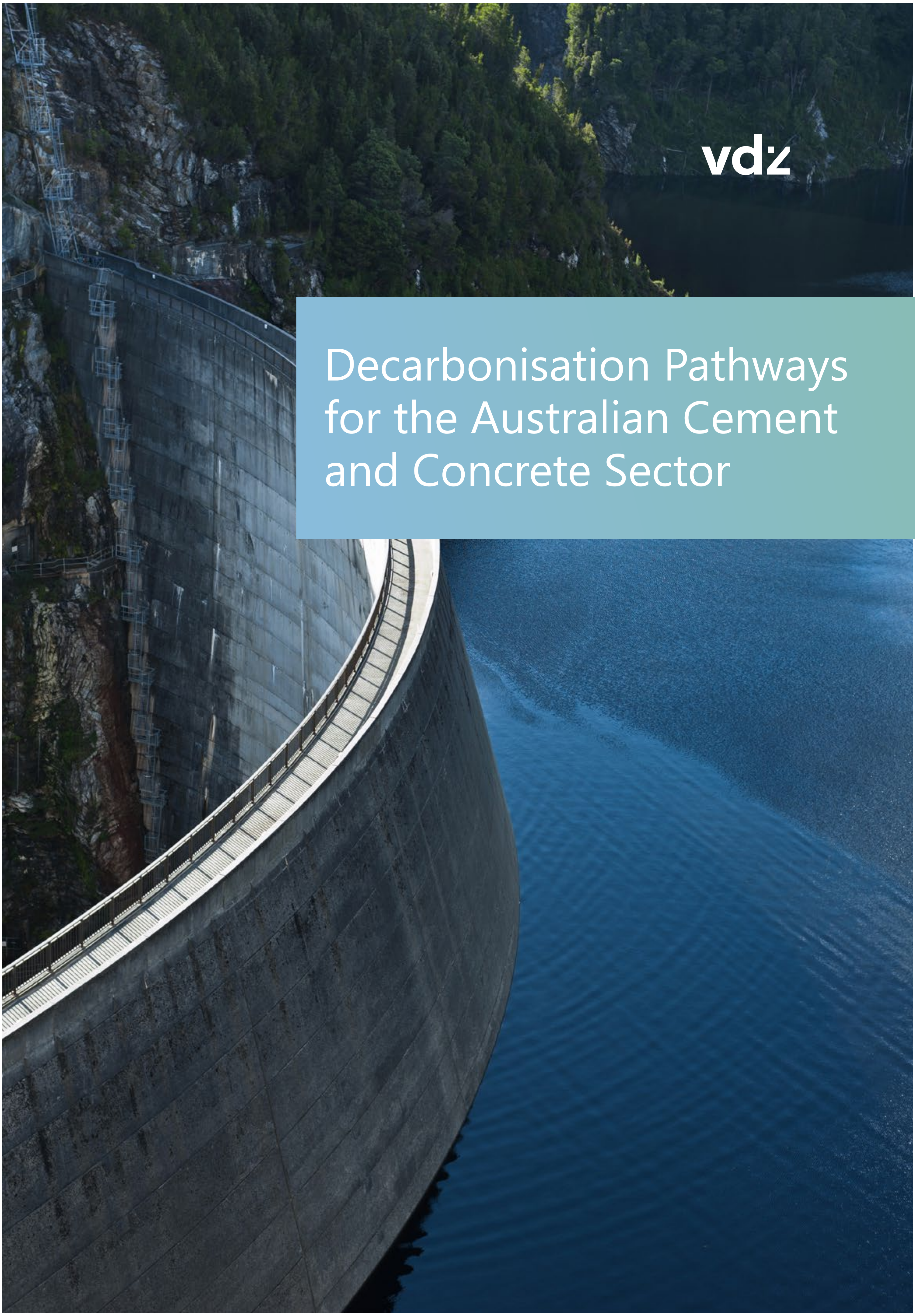

vdz

Decarbonisation Pathways for the Australian Cement and Concrete Sector

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1 Introduction

The **key purpose of this report** is to identify and communicate the critical pathways that will enable the cement and concrete sector value chain to continue to lower its CO_2 emissions and to decarbonise by 2050.

This **report has been developed by VDZ**, a world-renowned research centre, providing practical and quality-oriented joint research and services in the field of cement and concrete. VDZ has been commissioned to undertake this report based on its international credentials. VDZ has – for example – provided cement and concrete decarbonisation advice to the International Energy Agency, the World Business Council for Sustainable Development and the Global Cement and Concrete Association. VDZ employs over 100 research scientists, engineers and economists that are dedicated to international cement and concrete sector research and innovation.

The **Australian cement and concrete sector has a long history of reducing its CO_2 emissions** having delivered a 25 per cent reduction since 2000. The sector understands the challenge of decarbonising by 2050, which will require significant regulatory, technological, structural and behavioural changes across all segments of the cement and concrete value chain. It will also require cement and concrete customers, developers, designers, building material procurers, architects, standards authorities, government and non-government agencies, and concrete and cement manufacturers to work together closer than ever before.

The **development of interdependent engagement plans**, addressing the identified pathways in this report, will be an important next step. This will build on the past and current initiatives undertaken by the sector. For the industry to be successful in continuing to reduce its emissions, further R&D, investment and commitment from researchers, government and all stakeholders across the value chain will be crucial.

The **long term economic and societal benefits** of harnessing the identified decarbonisation pathways are clear, however, the investment requirements will be lumpy and significant. Financial and policy support will be essential to ensure the Australian cement and concrete sector remains sustainable during the transition. As a trade exposed sector, a fundamental requirement will be that the transition does not lead to undermining the competitiveness of the Australian cement and concrete manufacturing base and the thousands of jobs it supports.

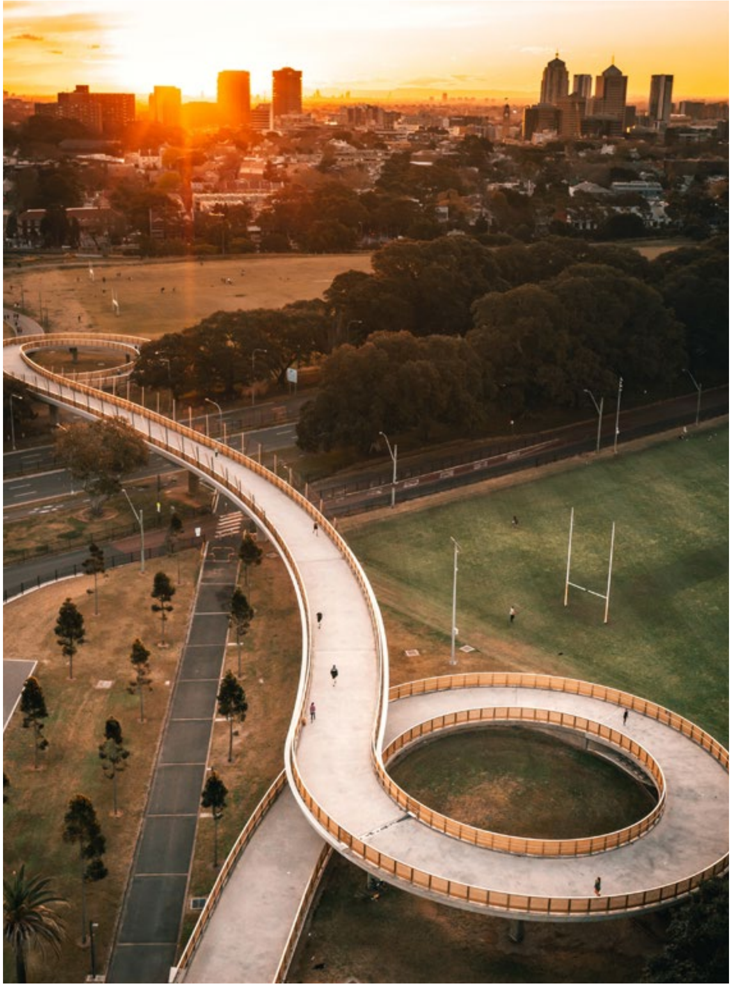
It is important to note that **this report does not propose targets for each identified pathway** – assumptions are

provided to demonstrate the important role the pathways can play across the Australian cement and concrete value chain based on the expert advice of VDZ.

A **review of the pathways is also recommended by VDZ at least every five years** to ensure new technologies and innovation, as well as regulatory and other changes, are included and current proposed pathways can be updated.

The set of interdependent pathways outlined by VDZ in this report demonstrates that **Australia can have a decarbonised cement and concrete sector** if all stakeholders harness the opportunity to continue to work cooperatively across the value chain developing and implementing the required engagement plans recommended in this report.

Financial and in-kind contributions have been provided by the Cement Industry Federation (CIF), Cement, Concrete and Aggregates Australia (CCAA), the SmartCrete CRC and the RACE for 2030 CRC to commision this indpendant report.



2 About this report

This report has been prepared by VDZ, an international research centre, providing practical and quality-oriented joint research and services in the field of cement and concrete. The brief provided to VDZ was to:

- Develop an independent Australian decarbonisation report for the sector to 2050;
- Include the whole value chain of cement and concrete;
- Identify key decarbonisation pathways for the sector; and
- Determine key R&D projects to support the findings of the report.

As a result, VDZ has prepared this report titled 'Decarbonisation Pathways for the Australian Cement and Concrete Sector' that can be used to inform the industry and other important stakeholders involved in the use of concrete as the final product, inform policy makers and guide future R&D partnership requirements across the value chain.

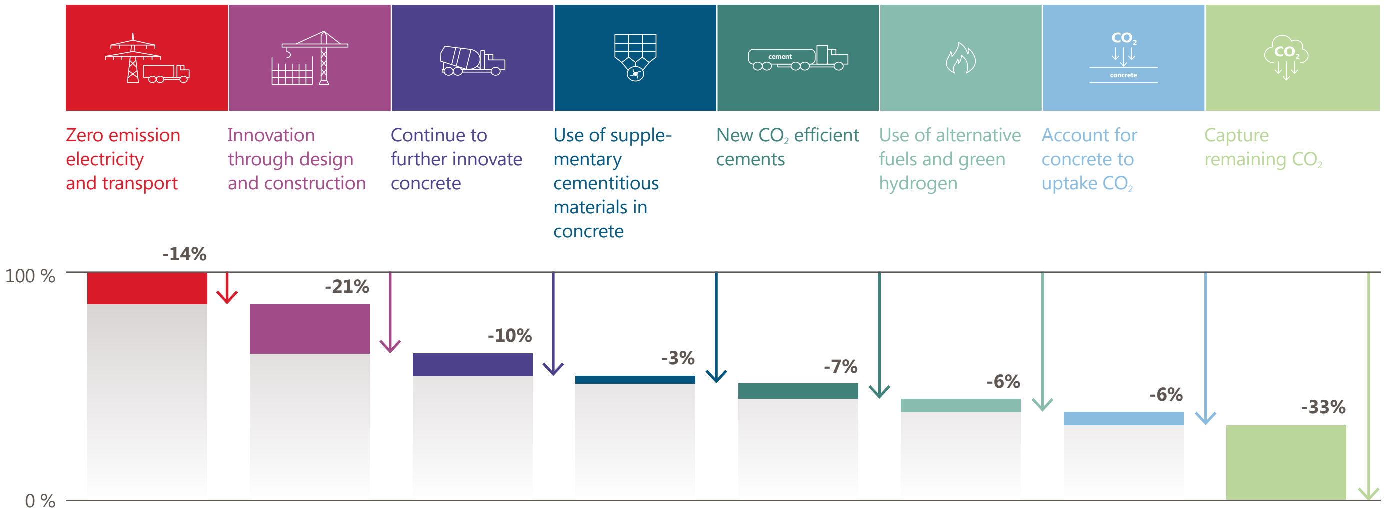
This report includes the following chapters:
Chapter 3 provides a short overview of the cement and concrete industry. **Chapter 4** highlights the challenges for a net zero CO_2 cement and concrete supply chain. **Chapter 5** describes the current Australian cement and concrete emissions profile. **Chapter 6** highlights technologies and innovations for net zero CO_2 in concrete construction. **Chapter 7** identifies and depicts the pathways to reduce CO_2 emissions for cement, concrete and the built environment. **Chapter 8** analyses the economic benefits and costs associated with the identified pathways to reduce emissions. **Chapter 9** presents future R&D priorities and project recommendations to support the implementation of the key identified pathways to reduce emissions.
Chapter 10 covers the prerequisites and boundary conditions for a successful industrial transformation.

A bibliography and glossary of terms can be found in **Chapter 11** and **Chapter 12** respectively, followed by a number of Annexes that provide further detail on carbon capture technologies, technology readiness levels (TRL) and thermal efficiency of clinker production.

In summary, VDZ identifies eight key pathways for the Australian cement and concrete sector to decarbonise by 2050 (see Figure 1):

- Zero emission electricity and transport;
- Innovation through design and construction;
- Continue to further innovate concrete;
- Use of supplementary cementitious materials in concrete;
- New CO_2-efficient cements;
- Use alternative fuels and green hydrogen;
- Account for concrete to take up CO_2;
- Capturing remaining CO_2.

Figure 1: Cement and concrete decarbonisation pathways – percentage CO_2 reductions 2020-2050



Cement and Concrete Decarbonisation Pathways

Zero emission electricity and transport

- Promoting methods to decarbonise Australia's electricity network, whilst ensuring it remains reliable and affordable.
- Sourcing price competitive renewable purchase agreements.
- Adopting energy efficiency measures – including artificial intelligence and sensors.
- Supporting and adopting competitive technologies and energy sources to decarbonise the transport sector.

Innovation through design and construction

- Promoting design of building and infrastructure that includes a clear focus on material efficiency, specifying lower carbon concrete and improved construction technologies.
- Ensuring structural optimisation that allows for lifetime extension, repair and reuse.

Continue to further innovate concrete

- Improving the mix design and mixing technology for concrete, e.g. packing density optimisation, optimised use of admixtures.
- Developing an appropriate balance between performance and prescriptive approach in standards and building codes to lower clinker content in concrete.
- Reducing volumes of fresh concrete waste.

Use of supplementary cementitious materials in concrete

- Ensuring the benefits of using SCMs in cement and concrete are understood and reflected in procurement strategies.
- Focussing strongly on embodied carbon in concrete construction to create a market pull for low CO_2 concretes.
- Changing standards and building codes to reflect the benefits of increased SCMs.

New CO_2 efficient cements

- Producing cements with higher content of SCMs like fly ash, GGBFS, calcined clay and unburned limestone.
- Further lowering the clinker factor in cement.
- Creating and obtaining acceptance of new innovative cements.
- Developing standards and application rules which will be required to reflect the benefits of CO_2 efficient cements and enable their use in concrete.

Use alternative fuels and green hydrogen

- Increasing the use of alternative fuels to replace coal and gas to heat the cement kiln.
- Using alternative fuels in cement kilns will also be beneficial for lowering the emissions from landfills, although transport costs can prevent the uptake of alternative fuels.
- Applying the required pre-processing technologies.
- Utilising green hydrogen as fuel to lower the amount of fossil fuels in clinker production – substitution rates greater than 10% will require further research.

Account for concrete to uptake CO_2

- The International Panel on Climate Change (IPCC) Draft Report (2021) notes concrete absorbs CO_2 emissions from the production of cement and concrete.
- Recarbonation occurs during the lifetime of the concrete structure and after the end of its life.

Capturing remaining CO_2

- Proposed mitigation measure for CO_2 emissions that cannot be mitigated by conventional means.
- Several technologies are currently in pilot and demonstration phase.
- Australia provides good conditions for CCS and CCUS.

3 The cement and concrete industry in Australia

There are currently five cement plants in Australia which produce clinker and cement in an integrated process. This domestically produced cement is delivered to the Australian market through distribution centres located across the country. Almost 60 per cent of the cement manufactured in Australia is produced in integrated manufacturing plants. About 40 per cent involves the use of clinker which is imported and manufactured into cement at grinding facilities located around Australia's coastline. Cement is also directly imported into Australia, averaging around 5-10 per cent of today's domestic cement production. Australian integrated clinker and cement production is currently highly trade exposed.

Over 97 per cent of Australian clinker is produced in energy and emission efficient calciner systems fuelled by coal and gas, which are partly replaced by alternative fuels derived from different waste streams, including biomass that would normally go to landfill.

Supplementary cementitious materials (SCMs) can partly replace clinker in cement or are used as additions in concrete. SCMs most commonly used in Australia are ground granulated blast furnace slag (GGBFS), fly ash from coal-fired power plants and limestone. These materials have a long tradition as cement or concrete constituents and, because of their chemical and mineralogical composition, these materials have a positive impact on some cement and concrete properties. SCMs are used in Australia today largely by way of direct addition to concrete mixes in concrete plants. An extended use of 'clinker efficient cements' containing higher proportions of SCMs would on the one hand take place in the context of this tradition. Ultimately, the partners in the value chain have to work together to determine how cement clinker can be used most effectively in the future.

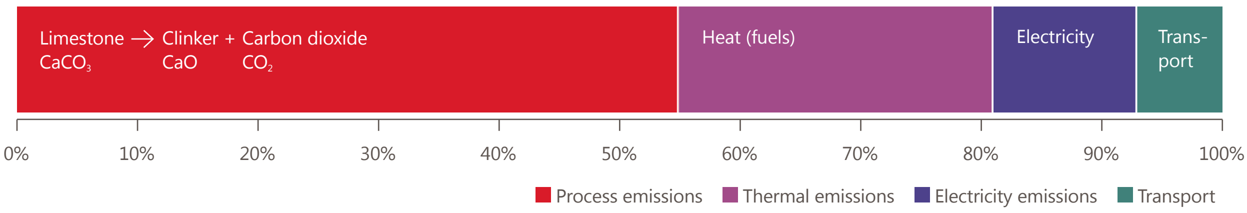
Clinker

The key constituent of cement is clinker which is produced under high temperatures in rotary kilns from locally sourced raw materials such as limestone and clay. Cement can also contain other supplementary materials such as fly ash, ground granulated blast furnace slag or unburnt limestone. An essential part of the production process is the cement mill in which clinker and other supplementary cementitious materials are ground into cement.

Cement and concrete CO_2 emissions profile

Approximately 55 per cent of the CO_2 emissions from cement production originate from the calcination of limestone and are commonly referred to as 'process emissions'; about 26 per cent can be identified as fuel-based emissions, mainly from the heating of the kiln and around 12 per cent are indirect emissions from electrical energy usage. Indirect emissions based on the transport of cement and concrete to the customer are estimated to be 7 per cent[1].

Figure 2: Today's CO_2 emission profile of the Australian Cement and Concrete Industry



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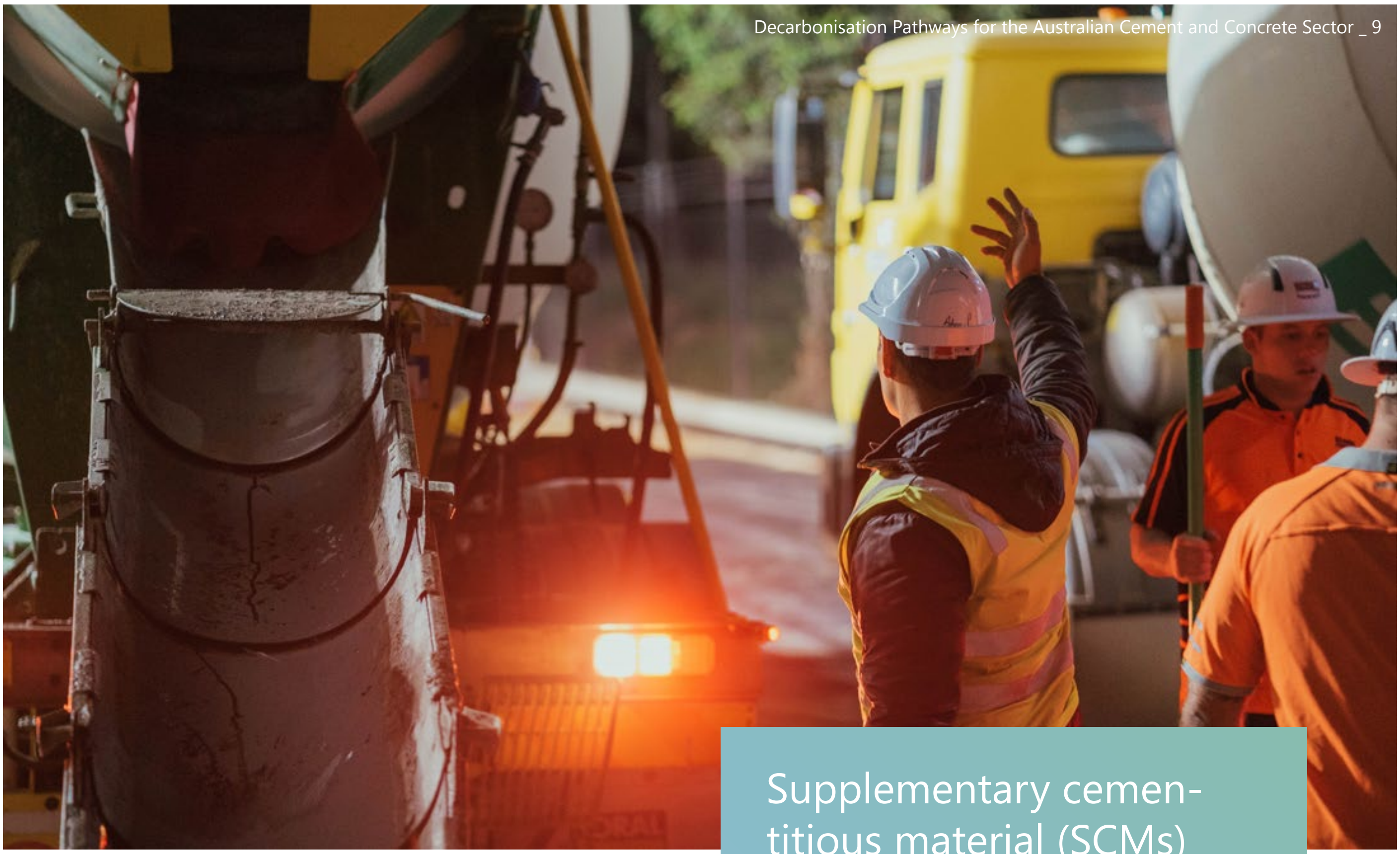
[1] VDZ proposes that a survey be conducted to enable an estimate of all transport emissions to be calculated.



Approximately 70 per cent of cement sold is for ready-mix concrete – corresponding to about 29 million cubic metres annually produced in more than 1,500 batching plants across Australia. The majority of ready-mix concrete is produced as dry mix. 10 per cent of Australian cement is sold as bagged products and mortars, the largest part of which is used for on-site mortar applications in residential buildings. The remaining 20 per cent of cement is used for concrete prefabrication, a trend observed in many markets as concrete production becomes more industrialised.

About 40 per cent of Australian concrete is currently used for infrastructure, 30 per cent for commercial and non-residential buildings and around 30 per cent for housing.

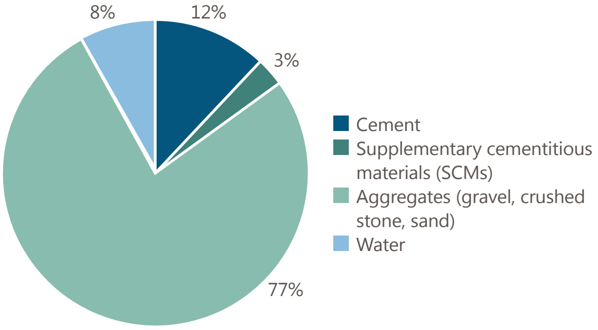
Supplementary cementitious material (SCMs)

Cement and concrete can contain constituents or additions, such as fly ash (a by-product from the power sector), granulated blast furnace slag (a by-product from the steel manufacturing process) or unburnt ground limestone. These so-called supplementary cementitious materials (SCMs) have been used in the sector for a long time. They contribute to the cement and concrete performance and are also used to produce cements and concretes that can exhibit properties for dedicated applications. At the same time, SCMs substitute clinker in cement and in concrete and thus lower the CO_2 footprint of both.

Concrete production

Concrete is a mixture of cement, water, sand and gravel as well as SCMs as additions. A typical concrete mix is made up of 12 per cent cement, 8 per cent water, 77 per cent crushed stone, sand and gravel and 3 per cent SCMs addition – although proportions may vary depending on the type of concrete and other factors (Figure 3). Small percentages of admixtures are also used, which help to achieve good workability of the concrete.

Figure 3: The main constituents of concrete in weight per cent



4 Challenges for a net zero CO_2 cement and concrete supply chain

Cement is an indispensable material to produce concrete. After water, concrete (including cement) is the most used material in the world and will continue to be absolutely crucial in supporting a modern world.

Concrete can be moulded into any shape and, due to its strength and durability, will continue to be the base for housing and infrastructure and subsequently for economic growth, societal wellbeing and prosperity. It will also be the foundation of future low carbon infrastructure.

Taking into account the availability of raw materials, economics and a holistic ecological assessment, no viable replacement of clinker-based cement currently exists to satisfy the global demand of infrastructure and construction. Even over the long term, cement – and its main constituent clinker – will continue to be indispensable.

Cement manufacturing is associated with an inevitable demand for energy and CO_2 emissions, which is due to the physical and chemical characteristics of the cement production process. The emissions from cement manufacturing currently account for 6-7 per cent of global CO_2 emissions and approximately 1 per cent of Australia's overall emissions profile [1].

The entire cement and concrete value chain faces significant challenges (which can also be considered as opportunities) in its quest for climate neutrality. This is due to the fact that conventional CO_2 abatement measures – even if applied to the highest degree possible – will reach their limits and additional breakthrough technologies will be required. The main focus along the full value chain are (1) the efficient use of clinker in cement, (2) the efficient use of cement in concrete, and (3) the efficient use of concrete in construction. The efficient use of clinker is of particular importance against the fact that the demand for construction is expected to grow in Australia by almost 40 per cent by 2050, which is mirrored by the expected population growth and future infrastructure investment plans [2] [3] [4] [5].

CO_2 emissions from cement manufacturing

CO_2 emissions from cement production originate from the calcination of limestone – commonly referred to as 'process emissions' and the combustion of the fuels. A smaller amount of CO_2 emissions originate from indirect emissions, in particular the use of electrical energy, transport and logistics.

In addition, efficiency gains in clinker production through the use of alternative fuels containing biomass (and other waste products) continue to be successful measures to lower CO_2 emissions from cement kilns. They are, however, limited to fuel-based CO_2 emissions and will not reduce CO_2 emissions from the calcination of the limestone. Breakthrough technologies must therefore be implemented in which carbon capture will play an important role. Still being in demonstration and pilot phase, this technology will in the medium and long term eliminate CO_2 emissions at the plant level, which cannot be reduced otherwise with conventional measures. Part of the overall capture process is the subsequent utilisation of the CO_2 or its storage in underground geological formations (CCUS).

Hydrogen is also seen as part of a breakthrough approach in cement manufacturing. It can play a role as a non-fossil fuel and it will be indispensable in transforming CO_2 into other chemicals or respective products. As green hydrogen will also play an important role in the decarbonisation of other sectors and associated value chains, synergies between sectors and innovative ways to produce, distribute and utilise green hydrogen will be crucial and are planned to be further developed in respective research projects.

These pathways to produce net zero CO_2 cement and concrete will require the cooperation of the entire value chain, cement and concrete customers, developers, designers, building material procurers, architects, standards authorities, government and non-government agencies, and concrete and cement manufacturers. It will need an effective policy framework which ensures a level playing field that allows the production of low-carbon and successively decarbonised cements and concretes to be competitive.

To allow net zero CO_2 cement and concretes to be utilised in building and construction on a large scale, the relevant standards, specifications and building codes need to be adapted to reflect future sustainability needs. The industry collectively would need to be actively engaged in the process of developing standards and specifications, and there would need to be a very strong commitment by all partners in the value chain to the expected outcome. The establishment of a firm timeline will ensure progress towards the 2050 expectations.

In Australia, like in many other parts of the world, the CO_2 footprint of building and construction materials is not generally taken into account resulting in significant potential for the broader application of low CO_2 emissions cement and concrete in the near future. Cooperative research strategies can help to bring all stakeholders together to develop these measures, adapted to the Australian context.

Finally, it will only be possible to successfully master this transformation with the development of necessary infrastructure – for example through widespread renewable power production and the transportation of CO_2 and green hydrogen.

Clinker and cement – transforming limestone into strength

The key constituent of cement is clinker which is produced under high temperatures in rotary kilns from locally sourced raw materials such as limestone and clay or its geological mixture marl. Its main mineral constituents are calcium carbonate and silicon dioxide, both being abundantly available and easily accessible all over the world. Once heated to temperatures of 1,450 °C, these minerals are transformed into the so-called clinker phases which have the unique property of hardening when mixed with water.

Clinker burning is not only an energy intensive process but releases a significant amount of CO_2 as emissions into the atmosphere. The energy is required to provide the high temperatures for the mineralogical transformation of the raw materials into clinker. As an average for the Australian cement industry 255 kg CO_2 /t clinker are emitted from the combustion of the fuels. In addition, upon heating, limestone is converted into calcium oxide releasing 536 kg CO_2 /t clinker [6]. While the fuel-based CO_2 emissions can be optimised to a certain degree, the so-called process CO_2 from the limestone is unavoidable. In particular, the contribution of "process emissions" makes the cement clinker process unique relative to other manufacturing industries.

5 Baseline of today's Australian cement and concrete CO_2 emissions

5.1 Cement and concrete production: production and product portfolio

Australia is a mature cement market with an annual per capita consumption of about 450 kg, which is around the global average.

Key figures for 2019-20 (baseline) are as follows [7]:

- Over 97 per cent of domestic clinker is produced in efficient calciner kilns;
- Domestic clinker production: 5.2 Million tonnes;
- Imported clinker: 4.0 Million tonnes;
- Specific fuel energy demand: 3,445 MJ/t clinker which is state of the art and representative taking into account kiln design, fuel mix and raw material moisture;
- Specific electrical energy demand: around 100 kWh/t cement, which is state of the art and representative taking into account the applied grinding systems and the types of cement produced;
- Thermal substitution rate by alternative fuels: 18 per cent, which is low against the background of waste volumes available in Australia. Supplies (or sources) can be uneconomical due to high transport costs and further sorting and processing costs. Examples of the types of alternative fuels used today in the Australian cement industry include wood waste, carbon powders, used oils and solvents, as well as spent cell liners from aluminium production;
- Alternative fuels biomass content: 40 per cent which is high compared to other countries;
- Cement annual demand: 11.7 million tonnes
- SCMs use in concrete (GGBFS and fly ash): 3.3 million tonnes per year;
- CO_2 emission factor for domestically produced clinker: 791 kg CO_2/t of clinker being a typical number (4 per cent below global average) taking into account the fuel used and the thermal energy demand; and
- Electricity CO_2 emission factor: 680 kg of CO_2/MWh is the average value which reflects the Australian energy mix containing around 21 per cent of renewable energy today [8]. Since Australia does not have a single electricity market, lower emission factors can apply locally.

The overall CO_2 emissions from the Australian cement industry between 2009-2010 and 2019-2020 are depicted in Figure 4 – they are 25 per cent lower than 20 years ago due to the following internal and external factors:

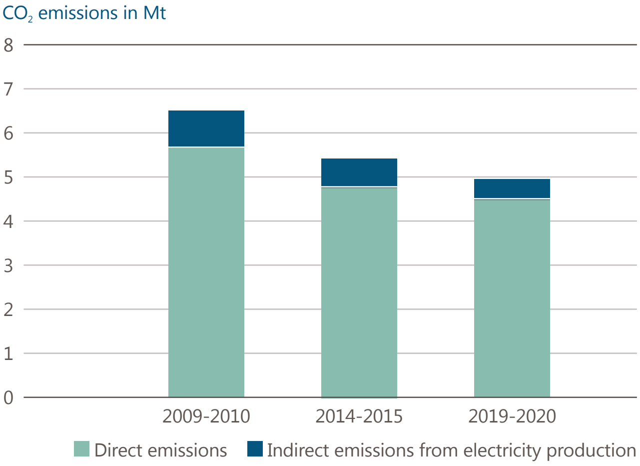
Internal factors:

- Continuous modernisation of the production process and kilns, closure of lower scale, less efficient wet kiln processes;
- Almost 20 per cent less energy consumption per tonne of cement since 1999-2000;
- 18 per cent alternative fuel usage;
- Around 40 per cent biomass in alternative fuels; and
- Reduction in electrical energy consumption.

External factors include changes in the cement market, most notably in terms of imports supplementing domestic clinker production and a growing amount of renewable energy in the power grids.

Over 1,300 people are directly employed in the cement industry, corresponding to over 5,000 jobs downstream. 30,000 people are directly employed in the whole cement, concrete and aggregate sector corresponding to over 80,000 jobs indirectly employed, generating annual revenue of A$15 billion [9].

Figure 4: CO_2 emissions from the Australian cement industry



Efforts taken by the Australian cement and concrete producers to reduce their CO_2 emissions

30 per cent improvement in thermal efficiency
More than 97 per cent of domestic clinker is produced in efficient calciner kilns. They are state-of-the-art technology and result from long term kiln optimisation programs. The current calciner kilns are thermally efficient and, as a consequence, the fuels are being used around 30 per cent more efficiently than during earlier periods e.g. pre-2000.

18 per cent replacement of fossil fuels
In Australia cement kilns basically operate on coal and natural gas. However, like in many countries around the world, Australian cement producers take advantage of certain waste to use as alternative fuels in their kilns. This not only contributes to the saving of fossil fuel resources but can have a direct and indirect effect on CO_2 emissions. Alternative fuels originate from waste, which in most cases would be disposed of. Examples of the types of alternative fuels used in the Australian cement industry include wood waste, carbon powders, used oils and solvents, as well as spent cell liners from aluminium production.

Around 40 per cent biomass in alternative fuels
Alternative fuels can be biomass (or a certain percentage of biomass) which has an immediate impact on the CO_2 emissions from the fuels. Therefore, the CO_2 emission factors from waste are typically lower than the ones from conventional fossil fuels. Indirect effects can come though avoiding methane and CO_2 emissions when waste – instead of being used as alternative fuels – are land-filled or incinerated.

Around 38 per cent reduction in clinker content in concrete
SCMs such as GGBFS, fly ash and limestone can partly replace clinker in cement or can be used as an addition in concrete as a cement replacement. The use of these SCMs has resulted in a clinker to cement factor of 0.84 and a total clinker to binder factor in concrete of 0.62 resulting in a 38 per cent reduction in clinker content and associated CO_2 emissions in concrete.

Alternative fuels

Alternative fuels are pre-treated waste of defined origin which replace conventional fuels used such as coal and gas. In most cases alternative fuels provide for lower CO_2 emissions because of their different composition and their biomass content.

5.2 Australian standards for cement and concrete

The current Australian cement standard AS 3972-2010 defines 3 types of cement:

- **General purpose cement (Type GP)** is mainly based on Portland cement clinker and calcium sulfate (gypsum). The use of mineral additions, for example limestone, is allowed up to a content of 7.5 per cent.
- **Blended cement (Type GB)**, which contains Portland cement clinker, calcium sulfate (gypsum) and at least 7.5 per cent of GGBFS, fly ash and/or amorphous silica alone or in combination. The use of amorphous silica is limited to 10 per cent.
- **General purpose limestone cement (Type GL)** with a limestone content up to 20 per cent. Further mineral additions are also allowed as part of the limestone content, but limited to a content of up to 5 per cent.

Additional properties of those cement types can also be specified. This results in special purpose cements with possible properties "high early strength (Type HE)", "low heat (Type LH)", "sulfate resistance (Type SR)" or "limited shrinkage (Type SL)". The aforementioned SCMs must comply with the same standards as concrete additions (AS 3582.1 for fly ash, AS 3582.2 for GGBFS, AS 3582.3 for amorphous silica). Limestone to be used as SCMs in cement is defined in the cement standard AS 3972.

The current Australian standard for concrete structures (AS 3600-2018) defines minimum compressive strength and curing of concrete depending on exposure and climatic conditions in the place of use.

The standard for concrete and concrete supply (AS 1379) specifies additional properties of concrete such as fresh concrete properties, seven day strength, aggregate size and use of admixtures. Additionally, production and plant requirements are described.

Additional requirements, such as minimum binder content and maximal water/binder ratios, are defined in specifications of organisations such as Australian infrastructure or federal transport authorities. In many cases this also includes the composition of cement or binder and limit values of porosity for concrete.

Type GP cement only allows 7.5 per cent mineral additions and this is the cement type that government infrastructure and road authorities, construction companies and procurers traditionally specify in Australian projects.

Limestone cements

It is essential that policies that require lower carbon cements are implemented along the value chain e.g. by encouraging the asset owners to adopt the additional use of Type GL cement within their specifications in a way that the durability and performance characteristics can be maintained.

5.3 Australian regulations and rating systems regarding sustainability

Existing regulations on sustainable construction in Australia have so far been based on voluntary actions:

The Climate Active partnership between the Australian Government and Australian businesses encourages voluntary climate action [10]. The Partnership has developed Climate Active Carbon Neutral Standards which provide best-practice guidance on how to measure, reduce and report emissions. They can be used to better understand and manage carbon emissions, to credibly claim carbon neutrality and to seek carbon neutral certification.

Climate Active certification is awarded to businesses that have credibly reached net zero emissions. Certification is available for buildings, events, organisations, precincts, products and services. Certification for buildings is possible via the Green Building Council of Australia (GBCA), the Green Star Rating or the National Australian Built Environment Rating System (NABERS). The Climate Active Carbon Neutral Standard for Buildings [11] focuses on the building's operational carbon account. Emissions from construction materials and processes are not yet covered by the Standard.

The Green Star rating system module "Life Cycle Impacts – Concrete" demonstrates the environmental impact of concrete in a project. Points are awarded in the three categories of Portland cement reduction (at least 30 per cent compared to the reference case), water reduction (use of captured or reclaimed water) and aggregates reduction (replacement through crushed slag aggregates, manufactured sand or other alternative materials). Up to three points are available for the module "Life Cycle Impacts – Concrete". Compared to a total number of 110 points available, the lever of concrete on the overall rating of a project appeared to be small up to now. The Infrastructure Sustainability Council of Australia (ISCA) also applies a rating tool for concrete. Governments in Australia apply the ISCA rating tool to major projects (bridges, roads, tunnels etc.).

The Green Building Council of Australia (GBCA) supports the sustainable transformation of the built environment through different activities. It provided information that embodied carbon will play a bigger role in the future. By 2030 all new buildings must show a significant reduction in embodied (upfront) carbon and Green Star will set targets to decarbonise all buildings. This highlights that there is positive momentum in the market, but it is still necessary to remove barriers to accelerate action and have customers demand low emission products.

WWF-Australia emphasises the importance of the Materials & Embodied Carbon Leaders' Alliance (MECLA). MECLA is a collaboration of organisations working together to drive reductions in embodied carbon in the building and construction industry. It was founded by the NSW Department of Industry, Environment and Planning, WWF-Australia and Presync, along with a number of industry partners.

6 Technologies and innovations for net zero CO_2 in concrete construction

6.1 Innovation in design and construction

Designers and architects play a crucial role and will increasingly adopt aspects of resource efficiency and climate protection in their design and construction considerations. From the point of view of designers, architects and building owners, the selection and application of concrete (including the type of cement used) as well as the building structure, including its service life, are the main influencing factors. Structural optimisation, as well as improved design assumptions and methods, are the tools to be used by designers. Contractors also can contribute to new and improved construction technologies. Both designers and contractors will increasingly emphasise issues such as lifetime extension, repair and reuse.

6.1.1 Structural optimisation

Structural optimisation provides the opportunity to realise the same load bearing capacity with less material. Examples with a high technological readiness level are prestressed hollow core slabs or voided slabs. The application of these systems can result in savings of up to 35 per cent of the original concrete volume [12]. New developments are expected with regard to optimised (organic) shapes that use only as much material as necessary for the required load bearing [13] [14] [15]. The use of noncorroding reinforcement is another technology that can reduce concrete volumes because it allows for a minimisation of the concrete cover.

6.1.2 Improved design assumptions and methods

Improved design assumptions and methods can help to make the use of binders in a structure more efficient.

In the first instance, this could be achieved by providing a more differentiated selection of the concrete grade. For the sake of simplicity, designers often use the same concrete strength class for several structural elements. This means that some elements have a higher strength than necessary. Since a higher strength is usually related to a higher clinker or binder content, a more differentiated selection can result in CO_2 savings. The use of high strength concrete can be beneficial for elements under a high compressive load (such as columns) because the higher strength results in a reduced cross section. The reduced overall volume often outweighs the higher binder content of the high strength concrete per cubic metre. For elements that are mainly subjected to bending or shear, a higher strength class is less beneficial compared to elements under compression.

Another point with regard to design assumptions is the age of the concrete when assessing the concrete strength. The concrete strength is usually tested at an age of 28 days. This is the typical time after which the strength of concrete only made of Portland cement (i.e. without any SCMs used) usually reaches its final strength. In comparison, when SCMs are used in concrete its strength development is slower, because of the reactivity of SCMs being slower than Portland cement clinker. In particular, concrete with high amount of SCMs requires a longer curing time but will at the end of that time have similar strength performance as, for example, concrete made of Portland cement only [16] [17]. Therefore, assessment of the concrete strength at a later age than 28 days, for example, after 56 days, can make good sense. This would allow higher amounts of SCMs to be used since the concrete has reached its full strength by that time. From a technical standpoint this is achievable as long as this is communicated along the value chain to ensure that longer hardening time of the concrete is taken into account when progressing construction.

Improved structural analysis tools based on numerical simulation methods such as the finite element method (FEM) can also contribute to a more resource efficient design [18] [19] [20]. These methods are usually implemented in structural engineering software and allow for a more accurate

Pathway towards net zero CO_2 cement and concrete

The pathways towards net zero CO_2 cement and concrete will require conventional measures to be applied to the highest degree possible but also breakthrough technologies:

- Binder saving through innovation in design and construction;
- Binder saving through innovation in concrete;
- Supplementary cementitious materials (SCM) in concrete;
- Clinker efficient cements;
- Fuel efficiency in clinker production;
- Recarbonation; and
- Carbon capture and utilisation or storage.

computation of the stress state in structures with complex shapes. The realisation of complex shapes will become more important when the minimisation of the concrete volume in a structure comes into focus (see 6.1.1 "structural optimisation").

The design, planning and building processes will become more complex when the aforementioned points are put into action in parallel. As the opportunity for errors may increase, further industrialisation of the concrete sector appears necessary. Building information modelling (BIM) can help realising these complex processes and thus indirectly supports the pathway to higher resource efficiency and reduced CO_2 emissions [21].

6.1.3 New and improved construction technologies

The way a concrete structure is built has an indirect impact on the resulting CO_2 emissions.

Concrete that is pumped into the formwork usually needs a higher binder content and therefore a higher CO_2 footprint compared to concrete that is poured without pumping [22].

A more industrialised process, for example, by a moderate shift from onsite work to precast, can lead to lower material demand through higher precision at the factory and less waste. In principle, a modular production allows for a higher efficiency in construction. However, transport distances can make precast concrete economically challenging in rural areas, especially for large size elements. Additive manufacturing and new formwork technologies might enable material efficient shapes [23] [24]. As prefabrication is generally low in Australia, this allows for potentially significant uptake of innovation in concrete structures.

6.1.4 Lifetime extension, repair and reuse

In terms of resource efficiency, it is preferable to extend the lifetime of existing buildings or infrastructure as long as possible and, if necessary, to upgrade it through conversions, modernisations and energy saving measures [25]. Residential or commercial buildings are typically replaced because of changing requirements in its use or functionality – and not because of a limited durability of the concrete structure. Most existing buildings have not been designed to be easily converted or renovated which makes it easier to replace them – technically but also with respect to cost predictions. In order to further increase the conversion and renovation rate in the future, the future use of a building should be taken into account at the design phase. This includes, for example, the flexibility of floor plans, the room height and the imposed loads. The reuse of concrete elements from disassembled structures can also contribute to resource efficiency and CO_2 reduction.

To enable the longest possible service life for buildings and infrastructure, a sufficiently high level of concrete durability against environmental effects in the respective application must also be ensured. A change in standards and regulations from the current prescriptive specifications to performance-based specification for concrete durability may be useful to realise a more accurate design which is safe and also resource efficient. This area will require further research before it can be transferred into practice (see Chapter 9: Future R&D priorities).

6.2 Innovation in concrete

6.2.1 Concrete with a high amount of supplementary cementitious materials (SCM)

Concrete with CO_2 efficient cements, supplementary cementitious materials (SCM) as concrete additions or alkali-activated binder/geopolymers [26] is a key pathway for the further reduction of CO_2 emissions in the concrete sector. Only certain cements or types are stated to be used in concrete according to the Australian concrete standard. Other countries have experience in the use of many cements not yet used in Australia. Their use in the Australian context is possible but it requires an adaptation of the relevant standards and technical specifications in cooperation with all relevant stakeholders. This will assure that the technical performance of concretes with new cements and binders is proven before these products are used in practice.

Geopolymers are widely seen as contributing to lowering CO_2 emissions due to their synthesis from industrial by-products or waste when compared to Portland cement. However, the environmental impact of alkali activators needs to be taken into account within a full life cycle approach [27], based on the specific local conditions. Therefore, further data should be collected and evaluated for the Australian context. Consideration should be given to using activated binders with high SCMs content to reduce 'curing' times and potentially improve construction speeds by virtue of early age strength gain. In addition, rheology when using geopolymers should be investigated dependent on temperature and water addition.

To establish a broad use of concrete with a high amount of SCMs as well as geopolymer concrete, the binder composition has to be chosen according to the relevant requirements (fresh concrete properties, strength, durability). This will result in a more differentiated use of concrete types depending on the application of concretes in commercial buildings and housing on one hand and infrastructure on the other hand. Different cement types and different clinker cement factors can be used. Quality control procedures will be important as CO_2 optimisation will increase the complexity along the value chain as well as the opportunity for errors.

6.2.2 Reduction of binder content

Besides the replacement of clinker by suitable SCMs or geopolymers, the reduction of the total binder volume (sum of cement and SCM) in concrete also plays a role in the reduction of CO_2 emissions.

The following information was discussed with experts from the Australian concrete sector:

Packing density optimisation of concrete and optimisation of aggregate grading are additional tools that can lower the binder content in concrete. Depending on the final binder content the use of modern chemical admixtures will be required to maintain the workability of the concrete.

Specifications sometimes prescribe minimum binder content and a maximum amount of SCM. In order to enable further optimisation, the introduction of performance specifications would be advantageous.

In fact, in AS 3600-2018 the performance of the concrete is specified in terms of its compressive strength. The standard for concrete and concrete supply (AS 1379) specifies additional properties of concrete such as fresh concrete properties, 7-day strength, aggregate size and use of admixtures. Additionally, production and plant requirements are described. In many cases, it is sufficient to focus on compressive strength as a performance criteria for concrete in the structure:

- The application / environmental conditions do not make it necessary to consider durability (for example interior components or very dry environmental conditions).
- There is a connection between durability and compressive strength (for example in many cases with carbonation).
- The durability has been proven elsewhere (for example through research or practical experience).

Since this report references further lowering the clinker factor in cement, the development of a comprehensive database on the properties of low-carbon cement and concrete is therefore proposed as a tool to develop trust in low-carbon products from all stakeholders. The basis is a set of (performance) tests and procedures agreed by all stakeholders. The scope of the evidence depends on the respective application. Performance specifications enable concrete producers to suggest the best concrete mix to meet the performance needs of the required application. The concrete composition can then be optimised with regard both to its technical performance and its carbon footprint. As an example, reference can be made to ongoing standardisation work in Europe: The next generation of Eurocode 2: "Design of concrete structures – Part 1-1: General rules – Rules for buildings, bridges and civil engineering structures" will contain "Exposure resistance classes (ERC)". ERC will be used to classify concrete with respect to resistance against corrosion induced by carbonation or by chlorides and damage caused by freeze/thaw attack. ERC may be satisfied by proving the performance in meeting specification of relevant physical characteristics determined using standardised test methods or by compliance with relevant limiting values. In order to establish a set of performance tests/procedures for relevant applications accepted by all stakeholders, a respective innovation area is proposed (see Chapter 9).

6.2.3 Avoidance of waste in concrete production

An efficient use of cement and concrete also implies the avoidance of waste in concrete production. Better forecasting of the demand and adapted truck size can reduce waste volumes. The same applies to a partial shift from on-site work to precast through better controlled processes at the factory. Further, fresh concrete recycling should be put into practice for the remaining waste volume to reuse the aggregates and part of the water. Increasing digitalisation may support a better process control with regard to the aforementioned points and thus also support the reduction of waste.

6.3 Clinker efficient cements, SCMs and new binders

Supplementary cementitious materials (SCM) can be used as main constituents in cement and as additions in concrete. Both lead to a decreased demand for clinker and therefore to lower CO_2 emissions. In this report, the clinker cement factor is forecasted to be reduced to 60 per cent in 2050 and a clinker binder factor in concrete of 50 per cent.

6.3.1 Availability of SCMs in 2050

GGBFS is produced at one steel plant in Australia [29]. Like the cement and concrete sector, the steel industry worldwide has to decarbonise its processes, including pig iron production [30] [31]. To what degree this will affect the availability and the quality of the GGBFS is currently not known but will depend on the technology used for future pig iron production (blast furnace or direct reduction / arc furnaces). In this report it is assumed that existing pig iron production in a blast furnace will be maintained for converter steel production and GGBFS will be available in similar amounts as today – both in terms of domestic and imported product.

Fly ash production will decrease due to decarbonisation of the energy sector, but significant amounts of stockpiled fly ash exist (at least 100 years' worth may be available in Australia) and can be used in later years of the decarbonisation plan period [32]. It will be necessary to dry and process the stockpiled fly ash according to its unburnt carbon content. Such technology exists and is applied in a broader context [33]. For using such technology in the Australian context, it has to be looked at in detail – also against the background of inherently high chloride levels in ponded fly ashes and the required thermal energy for drying.

Limestone is abundantly available in quarries of the cement industry.

Clays which can be calcined and used as SCMs for cement and concrete are available in Australia in sufficient quantities at locations basically all over the country [34] [35]. The calcination process requires fuel combustion which causes CO_2 emissions of around 100-150 kg CO_2/t of clay, corresponding to 15-20 per cent of current CO_2 emissions from clinker.

Calcined clays

When clays are heated to a high temperature they undergo a mineralogical transition which is called calcination. Calcined clays have properties which make them very useful as supplementary cementitious material.

For other materials the environmental impact needs to be taken into account within a full life cycle approach, based on the specific local conditions. Therefore, further data should be collected and evaluated for the Australian context.

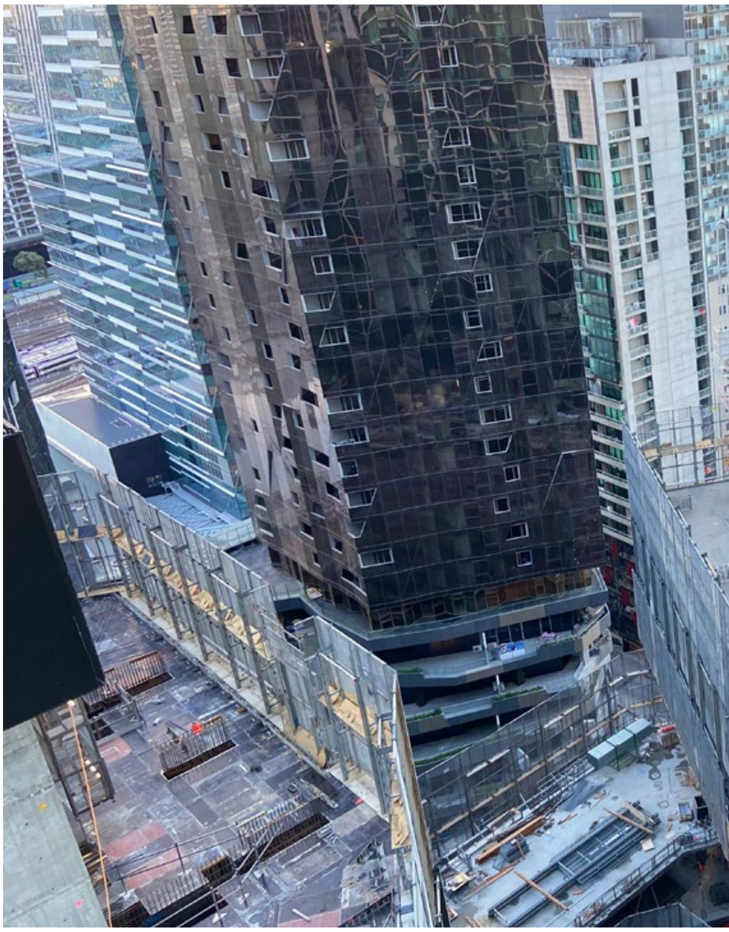
6.3.2 Examples for future clinker efficient cements

From a technical point of view, as well as from the availability of the necessary constituents, the following cements are seen as examples for future clinker efficient cements also in Australia:

- Cement with limestone content of 20 per cent or more
- "LC3" – cements with 50 per cent clinker, 30 per cent calcined clay and 20 per cent limestone;
- Cements with 35 per cent clinker, 45 per cent fly ash / calcined clay / GGBFS and 20 per cent limestone.

Significant international experience exists for most of the cements mentioned above or extensive experience from research or demonstration projects is available [36] [37] [38] [39] [40]. This also applies to cements containing calcined clays which are today in the early stages of application on an industrial scale [41] [42].

Cements which may contain other SCMs like natural pozzolana, waste from lithium production and geopolymers are seen to be used in limited amounts in selected applications.



6.4 Fuel and electrical energy efficiency in clinker production

6.4.1 Fuel efficiency

Thermal energy accounts for one third of the CO_2 emissions from clinker production. Because of the high energy demand, cement producers worldwide have always been striving to lower the thermal energy demand of their kilns. With such state-of-the-art technology, cement kilns provide for thermal efficiencies of more than 70 per cent which are among the highest of all industrial processes due to its counter current principle, high efficiency clinker coolers and raw material preheaters [43] [44].

The thermal efficiency not only depends on the kiln performance itself but also on the fuel types used. In particular, fuels containing a higher amount of hydrogen or moisture tend to increase the thermal energy demand for clinker burning. Taking into account the relationship between energy consumption at best available technology (BAT) kilns and the anticipated substitution of fossil fuels of 50-60 per cent and 10 per cent substitution of green hydrogen – the thermal energy demand of the Australian cement industry will by 2050 be 3,345 MJ/t of clinker in which efficiency gains of up to 6 per cent linked to technological upgrades have been implemented, see Annex C. A slight increase in thermal energy demand by 2030 reflects the uptake of low carbon fuels before efficiency improvements take over.

Alternative fuel

Future alternative fuels will also be based on waste with high biomass content. This will lead to lower CO_2 emission factors of the fuels taking into account a biomass content of about 50 to 60 per cent in the alternative fuels. In addition, green hydrogen is estimated to represent a thermal energy share of approximately 10 per cent in the total fuel mix. This is seen as a technical limit from today's point of view. Research will be needed to explore if higher levels are possible.

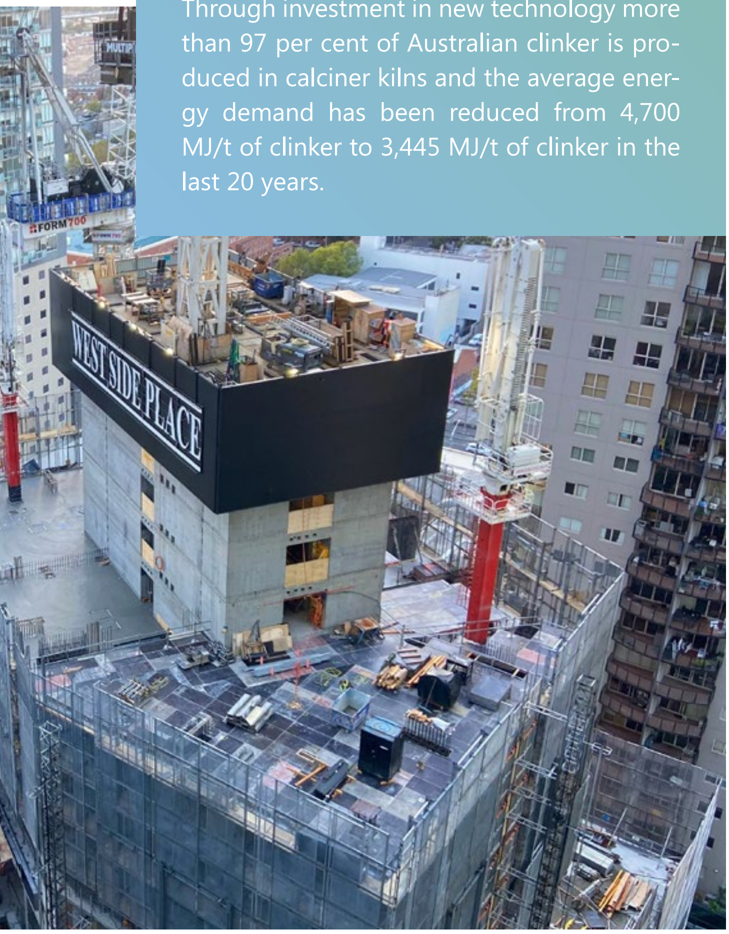
The energy demand of clinker production is based on the chemical and mineralogical transformation of the raw materials and cannot be further optimised. This is also due to the fact that the waste heat is used to the highest degree possible. Remaining waste heat has temperatures of less than 100 °C and can only be used for drying purposes. In countries with unstable power grids, cement producers tend to target higher waste heat temperatures in order to generate electricity (waste heat generation). However, except in special cases this is neither economical nor efficient in countries like Australia with stable and sufficient electricity from the grid.

Against this background, fuel mix optimisation is currently the main (conventional) pathway for reducing CO_2 emissions from clinker production and will remain so in 2050. Different fuels can have different CO_2 emission factors depending on the chemical composition and on their biomass content. Fossil fuels are typically coal and gas in the Australian integrated cement process. Alternative fuels are pretreated and processed waste.

In Australia, like in many other countries, the use of alternative fuels using waste is limited depending on the location of the plants. Sometimes it is also difficult to compete with landfill sites for waste. There are currently few policy options to incentivise the use of alternative fuels. With changes in policy, a further increase in the use of alternative fuels substituting coal and gas by 50-60 per cent is seen to be possible by 2050.

High thermal efficiency of Australian cement kilns

Through investment in new technology more than 97 per cent of Australian clinker is produced in calciner kilns and the average energy demand has been reduced from 4,700 MJ/t of clinker to 3,445 MJ/t of clinker in the last 20 years.



6.4.2 Thermal efficiency through advanced sensors and artificial intelligence AI

Digital tools, such as computer-aided design and planning tools or software for process simulation and the computation of fluid dynamics, play an important part in today's cement production. Expert systems for process control based on fuzzy logic or case-based reasoning were already implemented in the early 1990s, and even machine learning models are not completely new since these have been part of model-predictive control algorithms for more than 10 years. Today, however, digitalisation is not only introducing a new generation of smart sensors and data-driven solutions, but also changing the way data is handled in the cement industry.

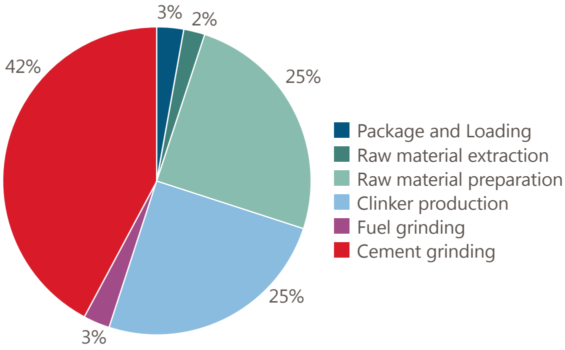
Artificial intelligence (AI) is applied in the cement sector, and many examples already exist. In predictive maintenance, AI detects anomalies in equipment operation, and the probability of failure can be lowered for critical components [45]. Smart (soft) sensors can virtually 'measure' product fineness or clinker and cement quality without taking any samples [46] [47]. Plant equipment such as, for example, high efficiency selective non catalytic NO_x reduction units (SNCR) is locally controlled and dynamically optimised by machine-learning algorithms [48].

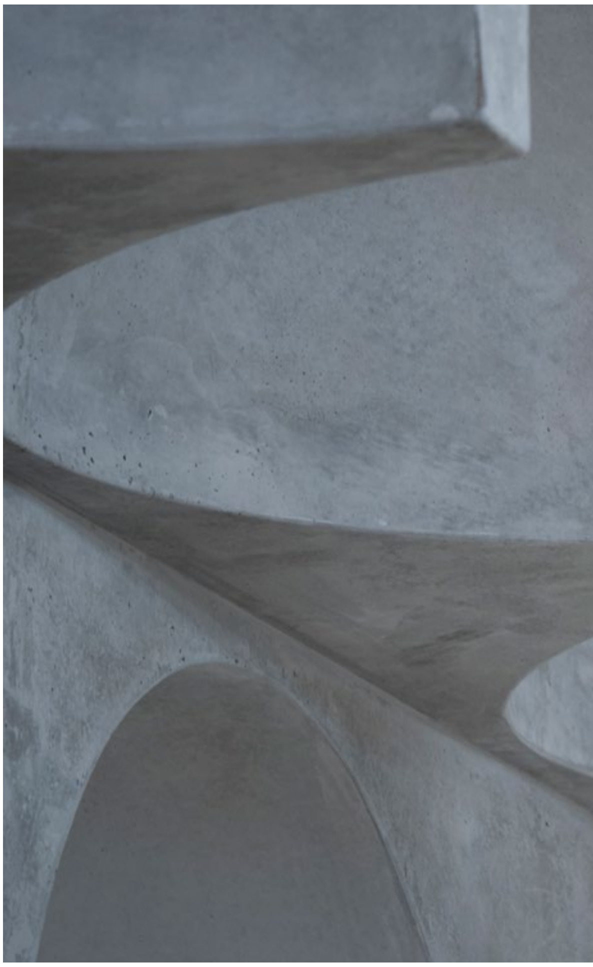
AI applications have also found their way into the control and optimisation of the pyroprocess and grinding plants. By taking into account more process data than an operator can assess at one time, these applications can directly react to slight fluctuations in kiln operation. There are also applications known in the process industry where AI solutions can even outperform operators by departing from the common ways of operating, for example, the cement kiln [49]. In any case, the precondition for all these benefits is data of high quality. Finally, AI has generally been proven to be of benefit for process control and optimisation in many projects.

Applying an AI solution to kiln operation, for example, requires the preassessment of data, optimisation of data structures and sensor infrastructure, and the analysis of different operation modes. AI-based solutions and smart sensors help to stabilise thermal and mechanical process operation. The availability of high-quality sensor data, additional virtual data or even recommendations for parameter settings reduce process fluctuations and reactions times. Consequently, the availability of kiln and mill systems is extended due to the reduction of process disturbances, such as coatings or cyclone blockages, and the increasing lifetime of critical wear parts. This in turn reduces the specific energy demand and CO_2 emissions. The CESMII project is a good example of the application of AI to cement production, aiming at more energy-efficient cement production with better quality control [50].

Digitalisation in cement plants today is still driven by stand-alone solutions bringing only a limited amount of data-driven services to the plant. The vision of the digitalised cement plant of the future incorporates the intelligent and standardised management of data. This will enable the use of various interconnected AI applications for a holistic approach towards minimum-carbon operation of cement plants, including the optimisation of the thermal and electrical energy demand and the maximisation of the use of alternative raw materials and fuels.

Figure 5: Distribution of the electrical energy demand of a typical cement plant acc. to [6]





6.4.3 Electrical energy efficiency

Electrical energy demand for integrated Australian cement production requires around 100 kWh/t of cement, which is state-of-the-art against the background of today's product portfolio and process technology. Most of the energy in a typical cement plant is used for grinding. The overall distribution is as follows: 2 per cent for raw material extraction, 25 per cent for raw material preparation, 25 per cent for clinker production plus an additional three per cent for fuel grinding, 42 per cent for cement grinding and three per cent for packing and loading [6]; see Figure 5.

Future demand for electrical energy takes into account the application of modern grinding technologies such as high-pressure grinding rolls and vertical roller mills for raw material and cement grinding, replacing ball mills which usually have a higher energy demand. However, this transformation is limited by performance of new low emission cements which will require higher fineness of its constituents. Additional energy will also be required for blending and homogenisation, as well as for more extensive emission control devices to meet future regulatory requirements.

Reduction in energy demand is expected from sophisticated process control based on artificial intelligence, modern sensors and kiln control systems. Compressed air for material transport has already been widely replaced by mechanical systems, and modern motors and drives are already implemented in most stages of the production process.

Taking into account the future market for cement and improvements in energy efficiency of cement technology, the electrical energy demand for future Australian cement production is expected to be 90 kWh/t of cement. This does not include the application of carbon capture and utilisation or storage technologies (CCUS) which will significantly increase the demand for electrical energy.

It is expected that both the power sector and the transport sector in Australia will be fully decarbonised by 2050. Several sources of information ([51] [52] [53] [54]) underline this assumption. Major steps have been already achieved and targets for future development of renewable power production have been outlined.

Even if electrical energy is going to be decarbonised in the future, it must still be used as efficiently as possible. Australia has been addressing energy efficiency for some time already. Organisations such as the Australian Alliance for Energy Efficiency (A2EP) and RACE for 2030 CRC, for example, have developed and pursued important projects and can certainly assist in further efficiency measures with a dedicated focus on cement production.

6.5 Recarbonation

CO_2 emissions from the production of cement and concrete are partially adsorbed during the lifetime of a concrete building and after its end of life. Studies have analysed and estimated the CO_2 uptake by concrete indicating the complexity to fully quantify the total CO_2 uptake by concrete in its full lifetime. The studies have shown – depending on the methodology and data sources used – that a range between 20 per cent [55] and 43 per cent [56] of equivalent process CO_2 emissions being taken up by all concrete structures in its use phase. These percentages refer to the process emissions which originate during clinker production [55]. The IPCC Sixth Assessment Report (2021) [57] notes "the uptake of CO_2 in cement infrastructure (carbonation) offsets about one half of the carbonate emissions from current cement production". Reference is made here to [58] which is based on the findings in [56]. For this study, the most conservative approach of 20 per cent of process CO_2 emissions for recarbonation was taken into account.

Fresh concrete can also absorb CO_2. Two aspects can be considered here: How large is the amount of CO_2 that can be reintegrated and can the performance of the concrete be increased as a result. Experience is available with regard to both aspects [59] [60]. The potentials appear comparatively low from todays' perspective and are not shown separately in this report. The same applies regards the impact of carbonation when curing concrete elements in a CO_2 enriched atmosphere and the influence of carbonated secondary aggregates and crushed concrete fines on the properties of recycled concrete. However, all of these possibilities are worth investigating further in terms of their potential in Australia. Therefore, a separate innovation area is proposed for the topic of "Recarbonation".

Recarbonation

Concrete takes up CO_2 from the surrounding environment through a chemical reaction which transforms calcium hydroxide to calcium carbonate. This natural process is called (re)carbonation.

6.6 Carbon Capture

Several capture technologies exist today which exhibit a sufficient technical maturity. In order to compare technologies of different maturity they are characterised by their Technology Readiness Levels (TRL). Many carbon capture technologies have been investigated in the past decades with the goal of increasing their TRL and to bring these technologies into the market [61] [62] [63] [64] [65]. The most promising technologies are given in the Annex A in the form of a brief profile describing the technology, the working principle, the TRL level and whether it can be applied to existing facilities.

6.7 Thermal Mass

The relatively high thermal mass of concrete can be beneficial for the regulation of room temperature and comfort in a building. During winter heat from sun exposure is stored during the day and released during the night. In summer heat is released from the air to the concrete during the day and removed from the concrete during the night. Thermally massive elements have the ability to reduce variations of the room temperature because they can store a large amount of thermal energy and slowly absorb or release it [66] [67].

A high thermal mass is particularly advantageous for climates with a significant difference between day and night outdoor temperatures. This is the case for many climates in Australia, including dry desert climates, but less so for tropical climates [68]. Studies from Europe show that thermal mass can reduce the heating energy consumption of a building by up to 15 per cent. Night ventilation coupled with high thermal mass can decrease the energy needed for cooling by up to 50 per cent [69]. An efficient use of thermal mass in moderate climates can even eliminate the need for heating and cooling systems. To maximise the benefit from thermal mass it needs to be included into an overall thermal design approach which takes into account orientation, glazing, shading and insulation [66] [68].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7 Pathways to reduce CO_2 emissions for cement, concrete and the built environment

7.1 Boundaries for CO_2 inventory

This report covers CO_2 emissions for the whole cement and concrete value chain. It includes direct (scope 1) emissions from cement production emissions, based on CO_2 emissions from clinker production. The CO_2 emission factor has been derived from Australian plant data provided to VDZ on a confidential basis by all Australian cement manufacturers. It is also applied to imported clinker as these emissions are not covered by the Australian reporting scheme.

Electrical energy for cement production is covered in this report as indirect (scope 2) emissions. The emission factor reflects the power mix of average electrical power production in Australia, taking into account that locally lower CO_2 emission factors from electricity production can also apply. No further demand of electrical energy from the value chain has been included.

Transport emissions have been included for the movement of cement and concrete to customers, reflecting around 7 per cent of the total CO_2 emissions covered in the report.

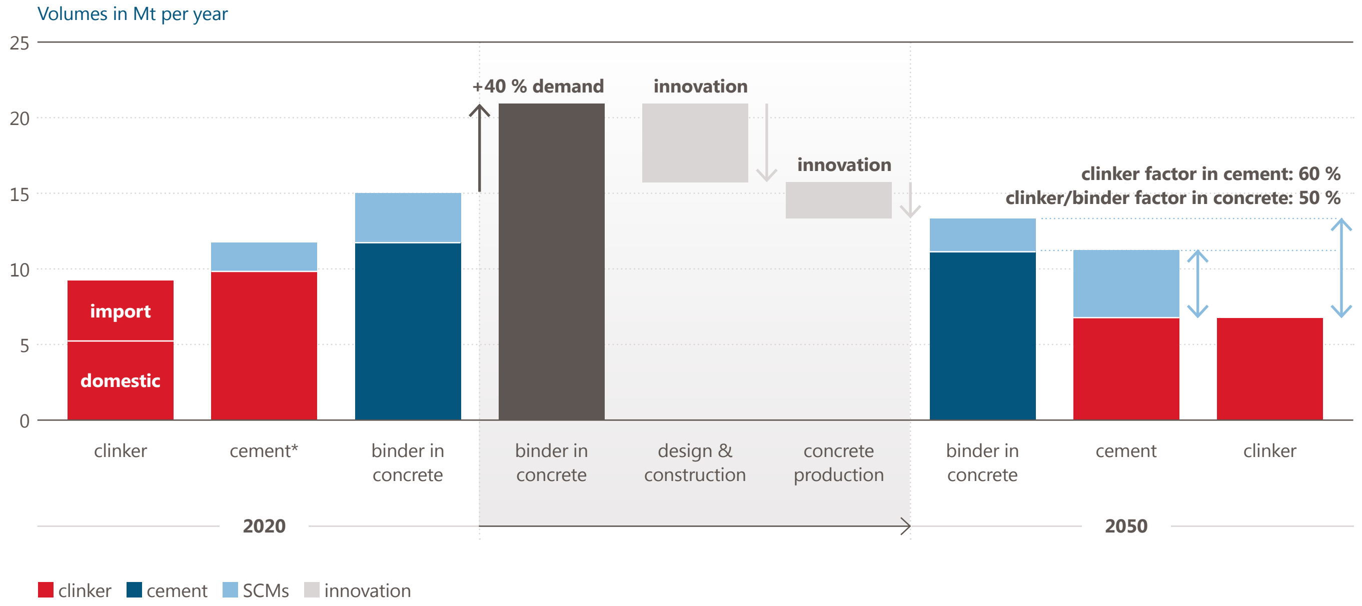
7.2 Methodology and assumptions

The pathways to decarbonise cement and concrete focus on CO_2 emissions which are mirrored by the development of current clinker, cement and binder volumes and its development until 2050 as shown in Figure 6.

The volumes are based on the analyses and assumptions described in the previous chapters. Starting points are the clinker and cement volumes in 2020, which reflect both domestic production and imports. Together with the amount of supplementary cementitious materials (SCM) in concrete (3.3 Mt in 2020), the amount of binder in concrete was calculated to be 15.0 Mt in 2020.

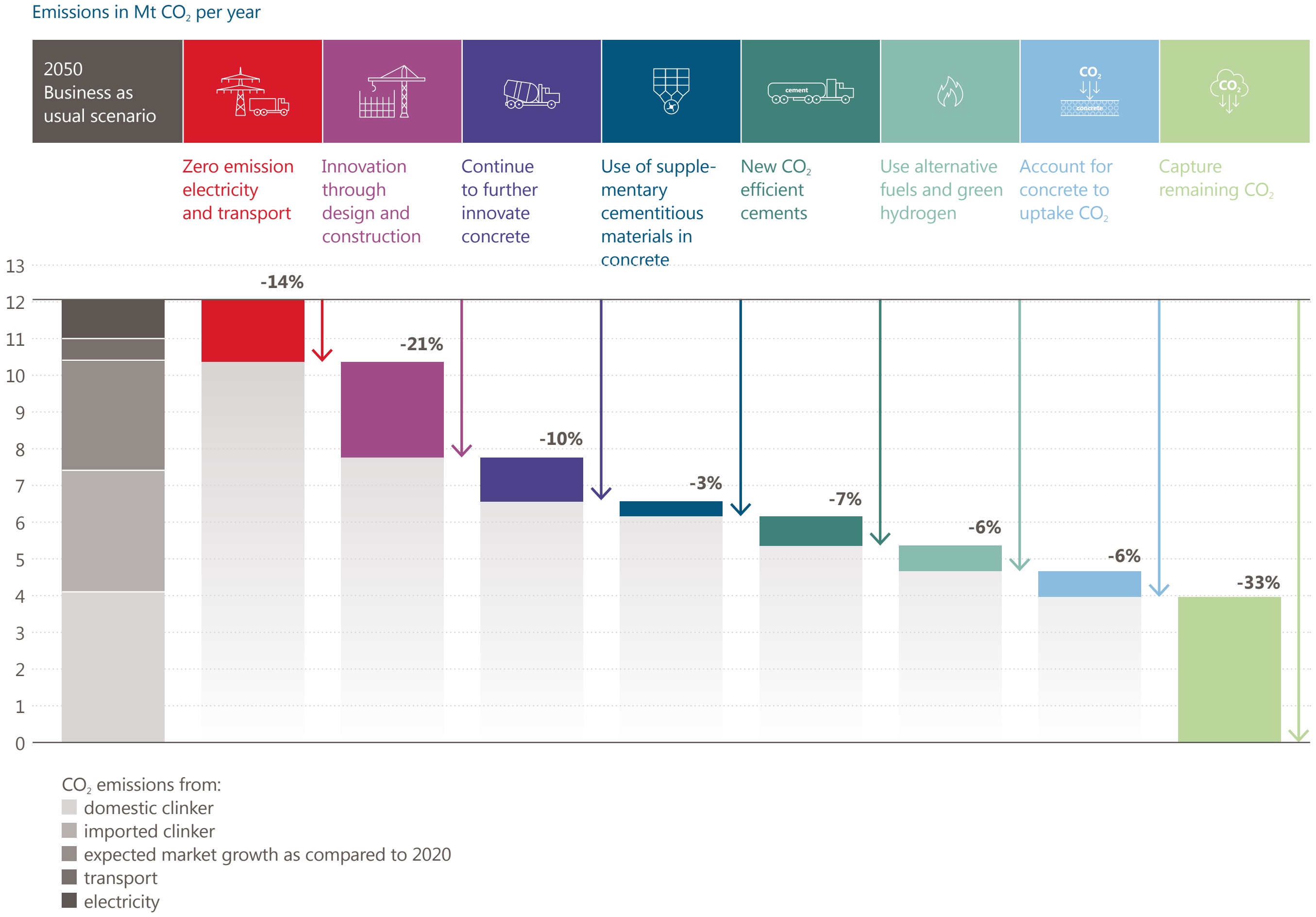
The demand for binder is expected to grow by 40 per cent by 2050. This assumption is based on the medium series population projections published by the Australian Bureau of Statistics [70]. Data on cement and SCMs consumption combined with population statistics in the period 1990 to 2020 show that, on average, there has been a significant correlation between cement consumption and

Figure 6: Clinker and cement volumes 2020 and 2050



*includes imported cements and cement from imported clinker not covered by CIF members

Figure 7: Pathways for CO_2 emissions reduction by 2050 in the cement and concrete value chain



The business as usual scenario is based on a 40 per cent growth of the construction market by 2050

population size over the past 30 years [71] [72] [73]. It is assumed that this relationship will continue to apply over the next 30 years and as such the demand for binder should follow the increase in population.

This results in a demand for binder in 2050 of 20.9 Mt. Through innovations in design and construction approx. 5.2 Mt of the binder (25 per cent) can be saved per year. Innovations in concrete technology can save another 2.4 Mt/a binder (15 per cent of the remaining binder after innovations in design and construction). The remaining binder demand by 2050 accounts for 13.3 Mt. Taking into consideration a mean clinker/cement factor in 2050 of 60 per cent and 50 per cent total SCMs in concrete (= clinker binder factor of 50 per cent), the final requirement for clinker will be 6.7 Mt.

Based on the clinker quantities implemented in Figure 6, CO_2 emissions from the cement and concrete value chain for a business-as-usual-scenario (BAU) in 2050 have been derived as shown in Figure 7. The baseline for CO_2 emissions includes direct (scope 1) emissions from domestic clinker production and imported clinker in 2020 plus the market growth as compared to 2020, as well as the CO_2 emissions from electricity and transport in a BAU scenario without any additional measures applied to reduce these CO_2 emissions. The BAU emissions have been calculated to be 12 Mt CO_2/a.

It is assumed that Australia will have zero emission electricity and transport by 2050. Innovation in design and construction will ultimately allow building with less concrete even though the demand for infrastructure or buildings will grow. The pathways for CO_2 savings in cement and concrete rely on the further development of concrete and lowering the clinker factor in cement and concrete through SCMs and the introduction of new CO_2-efficient cements. CO_2 emissions from clinker production will be lowered by the use of alternative fuels and green hydrogen as well as capturing the residual amount of CO_2 and its subsequent use or storage.

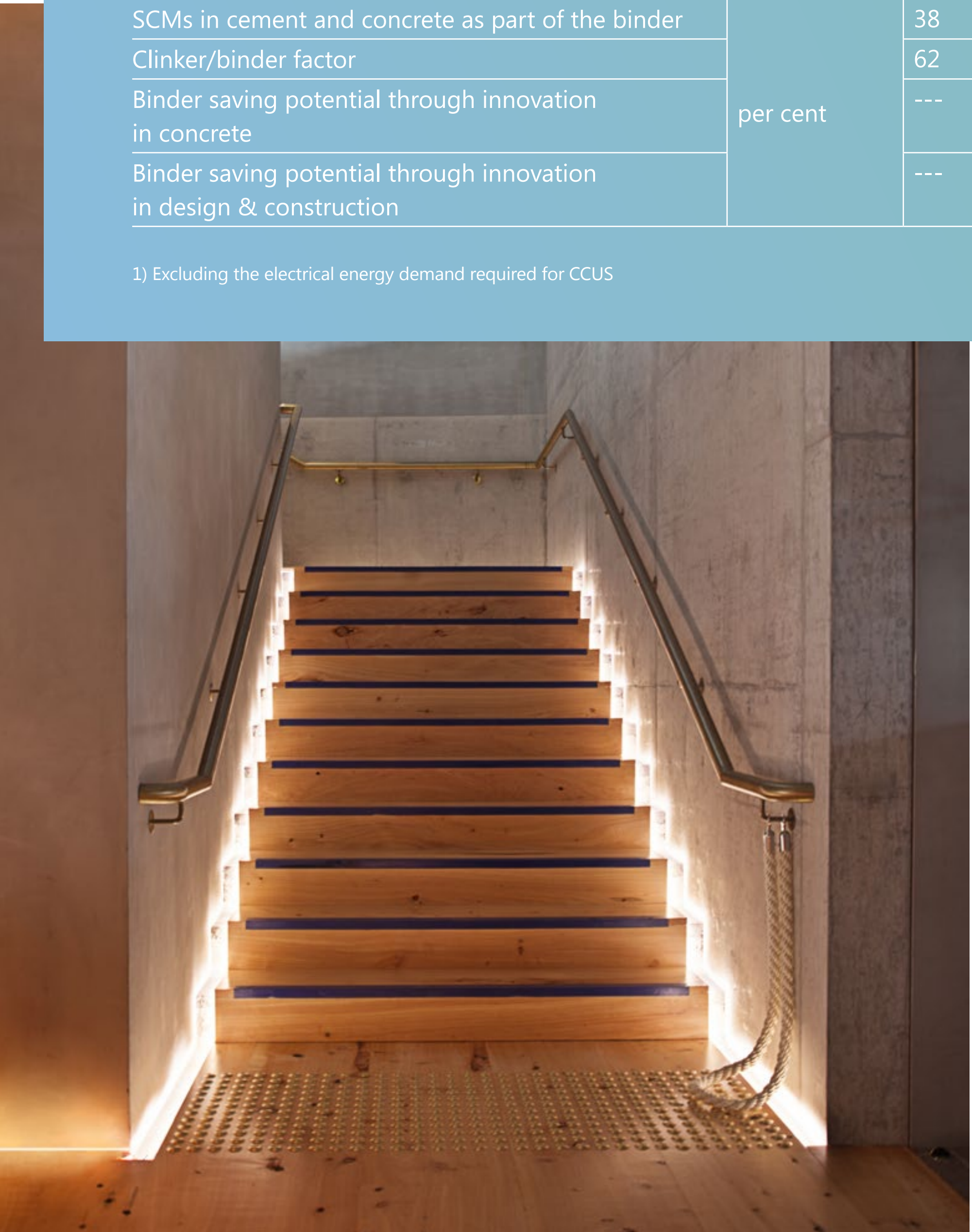
7.3 Results and evaluation of the scenario

The main results of the decarbonisation pathway can be summarised as assumptions for the CO_2 reduction measures – see Table 1.

Table 1: Assumptions of the decarbonisation pathway

	Unit	Baseline (2020)	2030	2050
Domestic clinker production	Mt/a	5.2	5.2	6.4
Specific fuel energy demand	MJ/t clinker	3,445	3,486	3,345
Specific electrical energy demand	kWh/t cement	100	100	90[1]
Thermal substitution rate alternative fuels (green hydrogen)	per cent	18	30	50 – 60 (10)
Alternative fuels biogenic content		40	50	50
Clinker/cement factor		84	70	60
Cement (annual consumption)	Mt/a	11.7	12.4	11.1
Clinker CO_2 emission factor	kg CO_2/t cli	791	771	703
SCMs in cement and concrete as part of the binder	per cent	38	44	50
Clinker/binder factor		62	56	50
Binder saving potential through innovation in concrete		---	5	15
Binder saving potential through innovation in design & construction		---	8	25

1) Excluding the electrical energy demand required for CCUS



7.4 Decarbonisation measures and their technology readiness level

The measures described above are part of the pathway to decarbonise cement and concrete. A description of their contribution and the TRL are provided in Table 2. The definition of the different TRL is given in Annex B.

Table 2: Decarbonisation pathways and their technology readiness level (TRL)

Pathway	Description of the contribution	TRL
Electricity	It is assumed that energy efficiency will be continuously improved and that the sector in Australia will be fully decarbonised by 2050.	---
Transport	It is assumed, that all transport systems in Australia will be fully decarbonised by 2050.	---
Innovation in design and construction	▪ Structural optimisation to realise the same performance with less material ▪ Improved design assumptions and methods with higher accuracy ▪ New and improved construction technologies ▪ Lifetime extension, repair and reuse **25 per cent binder saving through innovation in design and construction by 2050**	Technologies like hollow core slabs or the reduction of pumping can be implemented immediately. Others have to be developed, see chapter 9.
Innovation in concrete technology incl. SCMs in concrete	▪ Replacement of clinker by SCMs and geopolymers in 2050: SCMs in cement and concrete is expected to be 50 per cent of the binder volume in concrete (clinker/binder factor of 50 per cent) ▪ Reduction of binder content through optimised packing density, use of new admixtures etc. ▪ Avoidance of waste in concrete production through better forecasting, adapted truck size, shift to precast etc. **15 per cent binder saving through innovation in concrete technology by 2050**	Technologies like packing density optimisation of concrete can be implemented within a short period of time. Others have to be developed, see chapter 9.
Reduction of the clinker factor	Examples for future clinker efficient cements: ▪ Cement with limestone content of 20 per cent or more ▪ "LC3" – cements with 50 per cent clinker, 30 per cent calcined clay and 20 per cent limestone ▪ Cements with 35 per cent clinker, 45 per cent fly ash / calcined clay / GGBFS and 20 per cent limestone To establish the use of concrete with such cements including additional use of SCMs in concrete, the concrete composition has to be chosen according to the relevant requirements (fresh concrete properties, strength and durability). This will result in a more differentiated use of concrete types dependent on the application. **Assumptions:** Around 60 per cent of the concrete market: commercial and non-residential buildings / housing, here clinker/cement factor: 50 per cent. Around 40 per cent of the concrete market: infrastructure, here clinker/cement factor: 70 per cent. **Average clinker/cement factor:** **60 per cent by 2050**	The Australian cement standard AS 3972-2010 does not yet reflect the need to lower the clinker factor. Also the concrete standard should make reference to the performance of new clinker efficient cements. It is recommended that a database on technical and environmental aspects be developed – see chapter 9.

Pathway	Description of the contribution	TRL
Fuel efficiency	The thermal substitution rate (TSR) will continue to rise in the coming decades. Technological upgrades are expected to occur in the Australian cement plants by 2050. The kiln lines will be optimised for high TSR, which will bring thermal energy efficiency gains when compared with current technology. It is suggested that green hydrogen be used as a fuel, substituting 10 per cent of the conventional fossil fuels. Higher rates may be possible in the future and should be subject to further research. **Thermal substitution rate of 50 to 60 per cent and 10 per cent green hydrogen by 2050** **Thermal energy efficiency gains of up to 6 per cent**	A TSR of 60 per cent is state of the art; the alternative fuel's biomass content of 50 per cent will require dedicated fuel preparation including separate drying or even gasification. Further research may be necessary for process optimisation, also with respect to the use of hydrogen [6] beyond a TSR of 10 per cent. Technological upgrades will be based on BAT (Best Available Technique) [43] [44] [74] .
Recarbonation	For this report, the most conservative approach was used. **CO_2 uptake equivalent to 20 per cent of the process emissions**	---
CCUS	Several carbon capture (CC) technologies have been investigated in the past decades. CO_2 capture leads to an inevitable increase of clinker cost, whose magnitude and uncertainty depend on the CCUS technology chosen. It is proposed that the CCUS value chain be evaluated at an industrial scale in this decade.	CC technologies are currently available at different TRLs – an overview is given in annex A.
Thermal mass	For this report, thermal mass is not taken into consideration as a (quantified) pathway.	---

8 Economic benefits and costs

All conventional measures to reduce CO_2 from clinker or cement manufacturing require a certain capital investment. They can result in additional operational costs or savings – depending on the specific situation in each case. Carbon capture, however, as a breakthrough technology will require significant investment and will entail higher operational costs. The use of green hydrogen as a fuel is likely to lead to a significant increase in operational costs while upfront investment costs might be moderate.

External factors, which can also be site-specific, include the availability and affordability of supplementary materials as well as alternative fuels. In this context, transport costs can have a significant impact on the overall economic feasibility of each of the measures.

Detailed investment and operational costs for the various decarbonisation measures depend on the specific situation at plant level and can only be accurately determined through specific feasibility studies. Nevertheless, generic figures can be given for decarbonisation measures in clinker and cement production [6].

Reduction of the clinker factor:

- Further reduction of the clinker content in cement through the increased use of limestone, GGBFS or calcined clays will require capital investment on a plant level of A$10-20 million for further storage capacity as well as technical equipment for handling, dosing and drying where required. Operational costs are expected to vary depending on the material, for example they are potentially lower in the case of limestone but higher for calcined clays.
- Further reduction of the clinker content in cement by use of fly ash requires capital investment on a plant level of A$10-20 million for further storage capacity as well as technical equipment for handling and dosing. Operational costs will increase by around A$70 /t of fly ash. This is based on future fly ash that will be taken from existing stockpiles and which will need to be dried and further processed. Investment for processing the various grades of fly ash by separating them with respect to their carbon content and lowering their chloride content, cannot be quantified at this stage – see suggestions for innovation areas in Chapter 9 of this report.

Use of alternative fuels and green hydrogen:

- The use of alternative fuels may lead to lower operational costs as compared to operating with coal and gas only. Nevertheless, alternative fuels have to be pretreated, stored and handled respectively. Investment and operational costs for this are difficult to estimate and are again dependent on plant specific conditions.
- Use of green hydrogen as a fuel will most likely entail higher operational costs. Assuming a stretch goal of A$2 /kg [75] and a substitution rate of 10 per cent, replacing a mix of coal and gas will result in an increase in operational costs of about A$5 /t of cement.

Carbon capture:

The Australian Government has set stretch goals to encourage the accelerated adoption of technology across key sectors [76]. In some cases, the stretch goals represent the price point at which technologies are commercially substitutable for existing highemissions enduses. For carbon capture and storage A$20 per ton of CO_2 has been seen as a preliminary value. The stretch target should cover the full cost of compression, transport and storage from point emissions sources [76].

For this study information from several international sources has been evaluated to assess the stretch goal of A$20 per tonne of CO_2 against the known cost range for CO_2 capture, transport, storage and use in the cement sector. Table 3 shows cost ranges for the various carbon capture technologies as well as for transport, storage and utilisation, where it can be seen that the cost ranges are still quite significant. This is also mirrored in the different Technology Readiness Levels (TRL, a list describing the TRL is given in Annex B). Some technologies still need to be further developed toward full scale applications, however, with TRL 6 and higher it is expected that a sufficient maturity level exists to start its application in cement plants. Exact cost figures can only be determined through plant-specific feasibility studies into CO_2 processing, transport, storage and/or utilisation of CO_2.

The abatement costs listed in Table 3 underline the fact that actual cost figures are likely to be much higher than the proposed stretch goal of A$20 /t CO_2. Since existing clinker producers are already significantly trade exposed, it can be assumed that a stretch goal of A$20 /t CO_2 will impact on the competitiveness of the industry. Further, targeted federal and state government policies and programs will be required in order to maintain the international competitiveness of the industry.

Table 3: Costs for carbon capture, transport storage and utilisation. The figures give total costs, combining capital investment and operational costs taking into account the relevant depreciation times for the equipment [61] [62] [64] [65]

Measure	Technology	TRL	Abatement costs	
			A\$ / t CO_2	A\$ / t clinker
CO_2 capture	Tail-End Calcium Looping	6-7	100-125	70-85
	Membrane-assisted CO_2 liquefaction	5-6	70-75	50-55
	Oxyfuel	6	60-95	40-65
	Integrated Calcium Looping	6	60-120	40-80
	Calix ®	6	no estimate available	
CO_2 transport	Inland by pipeline (300 km)	---	15	10
	Inland by train (300 km)	---	25-30	15-20
	Offshore by ship (< 1000 km)	---	15-50	10-35
CO_2 storage (CCS)	Intermediate for liquefaction	---	15	10
	Offshore storage *	---	10-30	5-20
CO_2 utilisation (CCU)	Various purposes	---	320-630	225-440 **

* Almost all cost figures are from offshore projects. Onshore storage is possible too – it can be expected that the costs are slightly lower than the figures given.

** Costs for CO_2 utilisation can be offset by revenues from chemical products into which the CO_2 is converted. This requires a deeper economic analysis which has to take into account the overall market situation (price and market size) of the respective chemical products [77].

9 Future R&D priorities and projects

In order to further develop low emissions cement and concrete, the entire infrastructure and construction value chain from clinker, cement and concrete to the construction site, the structure itself, the re-use of components and the recovery of construction waste have to be considered. Not all of the technologies required have yet been developed to such an extent that immediate application is possible. Therefore, ten areas of innovation were identified with regard to national and international sources of information and interviews with experts. These areas define future R&D priorities and projects – see Table 4.

Table 4: Innovation areas along the value chain

Pathway	Description of the contribution		TRL
Clinker	Alternative fuels with biomass	Cement companies, CSIRO, universities and related research organisations – both domestic and international, federal and state targeted programs.	< 2025
	Carbon capture	Calix, CO_2CRC, HILTCRC, ECRA, CarbonNet and other providers.	<2025
	Green hydrogen as a fuel and for CO_2 utilisation	Future Fuels CRC, H_2TCA, H_2council, ECRA and inter-governmental and research partnerships.	< 2025
	Energy efficiency	Cement companies, HILT CRC, Race for 2030 CRC, CESMII and its partners.	< 2025
Cement, Concrete	Beneficiation of fly ash to be used as SCM	SmartCrete CRC, Federal and State research organisations, governments and related bodies.	< 2025
	Database on low carbon cement and concrete	SmartCrete CRC, Race for 2030 CRC, L3C, universities and related research and government organisations – both domestic and international.	< 2025
Cement, Concrete, Construction	Specification of concrete durability by performance	SmartCrete CRC, fib*, RILEM*, universities and related government and research organisations – both domestic and international.	< 2025
	Potentials of additive manufacturing and digitalisation	SmartCrete CRC, ETH Zurich, CSIRO, RILEM*, universities and related government and research organisations – both domestic and international.	> 2025
	Recarbonation – potentials regards natural CO_2 uptake in Australia and further active CO_2 treatment technologies	SmartCrete CRC, fib*, RILEM*, universities and related government and research organisations – both domestic and international.	<2025
Construction	Resource-efficient design principles	SmartCrete CRC, Race for 2030 CRC, fib*, University of Stuttgart – formerly Werner Sobek, universities and related government and research organisations – both domestic and international.	> 2025

* fib and RILEM are research and pre-normative networks themselves through which multiple research contacts can be generated

** The list of potential partners is not exhaustive. There are other research networks and/or universities which can provide input to the respective innovation area.

Details of each innovation area are provided on the following pages in the form of a brief profile describing the starting point, the aim and the main item and work packages respectively.

INNOVATION AREAS

Alternative Fuels with Biomass

Alternative fuels with biomass provide positive impact on CO_2 emissions and circular economy

Starting Point

- Australia has a high potential to further substitute fossil fuels with alternative waste solutions.
- The use of alternative fuel is currently low compared with other countries and below what is technically possible. Clinker burning provides inherently good conditions for co-processing of waste.
- Future waste options are likely to be different from today's waste .

A thermal energy substitution rate (TSR) of 18 per cent in Australia is still relatively low compared to other countries, however, has been increasing steadily. With long residence times at very high temperatures and the incorporation of fuel ashes in the final product, the clinker burning process presents unparalleled conditions for the co-processing of waste. The continuous technological evolution of industrial processes and the increasing societal pressure towards higher recycling rates will drive the type of waste streams available for co-processing in the future.

Aim of the (joint) research project

- Show potential of cement plants to contribute to local waste management.
- Encourage the development and implementation of future fuel concepts based on defined waste streams.

The role that cement plants can play in local waste management needs to be further assessed. The availability of alternative fuels and/or favourable economic conditions has to determined (e.g. price of fossil fuels compared to alternative fuels and CO_2 costs) to enable a sustainable growth of the TSR in the future. Available waste streams need to be identified and characterised. Adequate pre-processing technologies have to be selected to enable the conversion of waste into suitable alternative fuels.

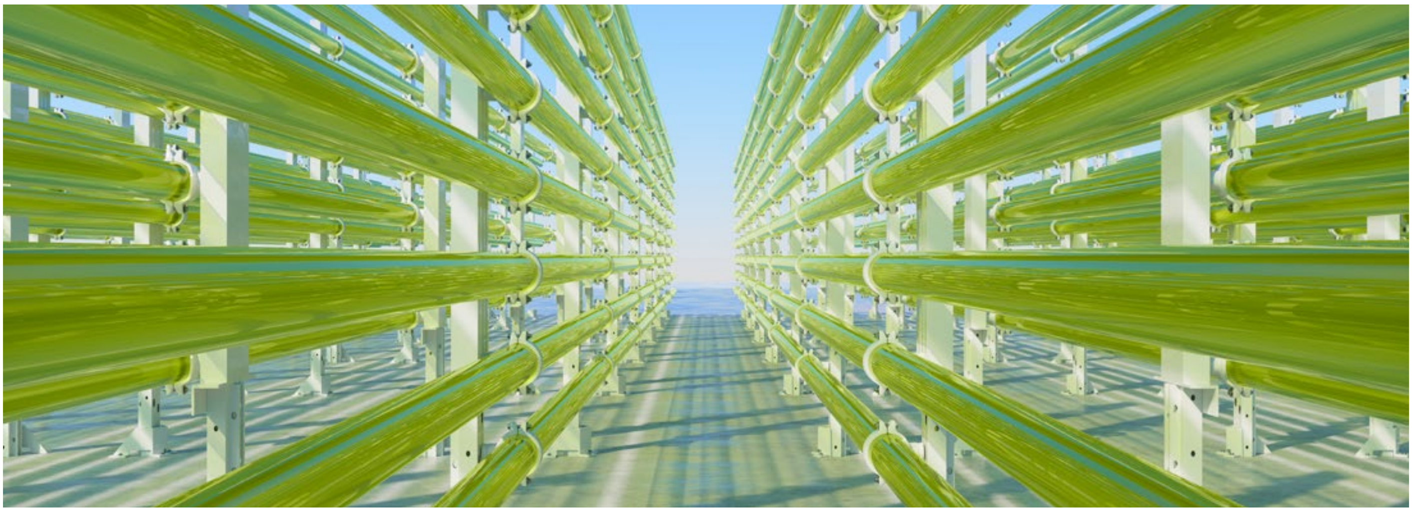
Work packages

- Show best practices: seminar, workshop, conferences.
- Engage local and regional stakeholders.
- Highlight and potentially test modern combustion technologies.

Seminars, workshops or conferences targeted at specific stakeholders (technical, local communities, etc.) for dissemination of the best practices in pre-processing and co-processing of alternative fuels should be organised to increase the awareness of the societal, environmental and technical benefits associated with this technology. The use of biomass at high TSR requires the deployment of modern combustion technologies which need to be assessed and tested.

Carbon capture

Carbon capture technologies and pathways towards storage and utilisation



Starting Point

- Carbon capture technologies ready for testing and implementation.
- High CAPEX and OPEX.
- First demonstration/industrial scale capture, storage and/or utilisation projects still to be realised.
- Australia can provide relevant CO_2 infrastructure, storage sites.
- Australia can provide H_2 for transforming CO_2.

Carbon capture technologies are currently available for testing and implementation at different TRLs. The first CCUS demonstration projects at industrial/ semi-industrial scale covering the whole CO_2 value chain are expected in the present decade. However, carbon capture is in general also linked to high CAPEX and OPEX. Captured CO_2 combined with H_2 can be utilised in the production of synthetic fuels. Several potential CO_2 storage sites in Australia have already been identified.

Aim of the (joint) research project

- Integrate capture in cement production into national CCUS plan.
- Produce the first CO_2 free clinker in Australia.
- Show costs and impact of competitiveness.

The project aims to investigate and demonstrate CCUS in semi-industrial scale adapted to the specificities of the Australian cement industry and ultimately produce its first CO_2 free clinker. In addition, it aims to inform and develop trust amongst all stakeholders and prove the value of integrating carbon capture in cement manufacturing into the Australian CCUS plan. Synergies with other local industrial partners needs to be investigated in order to identify new business opportunities, increase the value of CO_2 and reduce costs (e.g. creation of a CCUS cluster).

Work packages

- Develop a feasibility scenario for carbon capture in the Australian cement industry.
- Apply carbon capture on demonstration scale and then scale to commercial phase in the future.
- Test indirect calcination (CALIX) to integrate domestic technology.
- Study the synergies with H_2 production at site of cement plant.

A feasibility study taking local specificities into account can provide the launch pad for the demonstration of CCUS in Australia. The production of H_2 in a cement plant with electrolysers to substitute fossil fuels or convert CO_2 into a product with more added value shall be studied. Possible synergies with local carbon capture technology providers (e.g. CALIX) need to be further assessed.

INNOVATION AREAS

Green hydrogen as a fuel and for CO_2 utilisation

Synergies between H_2, O_2 and CO_2 generation

Starting Point

- Green hydrogen to play an important role in energy transition and decarbonising heavy industries.
- Australia well positioned in H_2 generation.
- Hydrogen infrastructure requires further development.
- International agreement in place.

The use of green H_2 is seen as a promising vector to reduce CO_2 emissions in energy-intensive industries, as only H_2O is generated from its combustion. The availability of renewable and fossil energy resources positions Australia well in the production of affordable green H_2, however, investment and new infrastructure will be required.

Aim of the (joint) research project

- Enable green H_2 as a fuel in clinker burning.
- Show synergies between H_2, O_2 and CO_2 generation.

The combustion of H_2 is yet to be tested in the cement industry. Prohibitive costs, scarce availability as well as safety and logistic/handling issues have always kept H_2 out of the list of potential "alternative fuels" to date. How exactly H_2 might impact on cement manufacturing process is yet to be determined. Demonstration of the technology is crucial to aspire a wider dissemination in Australia and overseas by 2050. The electrolysis of water on-site can generate O_2 as a by-product. How O_2 can be used both for flame enrichment and, thus, to increase TSR in the main burner, or as substitute of air in some carbon capture technologies, needs to be investigated.

Work packages

- Develop framework of H_2 value chain.
- Identify the role of the cement industry.
- Test H_2 generation and simultaneous use of oxygen in oxyfuel and calcium looping technologies.

H_2 might be used in the future as fuel or feedstock in several industries. Thus, a national/regional regulation framework needs to be developed to provide the necessary guidance and confidence to all emerging players and investors in the H_2 value chain. The role of the cement industry will much depend on the envisaged demand of H_2 and if its generation can be decentralised (electrolysers on-site). The techno-economic and environmental benefits of carbon capture combined with H_2 and O_2 generated on-site have to be determined. Valuable data can be collected if the technology can be tested at plant level.

Energy efficiency

Increasing energy efficiency to the highest level

Starting Point

- Both thermal and electrical energy efficiency in cement plants are at a very high level.
- Increasing energy efficiency to the highest level – even if electricity is fully decarbonised or CO_2 from clinker manufacturing is captured.

Since energy constitutes a high share of costs in the production of cement, cement companies have always been striving to lower the demand for electricity and fuels. Further improvements in energy efficiency will lower the need for both decarbonised electricity and CCUS. To optimise and automate the production process IoT (Internet of Things), smart sensors, artificial intelligence and advanced control systems should be increasingly applied in the cement industry as they will also have an impact on energy efficiency.

Aim of the (joint) research project

- Show potential of IoT, smart sensors, artificial intelligence and advanced control in the cement industry, and in particular their effect on energy efficiency – both electrically and thermally.

The RACE for 2030 CRC has been involved in the CESMII research project, in which smart manufacturing has achieved more than 15 per cent improvement compared to previously with glass kilns. The gains with CESMII in fuel efficiency in the glass industry were achieved using smart sensors and AI for combustion controls, which is the starting point for a major part of the work which the consortium is now undertaking in modelling the cement production process.

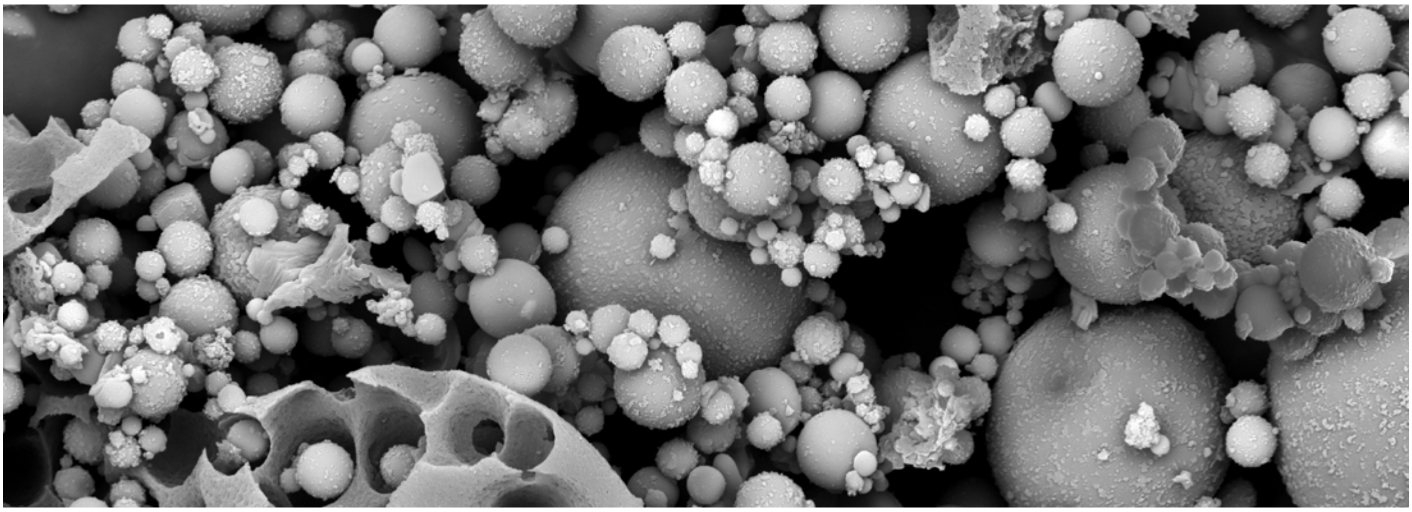
Work packages

- Search for existing or develop new predictive models which include data analysis based on data collection with smart sensors and meters.
- Study the application of smart (and lean) manufacturing strategies in cement production to show potential to automate the process and to lower the overall energy demand – both electrically and thermally.

Predictive modelling is already today an integrated part of the cement production process. Less kiln stops through predictive maintenance, combustion control assisted by artificial intelligence, and predicting the cement performance based on the analysis of laboratory data are increasingly being implemented. The work packages will take advantage of existing experience and will show existing potential for the application of smart manufacturing and its role in increasing energy efficiency.

Beneficiation of fly ash

Fly ash which has been stockpiled can qualify as SCMs – once its quality has been assured



Starting Point

- Decarbonisation of the power sector will likely lead to less fly ash production in the future.
- In Australia, coal combustion products (CCP) are stockpiled.

In Australia, about 500 million tonnes of Coal Combustion Products like fly ash are stockpiled, some of which can be used as SCMs in cement and/or concrete. Fly ash must be sorted and the quality of suitable fractions must be checked and improved (beneficiation).

Aim of the (joint) research project

- Make stockpiled fly ash available in high amounts as SCM in cement and/or concrete.
- Show the potential (volume and quality-wise) of Australian CCP which are stockpiled.
- Apply methods of beneficiation and check its technical and economical relevance.

The quantity of the fly ash as a fraction of the total CCP needs to be evaluated. In addition, its quality, of which the unburnt carbon and chloride content are the most important indicators, must be determined. Clear techno-economic indicators are required as a basis for near-term decisions on to which degree fly ash can be recovered from existing volumes. Several techniques should be evaluated – always against the background of the final quality of the processed fly ash, the overall recovery rate and the costs entailed. Since most of the CCP have been kept wet to avoid fugitive dust emissions, drying efforts must be included in the recovery and beneficiation process. A special focus should be given to the chloride content of fly ashes which are ponded in saline waters.

Work packages

- Make stockpiled fly ash available in high amounts as SCMs in cement and/or concrete.
- Show the potential (volume and quality-wise) of Australian CCP which are stockpiled.
- Apply methods of beneficiation and check its technical and economical relevance.

The work packages could be jointly worked on with experts from respective research organisations, coal producers and technology providers. A techno-economic analysis is needed to ensure proper decisions for scaling up the findings of this project.

Database on the properties of low-carbon cement and concrete

A tool to develop trust in low-carbon products from all stakeholders

Starting Point

- Cement and concrete with a low clinker-binder factor are key pathways to further reduce CO_2 emissions in the concrete sector.
- Insufficient database on the performance.

Cement and concrete with a low clinker-binder factor are key pathways to further reduce CO_2 emissions in the concrete sector. Within the Australian concrete standard, only certain cements or types of cement are mentioned and are therefore permitted, and the durability-performance of new cements and binders would need sufficient proof e. g. by testing. Therefore, the database on the durability performance of such cements and concretes should be improved.

Aim of the (joint) research project

- Development of a comprehensive database on the properties of low-carbon cement and concrete.

The development of a comprehensive database on the properties of low-carbon cement and concrete is essential as all stakeholders, clients, designers, contractors and authorities will help to develop trust that these cements and concretes will also produce high-quality, durable and therefore sustainable concrete structures. The project is linked to the innovation area “Specification of concrete durability by performance tests and service life considerations”, where the correlation between lab-performance and the performance of concrete in the building is further investigated and established.

Work packages

- Production of clinker-efficient cement and concrete (lab/plant).
- (Lab)Properties of clinker-efficient cement and concrete:
  - cement properties
  - fresh and hardened concrete properties
- Field site properties of clinker-efficient concrete.

Clinker-efficient cements and concretes are to be produced on a lab-scale and in the plant. Cement properties as well as fresh and hardened concrete properties are to be determined for a broad range of cement and concrete compositions. In addition to the innovation area “Specification of concrete durability by performance tests and service life considerations”, field site tests are an essential part of the project.

INNOVATION AREAS

Specification of concrete durability by performance

Performance-based specifications as a contribution to decarbonised and resource-efficient concrete

Starting Point

- Only certain cements or types of cement permitted today in the Australian concrete standard.
- Prescriptive specifications by road authorities.
- Low flexibility to show durability of decarbonised and resource efficient concrete.
- Performance-based specifications as an option.

Only certain cements or types of cement are mentioned and are therefore permitted, and the durability-performance of new cements and binders would need sufficient proof e. g. by testing.

Further, road authorities in Australia usually have prescriptive specifications and therefore a low flexibility to show the durability of decarbonised and resource efficient concrete. Performance-based specifications are an option to effect change.

Aim of the (joint) research project

- Sufficient durability of decarbonised and resource-efficient concrete structures through performance-based specifications.

The project aims at significantly contributing to decarbonised and resource-efficient concrete and at the same time ensuring durability of concrete structures and a sufficient service life through performance-based specifications.

Work packages

- Investigation on a representative selection of existing structures.
- Limit states of durability.
- Test procedures (laboratory, building tests).
- Classification of resistances, production control and conformity criteria.
- Acceptance tests / criteria on site / for the building.

The correlation between the result of performance tests under laboratory conditions and the performance in the building or structure should be investigated. This should also include the knowledge of how the results of a concrete or nominally identical concrete composition vary under the conditions – for example, in a ready-mixed concrete plant: changes in the constituents, weighing tolerances, moisture of the aggregates etc. The durability of the building must be defined. Is this the point in time of the depassivation of the reinforcement or should the corrosion rate of the reinforcement be considered? The measures of production control and conformity criteria would have to be worked out for the corresponding concretes. Finally, acceptance tests and acceptance criteria on-site and for the building should be developed and defined.

Additive manufacturing (e. g. 3D printing) and digitalisation

What is the contribution to decarbonisation and resource efficiency?

Starting Point

- The methods of digital production with concrete are currently gaining maturity.
- What are the potentials for decarbonisation and resource efficiency?

The topic of digital production with concrete is being developed and evaluated in many places around the globe. A number of practical pilot-scale applications already exist. Some raise tremendous expectations with these technologies in terms of productivity and quality. However, the question of the contribution to decarbonisation and resource efficiency is also open.

Aim of the (joint) research project

- Greater use of digital production techniques in concrete construction: positive contribution to decarbonisation and resource efficiency?
- Advantages and limits of the existing technologies?
- Future areas of application.

The project aims to specifically answer the question of whether a greater use of digital production techniques in concrete construction – beyond the issues of skill shortages and productivity – would also make a positive contribution to the questions of decarbonisation and resource efficiency. Against this background, the advantages and the limits of the existing technologies as well as the future areas of application and the users should be addressed.

Work packages

- Required material properties of fresh and hardening concrete.
- Integration of the reinforcement.
- Technology-compliant or technology-promoting construction principles and design rules.
- Potentials for decarbonisation and resource efficiency, e. g. by Life Cycle Assessments (LCA).

A practicable procedure for the definition, adjustment and testing of the required material properties of fresh and hardening concrete should be elaborated. Adequate solutions for the integration of the reinforcement are to be developed. The development of technology-compliant or technology-promoting construction principles and design rules is also important. The future availability of resources in conjunction with the new manufacturing technologies must be taken into account. The potentials for decarbonisation and resource efficiency will be assessed e. g. by Life Cycle Assessments (LCA).

Recarbonation

Potentials for the natural uptake of CO_2 in Australia and further active CO_2 treatment technologies

Starting Point

- Hardened concrete takes up CO_2. This natural diffusion process is called (re)carbonation.
- Fresh concrete can also absorb CO_2.
- Active treatment of fresh concrete, concrete elements, secondary aggregates and crushed concrete fines with CO_2 is an option.

Carbonation is a chemical reaction which transforms calcium hydroxide to calcium carbonate. For this study, the most conservative approach of 20 per cent of process CO_2 emissions for recarbonation of hardened concrete was taken into account. Studies on active CO_2 processing of fresh concrete and recycled aggregates show further potentials.

Aim of the (joint) research project

- Demonstrate the potential of fresh concrete to uptake CO_2.
- Show the impact of carbonation when curing concrete elements in a CO_2 enriched atmosphere.
- What is the influence of (actively) carbonated secondary aggregates and crushed concrete fines on the properties of recycled concrete?

The carbonation potentials which are measured and which are documented in the literature should be examinded from an Australian perspective. The potential to develop a method for inclusion under the Emissions Reduction Fund in the future is to be evaluated.

Work packages

- Calculate CO_2 uptake in Australia.
- Show the impact of a CO_2 enriched atmosphere on concrete elements, secondary aggregates and crushed concrete fines.
- Calculate CO_2 uptake of mortar and concrete during their service life and after the end of life for the Australian situation.
- Demonstrate the potential of fresh concrete to uptake CO_2 and to save cement in concrete.
- Show the impact a CO_2 enriched atmosphere on concrete elements, secondary aggregates and crushed concrete fines.

Resource efficient design principles

A contribution to sustainability at the component and building level

Starting Point

- Concrete elements subject to bending stress with simple and compact full cross-sections become relatively inefficient with regard to the sustainable use of concrete.
- Typical examples are ceiling tiles, beams or wall-like slabs, which are used in large amounts.

In the case of components subject to bending stress, simple and compact full cross-sections become inefficient. Large cross-sectional areas are unused statically. Reinforced concrete structures of this kind primarily support themselves with a typical weight share of around 70 per cent. The traffic load therefore requires 2.5 times its share of the concrete ceiling for taking up the load.

Aim of the (joint) research project

- Create the basis for the broad introduction of resource-efficient design methods.
- Material that is not required is removed.

The aim is to create the basis for the broad introduction and application of resource efficient design methods e. g. by the alignment of outer forms and inner reinforcements with the flow of forces. The results are slim, material-saving constructions that largely have axial compressive and tensile stresses.

Work packages

- Topological optimisation.
- Material-appropriate control.
- Inner reinforcement finding.
- Hollow bodies in panels and walls.

Modern approaches to topology optimisation are numerically structured and use the finite element method (FEM) as an analysis method. For material-appropriate designs, it is important to include characteristics of the material to be used in the optimisation process. For concrete this means a distinction between compressive and tensile stress in the form-finding process and their prioritisation. Hollow or displacement bodies can reduce the concrete volume used in components such as slabs, walls or shells.

10 Successful industrial transformation: Prerequisites and boundary conditions

Lowering the clinker factor

Over the next few years, it will be essential to make further advances with regard to the efficient use of clinker in cement and concrete. Lowering the clinker factor in concrete will bring a fundamental shift in focus and requires a whole-of-supply-chain approach. There are different ways to deliver the required outcome and there will be no "hard lines" between the pathways, in particular between the use of SCMs in cement and concrete respectively.

New regulatory frameworks to reduce the clinker factor across the supply chain

The existing regulatory frameworks, which include standards and work methods that interact across the supply chain, should be updated. Barriers to lower the clinker factor should be addressed such as cement and concrete standards.

Standardisation of regulations to accelerate the transition process

Feedback from the supply chain clearly highlights the need to make regulations more coherent across the country avoiding multiple interpretations and implementations of regulatory frameworks across multiple jurisdictions such as specifications of road authorities or waste to energy regulations.

Transition from product push to market pull

It is obvious that merely producing clinker-efficient cements and concretes is not enough. It is essential to put them to practical use as well. Therefore, close cooperation and ongoing exchange of knowledge along the entire value chain of cement and concrete is crucial, including cement and concrete customers, developers, designers, building material procurers, architects, standards authorities, government and non-government agencies, and concrete and cement manufacturers. Overall, this cooperation will bring more significance to be attached to the topic of CO_2 in construction work.

Public investment provides a major part of infrastructure spending, and since state regulator´s standards will continue to determine how the majority of concrete is produced, the supply chain is expecting governments and regulators to take leadership in procurement processes with a strong focus on embodied carbon and subsequently clinker factor in concrete constructions.

Context for approaching the different pathways

This report provides the basis for comprehensive engagement plans for the Australian cement and concrete sector to decarbonise by 2050. Some pathways within this report can be implemented quickly, since the technologies are

Implementing the pathways

Engagement plans for the different pathways should be framed with the relevant horizons which will be useful in gaining early success and developing new technology for its commercial use.

available – for example, the increased use of SCM. Others such as CCUS are being tested and will need time for commercial application into existing plants.

The demand for electrical energy required for clinker production is likely to increase (potentially double) when carbon capture technologies are applied. This makes the availability of renewable energy and high-performance power grids an important prerequisite for reducing CO_2 emissions from the generation of electrical energy for cement manufacturing.

The cement industry needs long-term access to adequate amounts of alternative fuels containing biomass, which will play a role in minimising fuel-induced CO_2 emissions in the cement industry. It is therefore important to identify possible interactions between climate, air emissions, waste and resource policies and to balance potential effects on specific material flows accordingly.

The creation of a functioning CO_2 infrastructure is of crucial importance – both with regard to the decarbonisation of cement and concrete and to the development of new CCUS value chains. Only in this way will it be possible to ensure that CO_2 can be appropriately utilised or stored following its capture. The importance of developing a suitable CO_2 infrastructure can be illustrated by the many industrial carbon capture projects that are currently being planned.

Cooperative research will help support the adaptation of the standards and building codes which are needed to apply low emission cements and concretes in the market. Public funding should be encouraged to support R&D and commercialisation and to lower investment and operating costs hurdles as pathways and its technology are implemented.

Since existing clinker producers are already significantly trade exposed, the expected costs associated with carbon capture will impact on the competitiveness of the industry. Further targeted federal and state government policies and programs will be required in order to maintain the international competitiveness of the industry.

The set of interdependent pathways as outlined in this Report clearly shows that Australia can have a decarbonised cement and concrete sector by 2050. It is up to all stakeholders including representatives from the cement, concrete and construction industry, policymakers, researchers and sustainability experts to successfully implement the different pathways by closely working together along the full value chain.

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12 Glossary of terms

Table 5: Expression/Terms and their Description/Explanation

Expression/Term	Description/Explanation
Aggregate	Natural, artificial, reclaimed or recycled granular mineral constituent suitable for use in concrete
Admixture	Constituent added during the mixing process in small quantities related to the mass of cement to modify the properties of fresh or hardened concrete
Alternative Fuels (AF)	All non-conventional fuels used in the cement industry as thermal energy source for clinker production (e.g. waste, biomass)
Binder	Sum of cement and supplementary cementitious materials in concrete
Carbon capture (CC)	Separating the CO_2 from the emissions in order to further process it and to avoid its release into the atmosphere.
Carbon capture utilisation and storage (CCUS)	Process of capturing and transporting CO_2 to a safe location to be stored in (CCS) or to be utilised as feedstock in other industries (CCU)
Calcined clay	Calcined clay and metakaolin are produced by heating a source of kaolinite to between 650°C and 750°C. Kaolinite is the essential part of kaolin which is naturally occurring as clay. Koalinite and other clay minerals are also part of industrial by-products, such as some paper sludge waste and oil sands tailings.
Cement	Finely ground inorganic material which, when mixed with water, forms a paste which sets and hardens by means of hydration reactions and processes and which, after hardening, retains its strength and stability even under water.
Cement consumption	Cement consumption describes the amount of cement that is used in a domestic market in a certain time period. It consists of domestic cement deliveries by local cement plants plus imported cement.
Cement grinding	The step in cement manufacturing where clinker and the other supplementary cementitious materials are ground to the required fineness.
(Portland Cement) Clinker	The key constituent of cement produced under high temperatures in rotary kilns from locally sourced raw materials such as limestone and clay
Clinker/cement factor	Amount of Portland cement clinker as part of the cement
Clinker/binder factor	Amount of Portland cement clinker as part of the sum of cement and SCMs in concrete
Clinker-efficient cement	Cement which contains one or more SCMs besides clinker
Conventional fuels	All traditional fossil fuels such as coal or natural gas commonly used as thermal energy source e.g. in the cement industry for clinker
Fly ash	Fly ash is obtained by electrostatic or mechanical precipitation of dust-like particles from the flue gases from furnaces fired with pulverised coal.
Fresh concrete	Concrete which is fully mixed and still in a condition that is capable of being formed and compacted by the chosen method.
Geopolymer	Geopolymer is a binder based on the reaction of (alumo)silicates with alkaline and/or acidic solution to form a network of inorganic polymers.
Ground granulated blast furnace slag (GGBFS)	Granulated blast furnace slag is made by rapid cooling of a slag melt of suitable composition, as obtained by smelting iron ore in a blast furnace. GGBFS contains at least two-thirds by mass of glassy slag and possesses hydraulic properties when suitably activated.

Expression/Term	Description/Explanation
Hardened concrete	Concrete that is in a solid state and which has developed a certain strength
Innovation area	Innovation areas define future R&D priorities and projects
Limestone	The bases for clinker production and a main constituent in cement (unburned limestone). Its main mineral constituent is calcium carbonate.
Precast element	Concrete element cast and cured in a place other than the final location of use (factory produced or site manufactured)
Ready-mixed concrete	Concrete delivered in a fresh state
Recarbonation	Concrete takes up CO_2 from the surrounding environment through a chemical reaction which transforms calcium hydroxide to calcium carbonate. This natural diffusion process is called (re)carbonation.
Rotary Kiln	Large industrial oven used in cement plants for clinker production
Site-mixed concrete	Concrete produced on the construction site
Supplementary cementitious materials (SCM)	SCMs can partly replace clinker in cement or can be used in concrete to partially replace cement: e.g. fly ash, ground granulated blast furnace slag (GGBFS), calcined clay, natural puzzolana, amorphous silica, unburned limestone
Thermal Substitution Rate (TSR)	Thermal energy from conventional, fossil fuels that is replaced by the use of alternative fuels (AF)
Truck mixer	Concrete mixer mounted on a self-propelled chassis capable of mixing and delivering a homogeneous concrete

13 Annex

Annex A Carbon capture technologies

Note: TRL: Technology Readiness Levels; RF: Retrofitability

Tail-End Calcium Looping

Technology: Post-combustion CO_2 capture process

Working principle and main characteristics	TRL	RF
■ CaL reactors (carbonator and calciner) are circulating fluidised bed reactors (CFBs). Flue gas is rooted to a carbonator, where calcined limestone is used as a CO_2-sorbent ($CaO + CO_2 \rightarrow CaCO_3$) ■ The calciner operates in oxyfuel mode (O_2 generated in an ASU) ■ A portion of the CaO generated in the oxyfuel calciner is rooted to the carbonator (closing the loop) and CaO-purge is sent to the raw meal for clinker production, the CO_2-rich flue gas stream is generated and CO_2 is captured in a CPU ■ Thermal energy penalty: very high, electrical energy penalty: high ■ Cost of avoided CO_2: 100-125 A$/t CO_2 (65-80 €/CO_2)	6-7	high

Membrane-assisted CO_2 liquefaction

Technology: Post-combustion CO_2 capture process

Working principle and main characteristics	TRL	RF
■ Two different separation technologies are combined: membrane and phase-separation/liquefaction ■ In a first step, polymeric membranes separate CO_2 in the flue gas, resulting in a moderate CO_2-purity gas stream. The driving force for separation is the component partial pressure differential across the membrane. ■ Subsequently the moderate CO_2-purity gas stream is purified to moderate-to-high feed purity through condensation of CO_2 and removal of the volatile components nitrogen, oxygen etc. by phase-separation. ■ Thermal energy penalty: inexistent ■ Electrical energy penalty: high to very high ■ Cost of avoided CO_2: 70-75 A$/t CO_2 (45-50 €/CO_2)	5-6	high

Oxyfuel

Integrated CO_2 capture process

Working principle and main characteristics	TRL	RF
■ Relies on combustion with pure oxygen in substitution of air (primary, secondary and tertiary air), which gives origin to a CO_2-rich flue gas ■ Oxygen produced in a Air Separation Unit (ASU), CO_2 is captured in a CO_2 Purification Unit (CPU – cryogenic separation) ■ Thermal energy penalty: inexistent to very low ■ Electrical energy penalty: medium ■ Medium technological risks, due to: CO_2 dilution in flue gas with false air ingress (e.g. kiln seals, poke holes and maintenance doors in the preheater/calciner, etc.) ■ Flexible system to operate in air and oxy mode ■ Cost of avoided CO_2: 60-95 A$/t CO_2 (40-60 €/CO_2) ■ Note: A second generation oxyfuel technology is under development	6 no capture realised today; some components tested individually in industrial environment	medium

Integrated Calcium Looping

Integrated CO_2 capture process

Working principle and main characteristics	TRL	RF
▪ Kiln flue gas is rooted to a carbonator, where calcined raw meal is used as a CO_2-sorbent ($CaO + CO_2 \rightarrow CaCO_3$) ▪ The calciner operates in oxyfuel mode (O2 generated in an ASU) ▪ Calcination of $CaCO_3$ (from carbonator and in fresh raw meal) ▪ A portion of the CaO generated in the calciner is rooted to the carbonator (closing the loop) and the rest feeds the kiln (clinker production) ▪ CO_2 – rich flue gas stream is generated and CO_2 is captured in a CPU ▪ Thermal energy penalty: medium to high ▪ Electrical energy penalty: medium to high ▪ Medium technological risks, due to: ▪ Carbonator performance not yet proven in industrially relevant environment; ▪ Flexible system to operate the calciner in air and oxy mode ▪ Cost of avoided CO_2: 60-120 A$/t CO_2 (40-85 €/CO_2)	6 No capture realised today (expected to reach TRL 7 in 2022; project CLEANKER)	medium

Calix ®

Integrated CO_2 capture process
Separation of process CO_2 by an indirectly heated calciner (no capture of fuel CO_2)

Working principle and main characteristics	TRL	RF
▪ The raw meal is calcined by indirect heating ▪ Theoretically any type of heat source can be used (fuel / electricity) ▪ Efficiency depends on the heat transfer to the central tube ▪ Combustion gas stream and calcination CO_2 stream flow in separate tubes (outer and inner tube respectively) ▪ Very pure CO_2-rich gas stream from the calcination process is generated for further compression and transport ▪ Thermal energy penalty: low ▪ Electrical energy penalty: low (if not heated with electricity) ▪ Technological risks, due to: Scale-up is challenging ▪ Long-term stability of inner tube and heating with electricity needs to be proven ▪ No cost estimates available today	6 (envis-aged TRL 7-8 in 2024)	low

Annex B Technology readiness levels (TRL)

Table 6: Technology readiness levels (TRL)

TRL	Description
TRL 1	basic principles observed
TRL 2	technology concept formulated
TRL 3	experimental proof of concept
TRL 4	technology validated in lab
TRL 5	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	system prototype demonstration in operational environment
TRL 8	system complete and qualified
TRL 9	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Annex C Thermal efficiency of clinker production

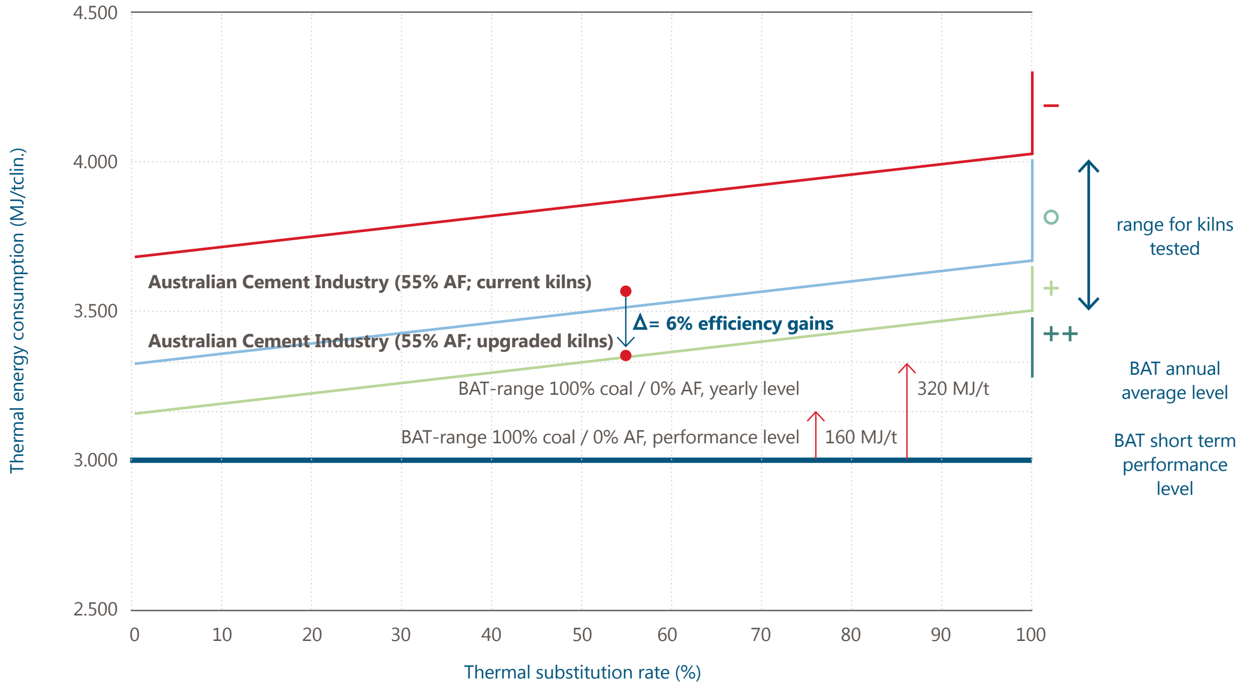
The thermal energy demand of clinker manufacturing is determined by many factors. External factors are the raw material moisture and the fuel composition. From a process point of view, the kiln design, the number of preheater stages or the recuperation rate of the clinker cooler are important factors. Results from plant data collected by VDZ in many kiln tests were summarised in 2017 by the European Cement Research Academy (ECRA) in its Technology Papers [6].

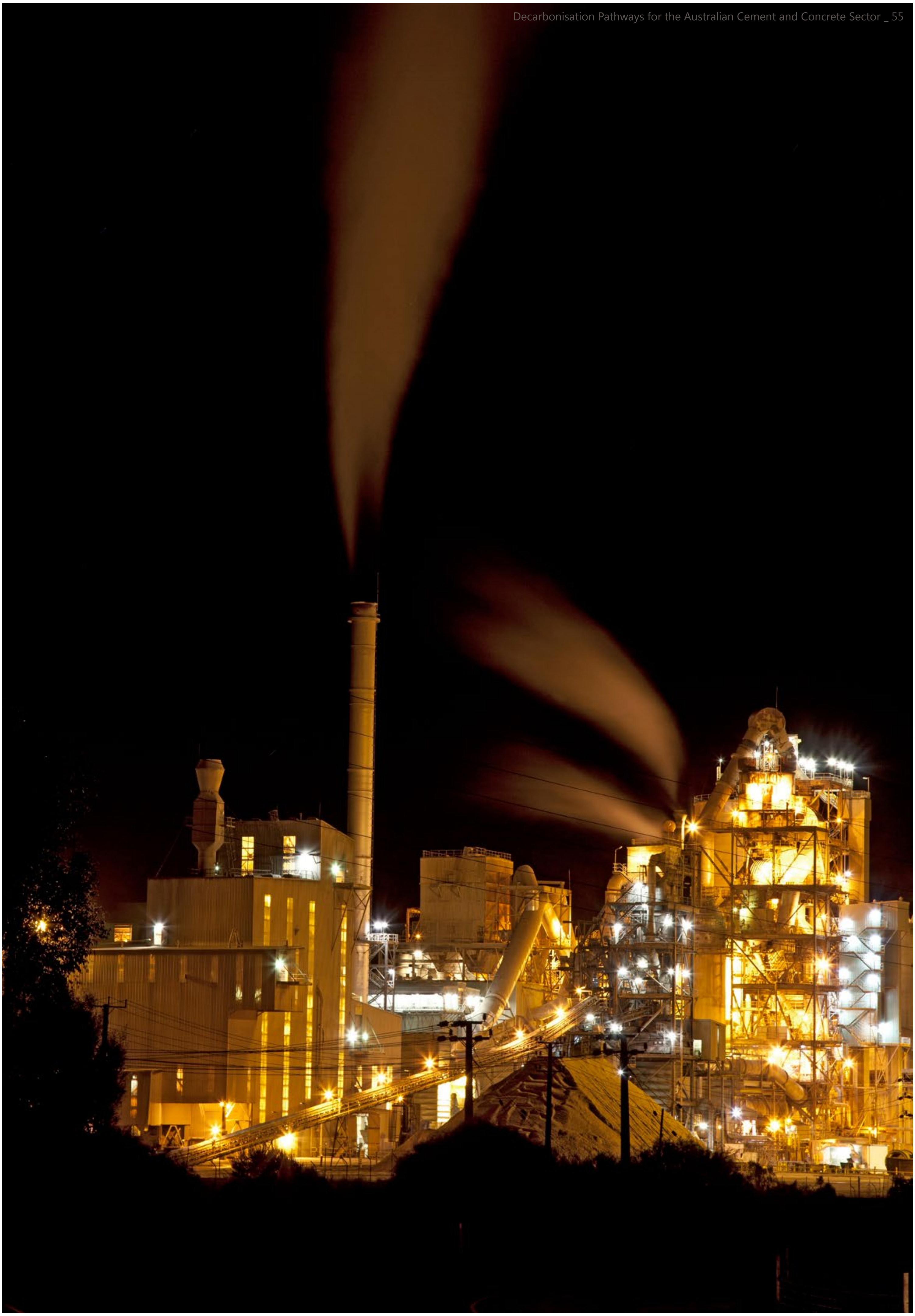
The key findings are as follows:

- The best performance levels can only be achieved by well-maintained large precalciner kilns, and the higher the production capacity, the lower the production-specific energy losses. For example: a 5,000 tonne per day kiln typically exhibits a specific energy demand that is up to 100 kJ/kg of clinker lower than a 3000 tonne per day kiln under otherwise identical conditions.
- The raw material moisture is a relevant factor which leads to differences in thermal energy demand. Kilns are typically designed in such a way that their exhaust gas temperatures fit the required drying capacity for the raw material at the site.
- Best available technology exibits a thermal energy demand of between 3,150 and 3700 kJ/kg clinker for a kiln size of 3,000 tonnes per day, depending on the moisture of the raw materials.
- Short-term figures (e.g. in a 24 to 36 h performance test) are usually lower than the yearly averages as they are not affected by unplanned kiln stops, heating up and shutting down the kiln or the market situation, etc. Therefore, the 'mean time between failures' (MTBF) should be as high as possible for good energy performance. The difference in thermal energy demand between short-term and yearly averages can be from 160 to 320 MJ/t clinker, depening on the raw material moisture.

Alternative fuels (AF) have the tendency of being of lower calorific values than fossil fuels due to their higher moisture content. Also, they typically contain higher per centages of green hydrogen, which leads to higher exhaust gas enthalpies. As a consequence, the thermal demand of clinker burning increases with increasing substitution rates as shown in Figure 8. In the case of the Australian cement industry, it is assumed that all kilns in 2050 will have a thermal energy demand based on state of the art technology as is already in place today. Taking into account the technical development, a 6 per cent improvement in thermal energy demand is expected resulting in 3,345 kJ/kg clinker.

Figure 8: Thermal energy demand of state of the art precalciner kilns depending on the substitution rate of fossil fuels by alternative ones.





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