinker proportions in concrete. Another way is by increasing the durability of the structure and thereby extending the service life and reducing the need for repair and replacement. According to Müller et al. (2014) there are three approaches to enhance the sustainability: 1) lowering the environmental impact of the concrete mix; 2) improving the concrete performance, i.e. reduction of cross-section of members

through high load bearing capacity and 3) by extending the life span of the material and the structure. By reducing the need for repair and replacement there can be a significant reduction in environmental impact over the life span of a construction.

However, an efficient use of resources will only reduce the GHG emissions to some extent. In order to further reduce the emissions, the CO₂ emitted during calcination needs to be captured. Techniques for carbon capture and storage or utilisation (CCS and CCU) are currently being demonstrated. One of the places that are considered for CCS is in the Norwegian deep sea.

Both Cementsa, part of Heidelberg Cement, (Cementa 2018) and CEMBUREAU (CEMBUREAU 2018) have estimated the GHG reductions by several measures (Figure 1 and Figure 2). According to both sources, current emissions are at a level of 674-700 kg CO₂-eq/tonne. If conventional techniques are used to lower the GHG emissions the reduction potential is about 26-32 %. By using breakthrough technologies like CCS and CCU the reduction potential is estimated to be 80 %.

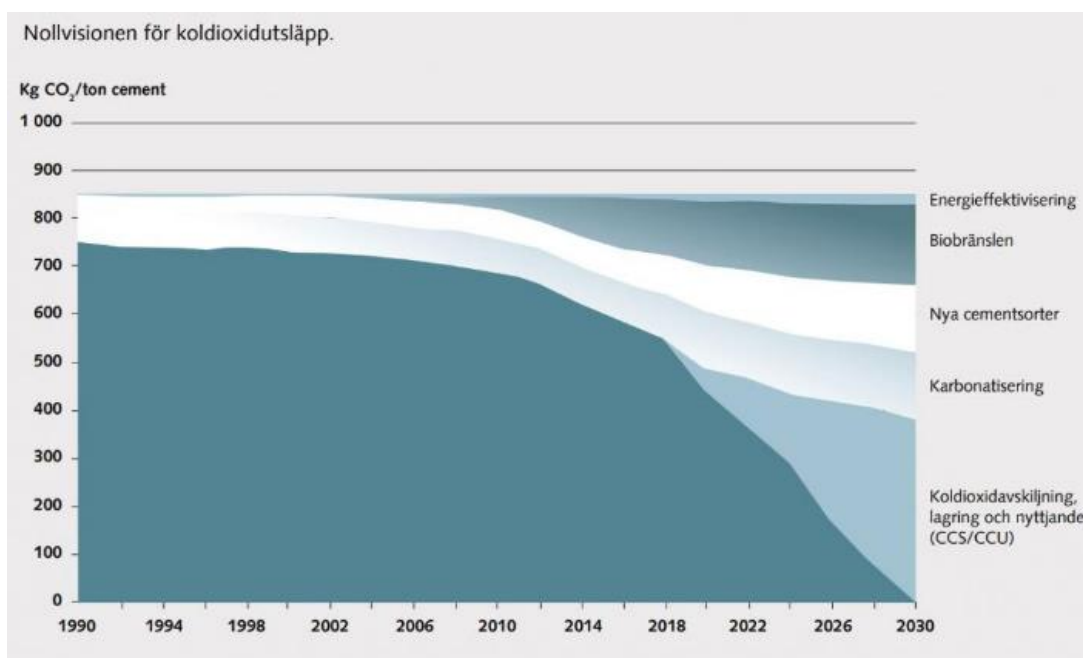


Figure 1 Cementsa's vision for net-zero CO₂ emissions until 2030 (Cementa 2018).

1. 1990-2015: what has been achieved (based on GNR 2015);
2. 2015-2030 and 2030-2050: linear projection of remaining reduction potentials;
3. 2030-2050: breakthrough technologies applied.

CO₂ REDUCTION MEASURES: 2050 PERSPECTIVE

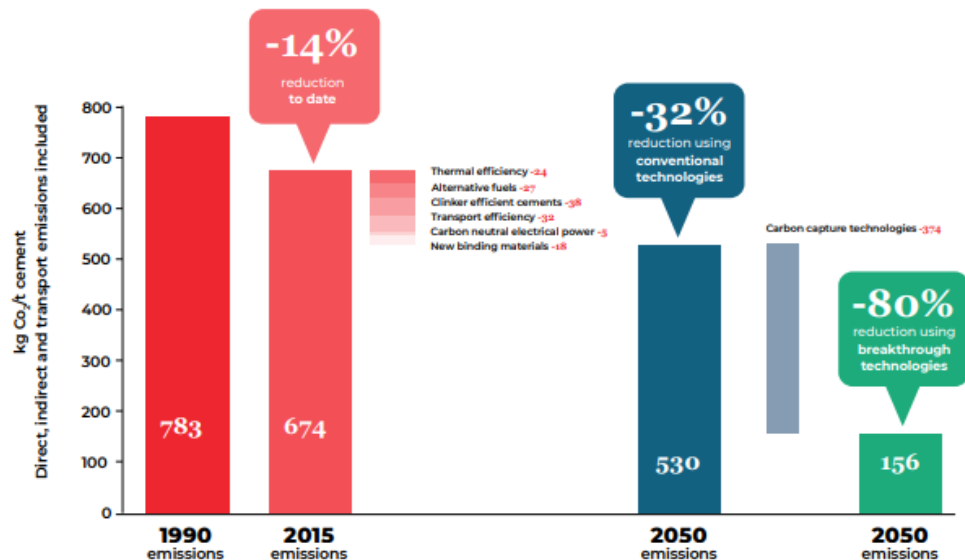


Figure 2 CO₂ reduction measures of concrete on a 2050 perspective (CEMBUREAU 2018)

In a report by Favier et al. (2018) the authors have investigated different techniques to lower the GHG emissions in the European cement and concrete industry. Four scenarios were compared:

- **Reference scenario:** It requires some investment by cement manufacturers to improve kiln technologies and some extension of the use of alternative fuels and clinker substitution.
- **Breakthrough technologies:** Requires massive investment by cement producers to equip their plants with CCS/CCU technologies as well as increased market penetration of alternative clinkers.
- **Efficient use and recycling:** Requires moderate investment. There is a significant increase in the use of alternative fuels; recycling of concrete with fines reused as raw material for clinkers; optimisation of the concrete mix design via better aggregate packing and strictly not exceeding the requirements of codes and standards to avoid the over use of cement in concrete.
- **Structural optimisation and circular economy principles:** This is similar to previous scenario and will require slightly higher investment at the level of the structure. In addition to the concrete mix, the structure is also optimised, and considering reusing elements.

According to the results of this study, an 80 % reduction in CO₂ emissions compared to 1990 levels could be achieved by combining the structural optimization scenario with a 25 % implementation of CCS. A 95 % reduction could be achieved by increasing the share of CCS to 80 %.

In the building stock model, we use different scenarios for the development of the cement industry. We have a “**conservative** concrete” and a “**optimistic** concrete”. The difference between conservative and optimistic concrete are based on the development of the cement industry when it comes to abating CO₂ emissions.

- **Conservative:** This is based on CEMBUREAU’s scenario of conventional technology to reduce GHG emissions of cement; optimizing the energy use at cement factory, choice of fuel, and clinker replacement with alternative binders. The reduction compared to 2015 values is 32 %.
- **Optimistic:** This includes breakthrough technologies like CCS and CCU. An 80 % reduction by 2030 compared to 2015 is assumed.

4 BioZement properties and application

The role of BioZement in the building stock depends on the properties of the end-product. As described in the project goals, BioZement is intended to be an alternative to conventional concrete and should therefore be able to be used as a structural element in buildings. In order to be an alternative to concrete in the building sector, the BioZement must have similar properties and market aspects.

In the BioZement production sand is bound with calcium carbonate through a bacterial process where limestone is dissolved and precipitated. This is similar to the process of calcium carbonate cemented sandstone. As BioZement is made of calcite (calcium carbonate) it may be considered, when fully developed, to have similar properties as limestone and sandstone or as lime mortar. BioZement is different from Portland cement concrete since it does not harden through hydration, have an increase of strength over time and contain all of the minerals which are included in concrete. However, being cementing, formable and having the possibility to include some type of reinforcement makes it an interesting alternative. Additionally, previous studies of microbial cements are investigated in order to understand what properties might be expected.

As previously mentioned, the environment and application determine the proportions and type of raw materials in concrete. And the main driving force that determines the durability is the liquid/water permeability in the pore structure. Regarding rocks the durability is partly related to the pore structure and concerns other mechanisms as well, which can be related to chemical and physical weathering. Chemical weathering involves i.a. dissolution due to acidic compound, carbonation and hydration. Physical weathering includes thermal stress, frost weathering due to expansion stress from ice formation and salt-crystal growth.

In an indoor environment there are not many weathering agents and BioZement could be considered to have a longer life span compared to exterior applications such as a façade element.

The physical properties of sandstone and limestone are related to porosity, modulus of elasticity, compressive strength, flexural strength, hardness, water sorption and density (Winkler 2013).

Microbially induced carbonate precipitation has been previously studied. One of these is the study of Zhang et al. (2015) where the authors test the physical properties of microbial mortars made of three different calcium sources (CaCl_2 , $\text{Ca}(\text{CH}_3\text{COO})_2$ and $\text{Ca}(\text{NO}_3)_2$). This study may indicate what to expect from microbial mortars such as BioZement in terms of physical properties.

Table 2 shows some of the physical properties of sandstone, limestone, concrete and a type of microbial mortar from Zhang et al. (2015). The physical properties of sandstone and limestone are derived from Winkler (2013) and Schouenborg (2011).

Table 2 Physical properties of sandstone, limestone and concrete.

Physical property	Sandstone	Limestone	Concrete for buildings^a	Microbial mortars (Zhang 2015)
Porosity [%]	5-25	2-20	8-15	~11-15
Modulus of elasticity [GPa]	3-78 (0,3-8 kg/cm·10 ⁵)	10-78 (1-8 kg/cm·10 ⁵)	14-41	N/A
Density [g/cm ³]	2-2,7	2,2-2,8	2,3-2,4	~2,2-2,4
Flexural strength [MPa]	3-15	5-15 ^b	2-5	0,43-1,28 ^c (tensile)
Compressive strength [MPa]	30-150	80-180 ^b	20-40	~10-43 ^d
Water absorption [weight-%]	0,5-8	0,2-0,6 ^b	6-7	2,5-5,5

^a Concrete properties are tested differently and may therefore not be directly comparable but can be considered to be a guidance.

^b For dense limestone

^c Using the Brazilian splitting tensile strength (BTS) tests. The tensile strength is usually a bit lower than the flexural strength.

^d The uniaxial compressive strength.

The low pH of BioZement makes it difficult to reinforce with traditional steel rebars. In an indoor environment where there is lower risk of corrosion it might be possible but in an outdoor environment, alternative non-corroding reinforcing materials needs to be considered. If the BioZement does not have any significant shrinkage and swelling during production (i.e. crack-free), the areas where it's only subjected to compression could be made without reinforcement.

In a study by Geffers et al. (2015) reinforcement strategies of a type of cement, which sets in a continuous dissolution–precipitation reaction, based on various intrinsic or extrinsic material modifications to improve their strength and toughness, have been investigated. It was found that altering particle size distribution in conjunction with using liquefiers decreases cement porosity and increases the mechanical performance but does not change the brittle nature of the cements. Additionally, the authors concluded that the use of fibres may lead to a reinforcement of the matrix with a toughness increase of up to two orders of magnitude. Figure 3 shows the strategies suggested by the authors to increase the load-bearing capacity of mineral biocements. It must be noted that the cement investigated by Geffers et al. is not a microbial cement but is of interest in this study as it sets in a continuous dissolution–precipitation reaction.

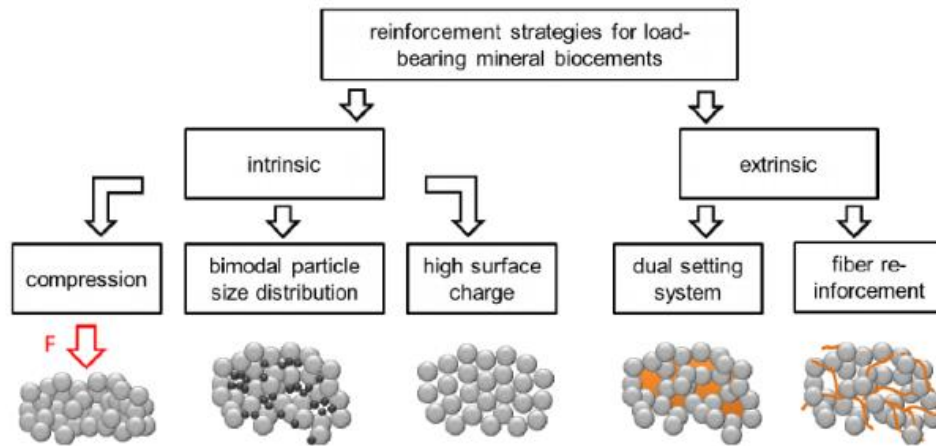


Figure 3 Reinforcement strategies for load-bearing applications from Geffers et al. (2015)

It should be noted that the properties of BioZement are still unknown and will be dependent on the cementing abilities and the bond strength between the calcite and the sand.

Some functions that could be interesting concerning BioZement is the usage of desert sand as the type of sand used for concrete is a scarce commodity. The use of desert sand in microbial cements has been studied by Chi et al. (2018). The authors examined Aeolian sand bio-remediated by microbially induced calcite precipitations in order to explore its behaviour as a desert bio-crust. It was indicated that formation of bio-crust could serve as protection against desert erosion thus reducing the environmental harmfulness and the negative effect on the infrastructure.

Another advantage could be the recyclability of BioZement which could save resources and construction and demolition waste, pushing towards a circular economy. These are some interesting aspects that needs to be investigated in a future research project.

5 Framework and data

Figure 4 shows the methodological framework, described in Peñaloza et al. (2018), used to estimate the material flow and global warming potential (by quantifying GHG emissions) of the new buildings constructed in Norway until 2100. The core of the modelling framework consists of a combination of (i) a scenario-based building stock model based on the future projection of heated floor area (HFA) and building typologies, and (ii) life cycle assessment (LCA) data on different construction materials. The framework is used to investigate the amount of BioZement that could be used in the residential building sector and the GHG mitigation potential by comparing it with the use of “conservative” and “optimistic” concrete (see section 3.1 for a description of the different concrete types). BioZement is assumed to have the technical properties to substitute concrete for foundation, outdoors, and pre-cast concrete (see section 3 and 4) in the different building typologies.

The scenario comparison considers the GHG emissions from the construction materials in the buildings and the carbonation effect for concrete products but excluding other information in the use phase of the buildings. This is excluded because it is assumed that the energy required during the lifetime of the building is rather similar for the different scenarios (Peñaloza et al., 2018). The model in Peñaloza et al. (2018) is relevant for Sweden and it has been updated to be representative for Norway.

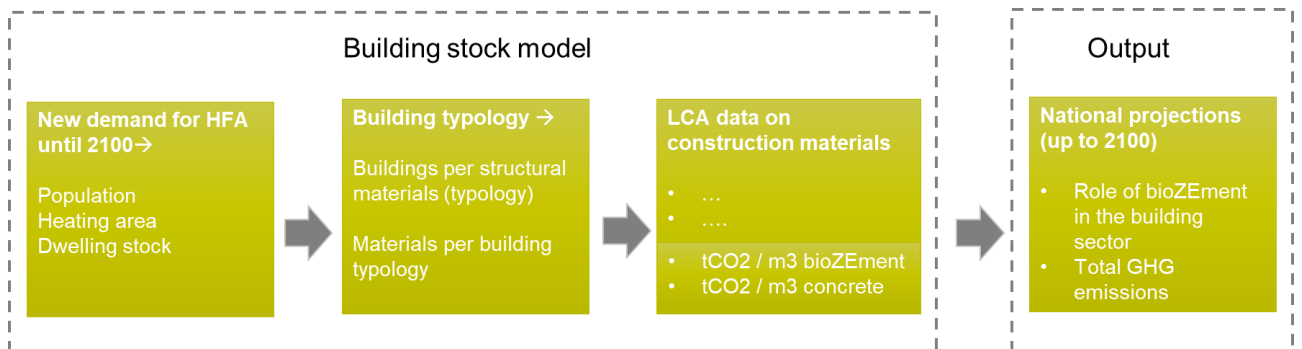


Figure 4 Methodological framework used in the analysis, adapted from Peñaloza et al. (2018)

5.1 Framework: The building stock model

The building stock model (Peñaloza et al., 2018) is used to estimate the material flow and associated GHG emissions for new buildings in Norway. It is based on the yearly demand for new HFA, which is combined with data on building typologies, and materials per building typology, to investigate the amount of materials over time. Such data is later coupled with LCA data on GHG emissions per material unit to quantify the emissions for the new dwellings and in each scenario (see Section 5.3 for the scenarios description).

5.1.1 Estimating the demand for new heated floor area over time

Future projections for the demand for new HFA per year is quantified from future population (Figure 5a) and total HFA in Norway (Figure 5b).

Historical and future projection on population is obtained from SSB (2018) until 2100. The medium scenario has been selected regarding fertility, life expectancy, internal migration, and immigration. By 2100, the forecast is that Norway will have approximately 7.3 million inhabitants, a 37 % increase with regards to the 5.3 million inhabitants Norway has today, see Figure 5a.

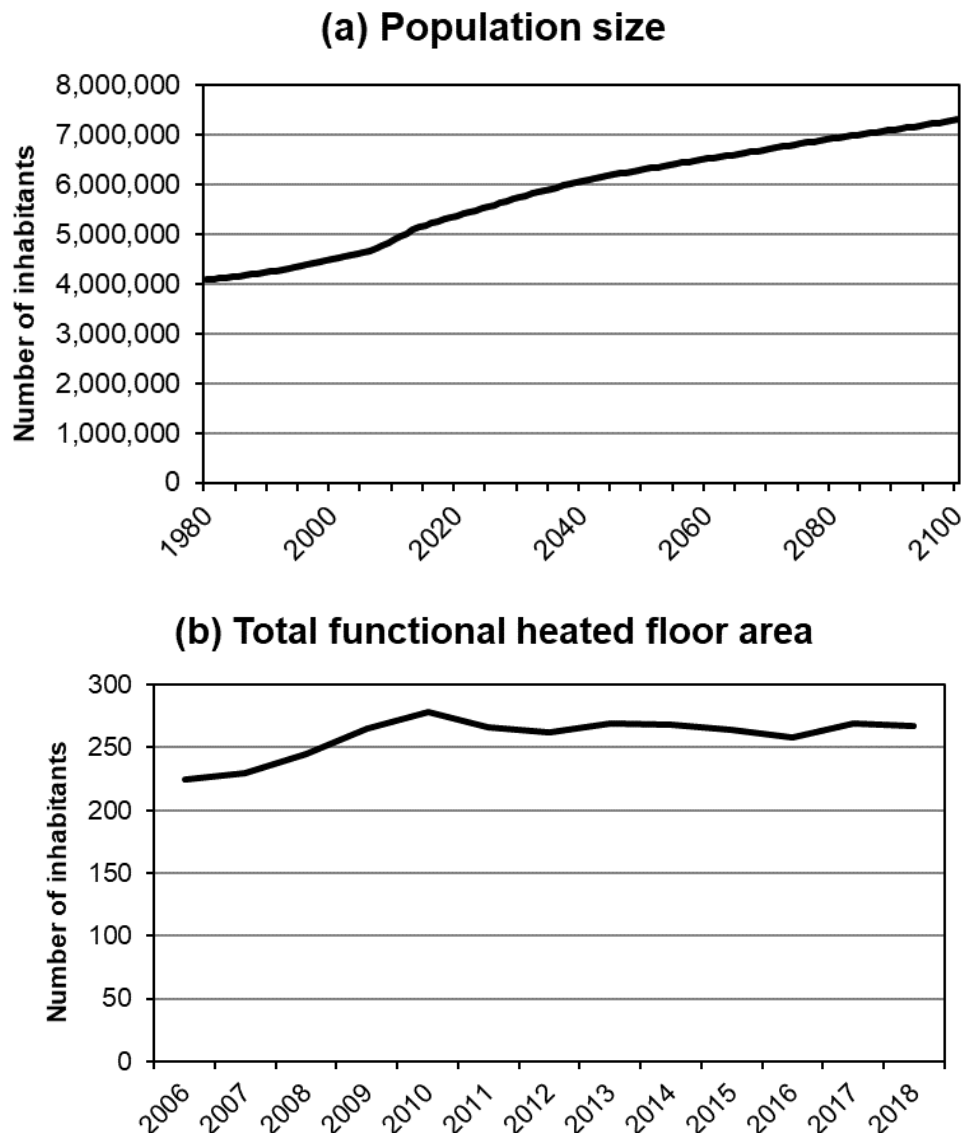


Figure 5 (a) Historical and future projection on population size in Norway available on SSB (2018); and (b) historical total HFA estimated from the utility floor area per dwelling, the number of dwellings, and a conversion factor from utility floor to heated floor area.

Information on HFA is not available on the Norwegian statistics, and the historical data in (Figure 5b) is calculated from (i) the utility floor area per dwelling (SSB, 2019a), (ii)

multiplied by the dwelling stock (SSB, 2019b) in Figure 6, and (iii) multiplied by a factor of 0.85 to convert from utility floor area to HFA (Sandberg et al, 2017). In this way, a historical series of the total HFA for the building stock is obtained for the last 13 years. The yearly HFA per inhabitant is estimated by dividing yearly total HFA by the future population, resulting in a yearly average decline rate for HFA per inhabitant of 0.19%. Such a declining rate is used to forecast future projections assuming the same development over time. From the projection on yearly HFA per inhabitant, the yearly HFA is estimated until 2100 and this data is used to calculate the new yearly demand for HFA in Figure 7.

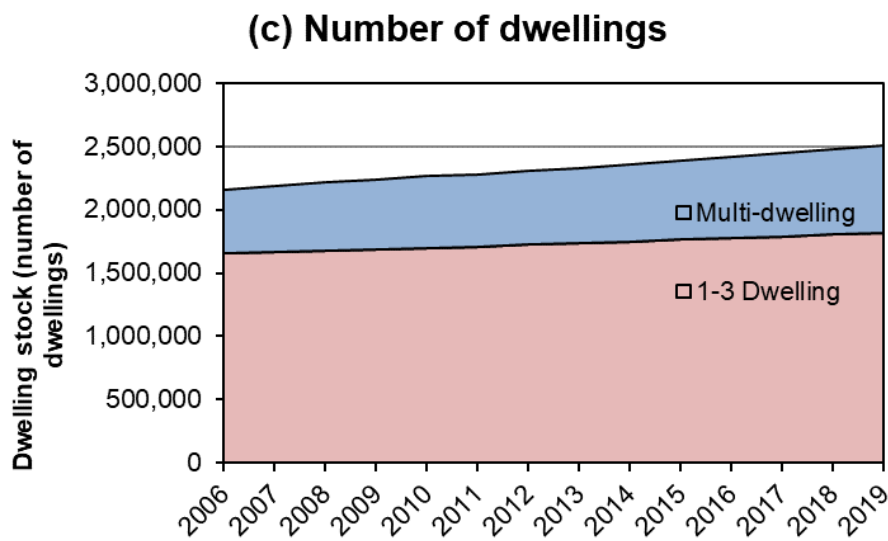


Figure 6 Number of dwellings, including multi-family dwelling and 1-3 single family dwelling, available on SSB (2019b)

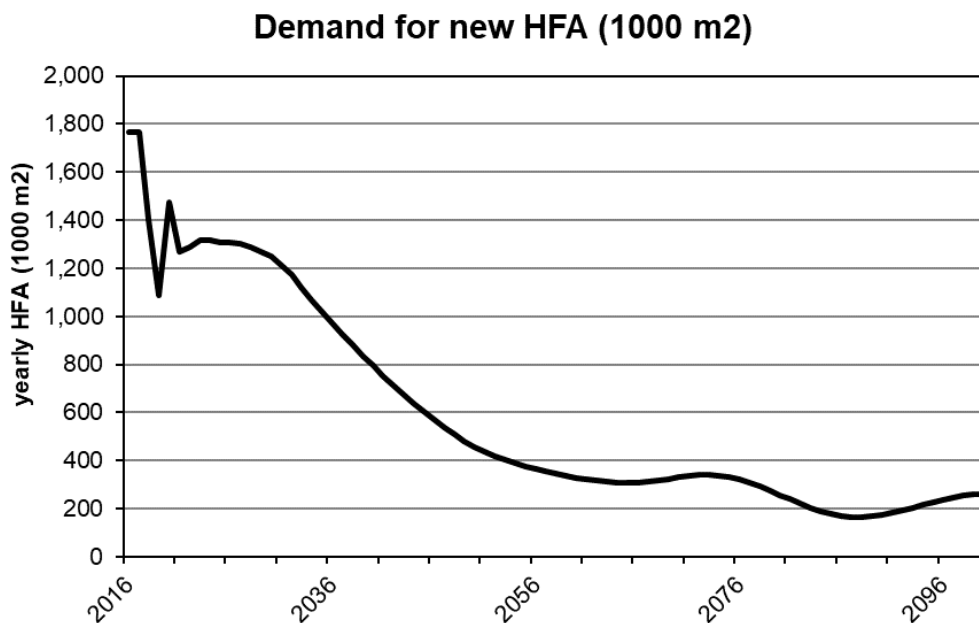


Figure 7 Estimated projections on yearly demand for new HFA up to 2100.

5.1.2 Estimating material flows

The material flow associated with the new dwellings that satisfy the demand for new HFA, depends mainly on the construction system of the dwellings. It is therefore important to define the building typologies, and to estimate the demand for HFA per dwelling typology and the materials required per HFA and dwelling typology.

Firstly, the dwelling typologies are established following Peñaloza et al. (2018) and based on the building size, concept, and materials. The typologies included depend on the availability of data for building typologies and on LCA data on the materials for each typology. The building typologies included in this study are (see Table 3 for a more detailed description and for references with information on the materials per typology):

- Single family dwellings (1–3 family dwelling)
- Multi-family dwelling
 - Timber-based multi-family dwellings
 - Prefabricated volume elements
 - Massive elements
 - Column-beam
 - Concrete structure multi-family dwellings
 - On-site casted
 - VST
 - Low-impact concrete
 - Steel structure

Table 3 Dwelling typology used in this study. Table adapted from Table 1 in Peñaloza et al. (2018).

<i>Typology</i>	<i>Short description</i>	<i>LCA data reference</i>
1-3 family house	2-storey house considered representative for Nordic single houses.	Dokka et al. (2013)
Prefabricated volume elements	Modular prefabricated volume elements transported and mounted at the site.	Peñaloza et al., 2013
Massive elements, CLT	Massive timber CLT element structure	
Column-beam, LVL	Structure of LVL and glulam beams and columns, including a concrete staircase.	
Traditional on-site casted concrete	Modern ZEB building design.	Sinha et al. (2016)
VST concrete system	Prefabricated remaining formwork with in-situ casted concrete	Liljeström et al., 2015

<i>Typology</i>	<i>Short description</i>	<i>LCA data reference</i>
Low-impact concrete	A concrete building type with several climate mitigation strategies implemented.	Kurkinen et al., 2015
Steel	Due to the lack of studies in Nordic countries, a case study from China was used as proxy.	Su and Zhang, 2016

Secondly, the demand for new HFA per building typology is estimated over time. Figure 6 shows the distribution and evolution of single- and multi-dwelling for 2006-2019. Such historical data is obtained from SSB (2019b). Based on the historical data, it is estimated that the share of single-family dwelling decreases by 0.3% every year, which is used to forecast the distribution between single and multi-family dwellings over the next 100 years. As of today, around 75% of the dwellings are single-family dwellings and these are assumed to be wooded frame (Peñaloza et al., 2018).

Contrarily, multi-family dwellings could be wooded, concrete, or steel frame (see Table 3). The market share of each multi-family dwelling typology and its development over time has been assumed following Peñaloza et al., (2018), see Figure a. In 2019, the market share of the different building typologies corresponds to: 9.3% timber frame, 88.9% concrete frame, and 1.2% steel frame. From the historical data, it was estimated that the timber frame multi-family dwellings will increase by 0.19 % every year, the concrete frame typology will decrease by 0.19%, while the steel frame buildings will remain rather constant over time.

The different construction types of timber multi-family dwellings (i.e., prefabricated volume elements, massive elements, and column-beam) are assumed to have equal market shares. Similarly, the two types of concrete multi-family dwellings (on-site casted and VST) also share the market equally, while the type “low-impact concrete” is assumed to be an alternative future option for climate change mitigation and to substitute both types of concrete multi-family dwelling at a 2% rate (Peñaloza et al., 2018).

Finally, inventory data from LCA studies on buildings typologies (in references in Table 3) is used to quantify the material flow per HFA for each building typology, see Peñaloza et al. (2018) for further information.

5.1.3 Estimating emissions from the demand for new buildings

Once the amount of materials required per unit of HFA per building typology is estimated, the yearly GHG emissions associated with the new buildings are obtained by applying LCA data for all the materials per building and by considering the total demand for HFA. The LCA data for GHG emissions per material unit is mainly obtained from Peñaloza et al. (2018), originally from commercial databases, Environmental Product Declarations, and other LCA studies. The data for GHG emissions for BioZement and the different types of concrete are updated and explained in Section 5.2.1 and 5.2.2, respectively. The GHG emissions included in the analysis correspond to the emissions

from the material manufacturing, energy supply for material manufacturing, building construction, and waste management.

Temporal changes in GHG emissions from the construction materials are considered by assuming that the energy supply is being decarbonized according to the Norwegian target of reducing GHG emissions by 40 % in 2030 and becoming a “low carbon society” in 2050 (Nordic Energy Research, 2019). These temporal dynamics are accounted for by estimating the share of the total emissions from energy supply over the total production emissions and by applying the corresponding yearly emission reduction assuming a linear rate until the target year.

Temporal changes in GHG emissions for BioZement and concrete are explained in Section 5.2.1 and 5.2.2, respectively. In addition to emissions for the manufacturing of material, concrete is also associated with a CO₂ uptake due to carbonation. This phenomenon occurs when concrete is exposed to air during its lifetime and end-of-life phase. According to Kurkinnen et al. (2017), a 6 % of the CO₂ emissions released via calcination during the cement production can be re-absorbed during the lifetime of the building. Such uptake was distributed during the 60 years of service life of the building. The carbon uptake that occurs when the building is demolished was not included in this analysis due to being outside the system boundaries of the study (Peñaloza et al., 2018).

5.2 Data and assumptions for BioZement and Concrete

This section presents the LCA data for bioZement and concrete, assuming that both can be used for the same applications. The comparison of concrete with BioZement is based on the assumption that BioZement will have the same properties as concrete. In the building stock model, it is assumed that the amount and type of reinforcement is the same for both concrete and BioZement. This enables to understand the influence of the new material on the climate impact of new buildings in Norway. At this stage of the material development it is also reasoned that a simplified model is preferable as the future properties of BioZement are not known (see section 4 for further information on BioZement properties). However, some assumptions need to be made at this stage and one essential is that the BioZement will have a density close to the one of concrete, i.e. 2350 kg/m³ meaning that 1 m³ concrete is replaced by 1 m³ BioZement.

5.2.1 Data for BioZement

The environmental impact for BioZement on a product level was assessed with LCA. An initial LCA of the BioZement product was conducted in the BioZement 1.0 project and is presented in a stand-alone report (Røyne 2017). The functional unit is 1 ton of BioZement, and the system boundaries are cradle-to-gate, meaning that they exclude use phase and waste management of the BioZement at end-of-life. Data sources and methodological procedures are described in Røyne (2017). Changes made since then are

described in Myhr et al. (2019). The BioZement recipe that the LCA results in BioZement 2.0 build upon are presented in Table 4.

Table 4 Inventory data for the production of 1 ton of BioZement.

Material and energy inputs to the BioZement production process	Amount	Assumption for amounts
Limestone	150 kg	10-20% should be precipitated, which means that 100-200 kg of limestone should be dissolved
Sand	850 kg	Estimated by project group
Urea (in bacteria medium)	2.8-4.2 kg	Estimated by project group. Adjusted upwards in 2018.
Glucose (in bacteria medium)	1-2 kg	Estimated by project group
Yeast extract (in bacteria medium), dry matter	0.03-0.07 kg	Estimated by project group
Peptone (in bacteria medium)	0.1-0.2 kg	Estimated by project group
Salt (in bacteria medium)	0.1-0.2 kg	Estimated by project group
Bacterial mass, dry matter	0.003 kg	Estimated by project group
Water	-	Not accounted for because of high uncertainty. Included in sensitivity analysis in Røyne (2017).
Oil	-	Excluded since insignificant amount
Cleaner Fluid	-	Excluded since insignificant amount
Electricity	5 kWh	As referred to conventional concrete (Skanska 2007, Thomas Bygg 2007).
Outputs from the BioZement production process	Amount	Assumption for amounts
Biogenic CO ₂ (from the fermentation of glucose conducted by bacteria)	14.7-29.3 kg	Estimated by project group
Fossil CO ₂ (from the hydrogenation of urea conducted by bacteria)	2.05-93.08 kg	Estimated by project group. Adjusted downwards in 2018, with the estimation "one mole of hydrolysed urea results in two moles of CO ₂ "

Material and energy inputs to the BioZement production process	Amount	Assumption for amounts
Ammonia	0.08-0.25 kg	Estimated by project group

A large proportion of the global warming potential from BioZement production is represented by the production of urea used in the BioZement production process (28-34 % of total global warming potential), and the release of fossil CO₂ from the hydrogenation hydrolysis of urea (one mole of hydrolyzed urea results in two moles of CO₂) (14-16% of total global warming potential).

The high global warming potential from the production process is much due to the energy intensive process (most commonly using fossil fuel). The global warming potential from the CO₂ release from hydrogenation is due to the feedstock for the urea most commonly being fossil hydrocarbon-based hydrogen (Bicer et al 2016). There are thus two factors that could potentially lower the global warming potential drastically – using renewable energy sources and using renewable sources for hydrogen production.

Emissions from urea production are dominated by CO₂ emitted during the ammonia synthesis (Wood et al. 2004). Singh et al. (2018) evaluated different ammonia production methods using life cycle assessment and found that the conventional steam methane reformation and coal gasification process global warming potential could be reduced with about 90 % using innovative processes like biomass gasification.

Based on these sources we assume that the global warming potential from urea production over time can be reduced with 90 %, when new renewable and biobased techniques are developed and introduced on the market. Based on the potential of using biobased feedstock we also assume that the CO₂ release from hydrogenation in the BioZement production process will be biogenic and thereby climate neutral (based on a carbon neutrality assumption, where emitted CO₂ is sequestered by growing plants. Whether carbon neutrality can be translated into climate neutrality has been debated. This is not further discussed in this report but should be kept in mind by the reader).

The environmental impact of BioZement can be expressed in four different figures (see Table 5). Two of them are the maximum and minimum levels with today's circumstances, and the third and fourth are the maximum and minimum levels for a future assumption of decreased impact from urea production. For the third and fourth figures, only global warming potential is presented, as the consequences for other impact categories of an innovative urea production process have not been assessed.

Table 5 Environmental impact of 1 ton of BioZEment under four different circumstances, assessed with LCA.

Environmental impact category (per ton BioZEment)	BioZEment lowest estimate	BioZEment highest estimate	Future BioZEment lowest estimate (novel urea production process)	Future BioZEment highest estimate (novel urea production process)
Global warming potential (kg CO ₂ -eq.)	1,25E+01	2,26E+01	6,60E+00	1,37EE+01
Ozone Layer Depletion Potential (kg R11-eq.)	1,00E-06	1,40E-06	-	-
Acidification potential (kg SO ₂ eq.)	1,76E-01	4,78E-01	-	-
Eutrophication potential (kg PO ₄ eq.)	4,22E-02	1,11E-01	-	-
Land use (occupation of sqm/year)	1,87E+00	2,98E+00	-	-

In the BioZEment 1.0 project, it was identified that ammonia emissions from BioZEment production could cause high levels of acidification and eutrophication (Røyne 2017). Therefore, ammonia capture and recycling will be considered in the further development of BioZEment. Ammonia capture and recycling has been demonstrated in other bio-cementation efforts (BioMASON 2016).

For reinforcing BioZEment constructions the same reinforcement type is used as for concrete. Further details are described in section 5.2.2.

5.2.2 Data for other concrete types

The LCA of the conventional concrete is based on EN 15804 “Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products”. This is an attributional LCA, which is the same method used to calculate the global warming potential of the BioZEment product. As for the BioZEment, only the production stage is accounted for and includes raw material extraction, transport to factory and energy use and emissions at factory.

Three types of concrete were used for the prospective LCA model of the building stock in Norway. Concrete for foundations, precast concrete and ready-mixed concrete. The LCA data are average data based on the Swedish market, which is assumed to be similar to

the Norwegian market. The different concrete types and their associated global warming potential are shown in Table 6.

Table 6 Global warming potential (GWP) of different concrete types.

Concrete type	Strength and w/c	Unit	GWP [kg CO ₂ -eq]	Reference	Comment
Foundation concrete	C32/40	1 m ³	362	EPD no. NEPD-1708-694-SE	
<i>ready mix concrete</i>					
floor slab	C30/37, w/c 0,50	1 m ³	251	EPD no. NEPD-1296-419-SE	average based on info from svensk betong members
exterior wall	C28/35-C30/37, w/c 0,55	1 m ³	244	EPD no. NEPD-1295-419-SE	average based on info from svensk betong members
floor slab or interior wall, green	C25/30, w/c 0,63	1 m ³	218	EPD no. NEPD-1297-419	average based on info from svensk betong members
average ready mix concrete		1 m ³	244		60%slab, 22%exterior wall, 18%interior wall
<i>precast concrete</i>					
Hollow core slab	C40/50-C50/60, w/c 0,40	1 m ³	258	EPD no. NEPD-1298-419	average based on info from svensk betong members
sandwich	C30/37, w/c 0,49	1 m ³	270	EPD no. NEPD-1299-419	average based on info from svensk betong members
interior wall	C30/37, w/c 0,49	1 m ³	270	EPD no. NEPD-1299-419	assume the same as sandwich
average precast concrete		1 m ³	263		
<i>Average concrete both ready mix and precast</i>					
Slab	w/c 0,45	1 m ³	305	(Svensk Betong 2019)	The lower co2 value
exterior wall	w/c 0,55	1 m ³	270	(Svensk Betong 2019)	
interior wall	w/c 0,55	1 m ³	255	(Svensk Betong 2019)	
average concrete		1 m ³	288		

The highlighted average for the concrete types has been used in the building stock model.

In order to estimate the change in global warming potential of concrete production over time, the two scenarios “conservative” and “optimistic” were used as described in section 3.1.

It should be noted that the changes are based on GHG reduction measures for the cement. Other measures to reduce the GHG of concrete, such as design mix optimization, concrete volume reduction in relation to properties and alternative binder components, which have been mentioned in section 3.1, are not included. CO₂ uptake due to carbonation is not included in Table 7 as only emissions from the production phase are included. CO₂ uptake due to carbonation is explained in section 5.1.3.

Future global warming potential of concrete was estimated based on the values of CEMBUREU and the reference values for concrete in Figure 1 and Figure 2. Table 7 shows the global warming potential of the reference concrete and the future concrete, based on the two scenarios. It is assumed that the cement accounts for approximately 94 % of the total GHG emissions.

Table 7 Conservative and optimistic CO₂ reductions for concrete used in the analysis.

Conservative	unit	kg CO₂-eq Today	kg CO₂-eq Tomorrow	percent decrease
Cement used in buildings	tonne	0,674	0,53	21%
Concrete for foundation	1 m3	362	302	17%
average ready-mix concrete	1 m3	244	203	17%
average precast concrete	1 m3	263	219	17%
average concrete	1 m3	288	240	17%

Optimistic	unit	kg CO₂-eq Today	kg CO₂-eq Tomorrow	percent decrease
Cement used in buildings	tonne	0,674	0,156	77%
Concrete for foundation	1 m3	362	89	75%
average ready-mix concrete	1 m3	244	60	75%
average precast concrete	1 m3	263	64	75%
average concrete	1 m3	288	71	75%

The calculated emissions are based on concrete without reinforcement. For the reinforcement it is assumed that the reference steel type is a global average with a global warming potential of 2093 kg CO₂-eq/tonne (Wernet et al. 2016). For the future scenario it is assumed that all reinforcement has reached a value of 360 kg CO₂-eq/tonne, which is equal to a type of reinforcement made in electric arc furnace from Celsa, used here as an example of low-CO₂ reinforcement (EPD no. NEPD-434-305-EN).

5.3 Future scenarios

Two sets of two scenarios are presented, representing two different dimensions: (i) whether concrete (Baseline) or BioZement (BioZement) is being used in the new buildings, and (ii) whether a more conservative or optimistic development of the cement

industry is assumed with regard to abating GHG emissions (conservative VS optimistic concrete).

The **Baseline** scenarios represent the evolution of the buildings stock as presented in Figure 8a, either with conservative or optimistic concrete in all the building typologies. In these scenarios, the typology “low-impact concrete” are assumed to substitute concrete multi-family dwelling at a 2 % rate based on Peñaloza et al. (2018). The **BioZement** scenarios represent the evolution of the buildings stock as presented in Figure 8b, where BioZement is introduced progressively in new buildings instead of conventional concrete (conservative concrete or optimistic concrete). The BioZement implementation rate is assumed to be the same as “low-impact concrete dwellings”; 2 %.

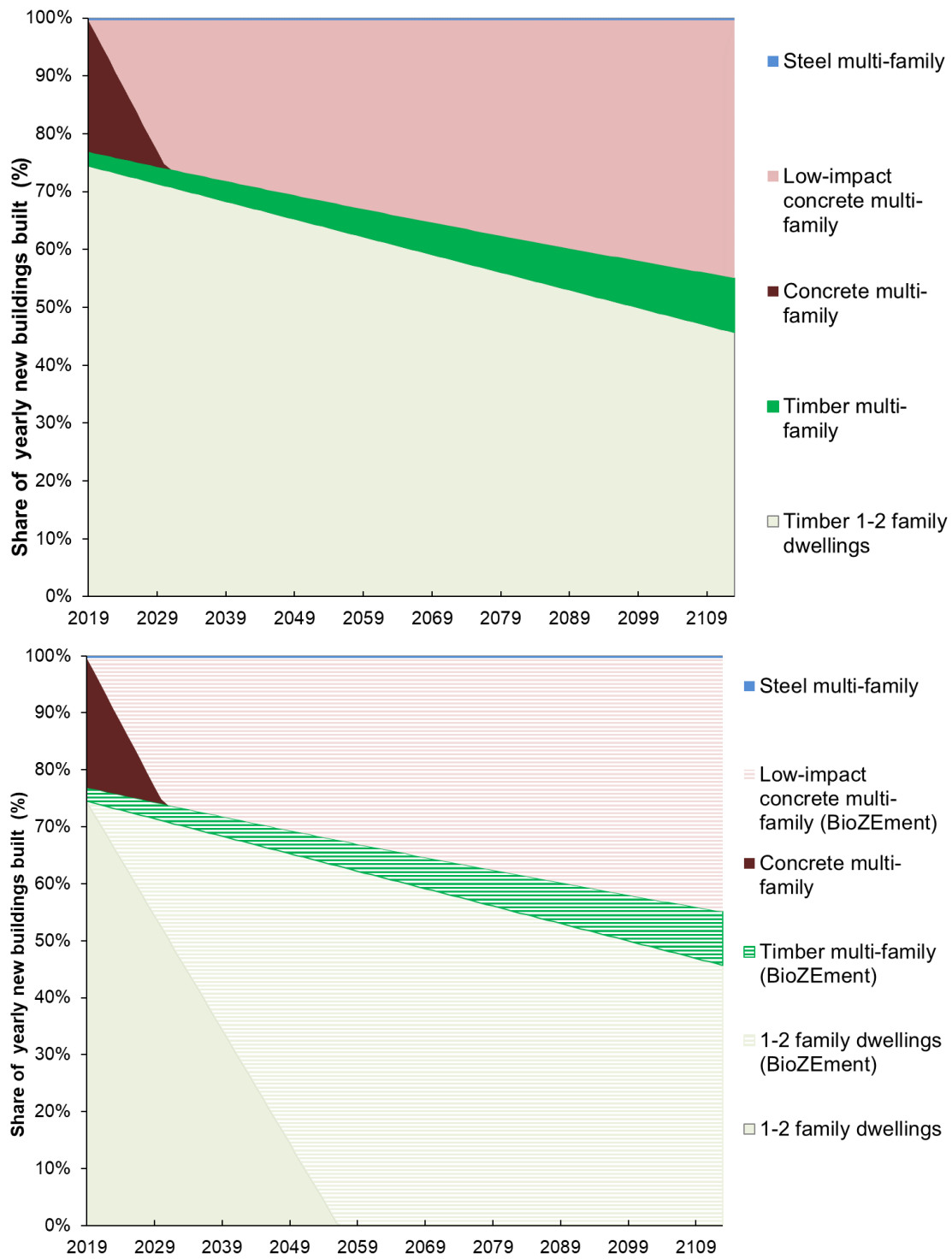


Figure 8 Market share of yearly new buildings constructed over 100 years, including building type and structural material in (a) baseline scenarios and (b) BioZement scenarios, representing the same situation as baseline where BioZement is penetrating the market at a 2 % rate in the single dwelling buildings and multi-dwelling concrete building. In the rest of the buildings, BioZement is assumed to penetrate the market from year 1. BioZement is only used to substitute concrete elements in the different building typologies and its implementation is represented by the hatched area.

For the rest of the materials (including reinforcement) and as explained before, the GHG emissions associated with energy supply are assumed to decrease based on the Norwegian climate targets. The climate target could, however, be tightened up or not met. Such a change would affect all the scenarios equally, involving the total scenario emissions, but not the conclusions on the mitigation potential of BioZement VS concrete resulting from the comparison of scenarios.

6 Results: Building stock level comparison

Results are based on the investigated scenarios (i) whether concrete (Baseline) or BioZement (BioZement) is being used in the new buildings, and (ii) whether a more conservative or optimistic development of the cement industry is assumed with regards to abating GHG emissions.

6.1 Conservative development of concrete VS BioZement

Figure 9 shows the total GHG emissions over 100 years for the Baseline and BioZement scenarios when a conservative development of the cement industry is assumed. In both scenarios, the emissions decrease drastically due to (i) the assumed decarbonization of the energy sector by 2030-2050, which reduces emissions intensity per material used and per building; and (ii) the decreasing demand for HFA every year (see Figure 7). The total HFA increases over time but the yearly demand for new construction decreases over time.

Figure 9 also illustrates that using BioZement instead of conservative concrete (in foundation, onsite and precast concrete) will reduce GHG emissions further. The current GHG emission intensity of BioZement is approximately 6-12¹ times lower than concrete and this difference increases over time (8-16 times) as GHG emissions from BioZement production are reduced at a higher rate than emissions from the cement production for conventional concrete. Using BioZement in the future building stock can decrease emissions by 24-28 % around 2060 and onwards compared to using conservative concrete with a conservative development. The emission reduction difference slightly decreases by the end of the century as carbon capture by carbonation in concrete is enhancing its effect.

¹ The range of 6-12 times illustrates the uncertainty range in GHG emissions from BioZement.

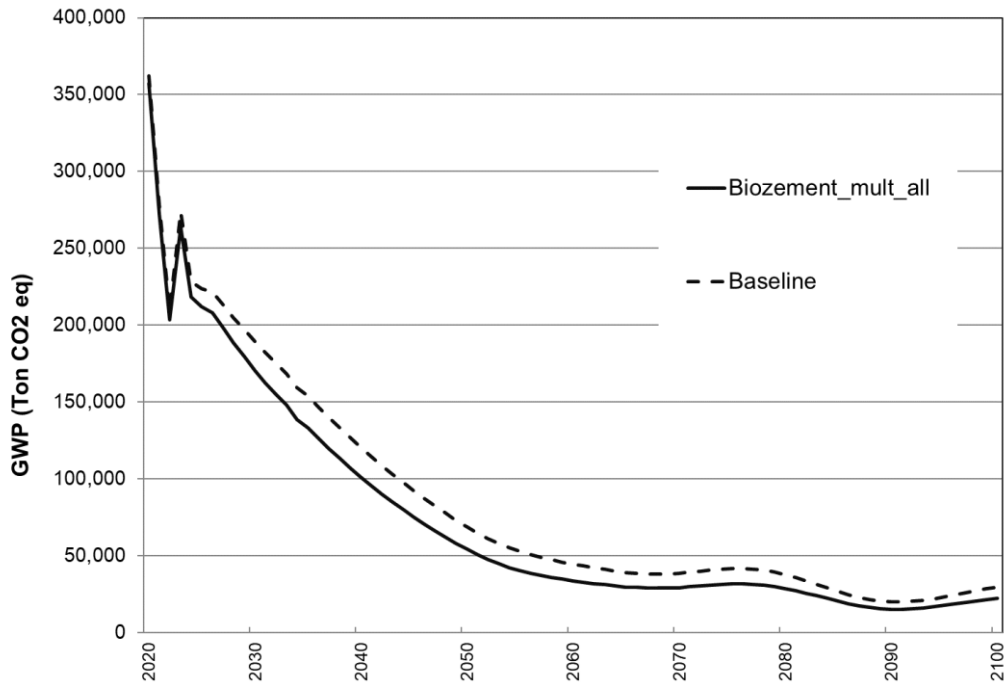


Figure 9 Global warming potential (Ton CO₂-eq) over 100 years for the Baseline and BioZement scenario when BioZement is assumed to displace conservative concrete.

Figure 10 shows the cumulative GHG emissions from the production of new residential buildings throughout this century. The cumulative GHG emissions show that the difference between using BioZement and conservative concrete is quite significant. About 0.13-0.15 million-ton CO₂-eq, 0.5-0.56 million-ton CO₂-eq, and 0.9-1.1 million-ton CO₂-eq (5-6 %, 10-11 % and 14-16 % of total cumulative emissions) can be saved by 2030, 2050, and 2100, respectively, if BioZement is used to substitute precast concrete, onsite concrete, and foundation, as well as it can be fully introduced by 2050 in all residential buildings. The emission-savings range corresponds to the assessed range of emissions intensity for BioZement (0.01-0.02 kg CO₂/ kg BioZement, see section 5.2.1). A large range of uncertainty regarding emissions intensity of BioZement (100 % difference), does not result in a large impact on the total emissions for the future building stock as BioZement emissions represents a small share of the total emissions per building. Consequently, the conclusions regarding the mitigation potential of BioZement VS concrete still hold. Different assumptions on market penetration or on concrete applications being displaced by BioZement will lead to different results.

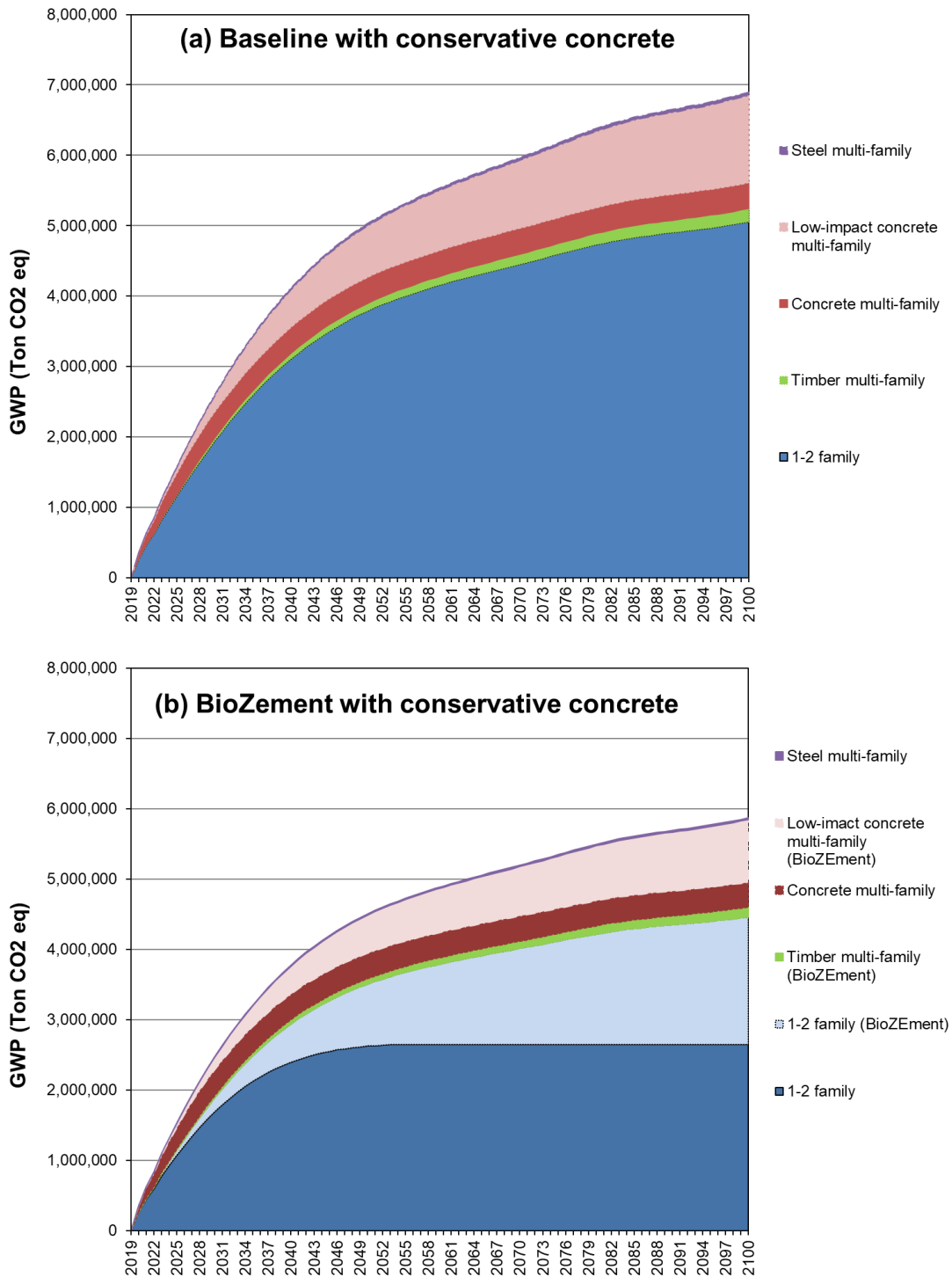


Figure 105 Cumulative global warming potential (Ton CO₂-eq) over 100 years for the (a) Baseline and (b) BioZement scenario where BioZement is assumed to displace conservative concrete.

6.2 Optimistic development of concrete VS BioZement

Figure 11 shows the total GHG emissions over 100 years for the Baseline and BioZement scenarios when an optimistic development of the cement industry (optimistic concrete) is assumed. In this set of scenarios, the GHG emission intensity of BioZement is

approximately 6-12 times lower than concrete as of today but this difference is reduced to 2.4-4.8 by 2030 as the cement industry is assumed to introduce CCS. Thus, in both scenarios, Baseline and BioZement, the emissions from concrete decrease faster than in scenarios where a more conservative development is assumed. Still using BioZement instead of concrete and regardless of the development of the cement industry, performs better from an GHG emission perspective. Similarly to Figure 10, the difference in emissions between the Baseline and the BioZement scenario increases progressively up until 25-27 % around 2060 and decreases slightly by the end of the century, when the effect of carbonation in concrete in the baseline scenario is larger.



Figure 11 Global warming potential (Ton CO₂-eq) over 100 years for the Baseline with optimistic concrete and BioZement scenario when BioZement is assumed to displace optimistic concrete.

When looking at the cumulative emissions at 2100 in Figure 12 it is clear that using BioZement instead of optimistic concrete performs better as initial emissions associated with concrete are higher. Using BioZement instead of optimistic concrete will reduce cumulative GHG emissions by 0.11-0.12 million-ton CO₂-eq, 0.39-0.43 million-ton CO₂-eq, and 0.75-0.8 million-ton CO₂-eq (4-5 %, 9-10 % and 13-14 % of total cumulative emissions) by 2030, 2050, and 2100, respectively. Figure 12 also shows that in both scenarios the cumulative emissions are much lower when CCS is included than in Figure 10, which assumed a more conservative future for the cement and concrete industry. For instance, using BioZement to displace concrete with an optimistic development (Figure 12b) compared to displacing conservative concrete (Figure 10b), could decrease GHG emissions by 11%.

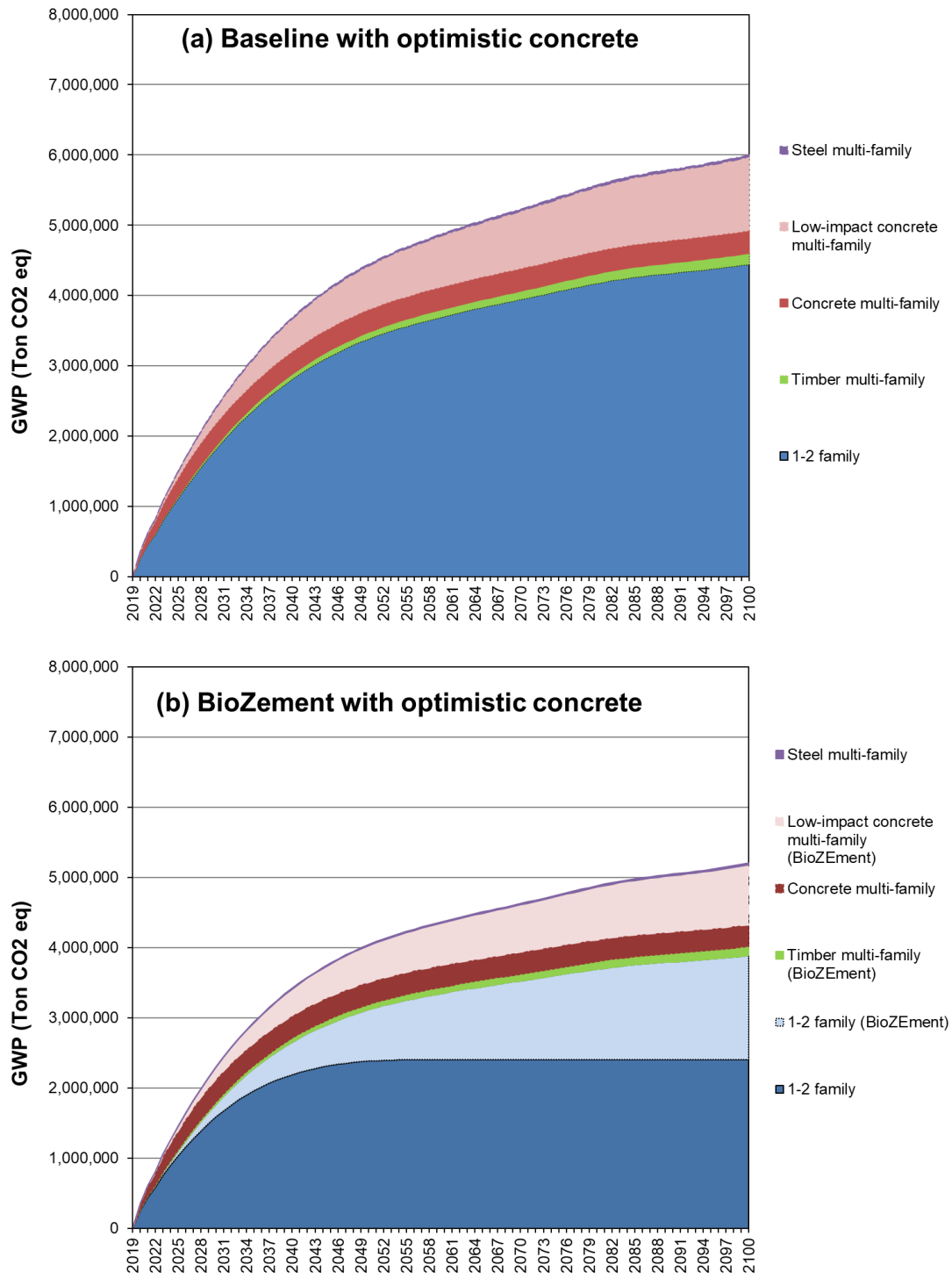


Figure 12 Cumulative global warming potential (Ton CO₂-eq) over 100 years for the (a) Baseline with optimistic concrete and (b) BioZement scenario where BioZement is assumed to displace optimistic concrete.

7 Conclusions

The aim of the presented study has been to strengthen the outlook of the BioZement product, by assessing its environmental mitigation potential. This was done through assessing the environmental implications for the Norwegian building stock of a theoretical technology implementation of BioZement within the next 100 years, with different projections. The investigated scenarios were (i) either concrete (Baseline) or BioZement (BioZement) is being used in the new buildings, and (ii) either a more conservative or optimistic development of the cement industry is assumed with regard to abating GHG emissions.

Results indicate that the global warming potential will decrease over the years no matter which scenario is chosen - continuing to only use conventional concrete or introducing BioZement - due to the trend of reducing living space per inhabitant.

However, results also indicate that the use of BioZement has a higher potential of reducing global warming potential than conventional concrete, regardless of the development of the cement industry. BioZement could decrease cumulative greenhouse gas emissions with ca 15 % by 2100 compared to using conventional concrete with a conservative development, and slightly less, ca 13%, if compared to using concrete with an optimistic development (including among other initiatives breakthrough technologies like carbon capture and storage, and carbon capture and utilization). A rather similar percentage of emission reduction from using BioZement instead of conservative or optimistic concrete is due to the fact that in both concrete scenarios the initial emissions are rather similar and higher than final emissions, which has a big impact on the total cumulative emission calculation. The assessed advantage of BioZement is dependent on the material having the expected material properties, and on a full implementation in the new residential building stock by 2050 (assuming a 2 % yearly introduction rate). The analysis indicates that it is also important that the development is not taking too much time.

Another important finding is that, while BioZement is not fully implemented in the entire building stock, using the optimistic development concrete instead of conservative concrete provides the lowest cumulative emissions by 2100. For the building stock it is thus beneficial to assess a combination of efforts rather than only comparing isolated efforts with each other. Other important emission reduction factors, that are not connected to material choices, are the decarbonization of the energy sector and reducing the living space per inhabitant. Material choices are thus only one part of the puzzle in reducing the global warming potential of the building stock.

It must be mentioned that the results are dependent on many assumptions and uncertain parameters, as for example market introduction and application possibilities. Still, the building stock model provides intriguing indications about the potential of BioZement which can guide further development. If Norway is to meet its ambitious goals of emission reductions and climate neutrality, it is important to design thought through and robust strategies for the construction sector.

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