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Propelling the Commercialization of ‘Novel Cements’

An investigation of demand-side factors to accelerate decarbonizing technologies within the cement industry

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Abstract

Accounting for approximately 8% of global CO_2 emissions, the cement industry is one of the greatest contributors to climate change, despite the lack of focus on this sector in popular discourse. Deep cuts in this sector are challenging to achieve due to necessitated alteration of material components and formulation of the traditional product in addressing non-energy related 'process emissions'. Technologies able to deeply decarbonize this sector are currently not fully developed or commercialized. This research explores one innovative technology with deep decarbonization potential: novel cements, classified as non-limestone clinker-based cements or those with low-limestone content produced through alternative manufacturing methods. It focuses on the demand-side landscape of these products as increasing demand and adoption may promote wider commercialization and corresponding emissions reductions. More specifically, demand-side stakeholder landscape, drivers and barriers for novel cement commercialization, strategic niche management, and strategies to advance these technologies are investigated. These themes are examined from a geographically broad lens through the utilization of a literature review and expert interviews. Results support the potential for and benefits of novel cements being incubated and commercialized within certain niche applications and market segments. Following successes of these products in certain niches, novel cements may then be suited to expand to other, larger markets. Several demand-side barriers to the wider implementation of these products were identified, particularly risk aversion and lack of inclusion in standards and specifications, along with some interrelated supply-side factors. Several strategies that various actors can pursue in attempts to propel these technologies forward were also recognized including business-oriented strategies for manufacturers, various policy options, and collaboration opportunities amongst various actor groups to optimize knowledge and resource sharing. While novel cements offer decarbonizing attributes that can help to significantly decrease emissions in the cement sector, other green cement and concrete technologies compete with sustainability-driven demand for these products. However, there is likely no 'silver bullet' technology to decarbonize this sector; deep emissions reductions will require the simultaneous utilization of several technologies. Accordingly, the pursuit, development, and commercialization of novel cements as one of these technologies needs to be pursued.

Keywords: cement, concrete, decarbonizing technologies, novel/alternative/green cements/concretes, demand-side

Executive Summary

Challenges unique to the cement industry lie in reducing large amounts of CO_2 emissions, over fifty percent of which are not associated with energy use, but rather process emissions derived from the chemical reaction in heating limestone in the manufacturing process. Essentially, these emissions can only be mitigated through changing the components and/or manufacturing process of the material. The majority of over four billion tonnes of cement produced annually is used to make concrete — the most widely produced substance in the world and used in the vast majority of building and infrastructure projects globally. As cements are versatile, durable, resilient, low-cost, and efficient, with such strong dependence on them, their widescale replacement is infeasible. Therefore, to strive towards global and industry emissions reduction goals, new technologies and solutions need to be implemented. While many emissions reductions deriving from energy efficiency and alternatives fuels have already been made, and as energy improvements do not reduce process emissions, the pursuit of other, innovative solutions is essential. Clinker substitution, CCS, CCU, and novel cements are the main types of technologies holding potential process emission reductions. Novel cements for the sake of this thesis are classified as non-limestone/clinker-based cements or those made through alternative manufacturing methods and offer decarbonizing solutions. This range of products comprise the focus of this thesis and are in various stages of development with a range of theorized emissions mitigation potentials, some even being considered carbon-negative. Novel cements exemplify an innovative technology underrepresented in research with potential to contribute to significant, untapped emissions reductions within the cement and concrete sectors.

Under the assumption that propelling commercialization of novel cements could help drive further decarbonization in these sectors, demand-side landscapes and variables constituted the primary areas of investigation of this research. Demand is a primary driver of both market existence and success. Accordingly, to help increase viability of the novel cement industry, demand barriers should be diminished while demand drivers leveraged. Understanding the industry landscape, particularly as it relates to demand aspects, barriers, and drivers, can help to attain a better comprehension of how success and commercialization of these products can be propelled. Accordingly, this research aims to enhance understanding of pathways to decarbonization in the sector through novel cement use by investigating this demand-side landscape, barriers, and strategies for change. To realize this objective focus surrounded four specific research questions:

1. What is the demand-side landscape surrounding novel cements?

2. What are the demand-side barriers and drivers of commercializing decarbonizing novel cements?

3. How can the pursuit of niche markets help to propel these technologies?

4. Which strategies can be used to address demand-side barriers and leverage demand-side drivers to increase uptake and commercialization of novel cements?

To answer these questions a literature review was performed in conjunction with nine expert interviews.

Demand-Side Landscape

Its general status as a commodity with slim profit margins, make the cement industry a difficult one to profit in. Without sufficient incentives for large incumbents to pursue novel cements, SMEs are left to incubate, develop, and commercialize these products. Once technologies

achieve success in niche markets, begin to garner wider demand, and/or with major market shifts, larger incumbents may become adequately incentivized to pursue these technologies. While greening demand may not be at present strong enough to encourage wider adoption of novel cements, this demand could grow overtime as climate concerns become more pressing. Key industry actors include:

> **Supply-side:** large, incumbent cement and concrete manufacturers; innovative novel cement SMEs; other green cement/concrete start-ups; and associated supply-chain actors
>
> **Demand-side:** end-users/customers; building developers; architects/designers; engineers; contractors; site-workers; and consultants
>
> **Other:** policy makers; financiers; academia; research institutions; industry groups and trade associations; standards organizations; sustainability certification bodies; and sustainability organizations

Landscape actors other than manufacturers, (e.g. industry groups, policy makers, and academics), also have vested interests and play roles in propelling novel cements. Through their own actions and collaborative efforts, they can help boost awareness, share knowledge and address uncertainties of demand-actors surrounding these products and help incentivize novel cement adoption. Collaboration amongst demand-side actors is especially important due to the disjointed, multi-actor-layout of the demand-chain and construction sector. Further, commitment and enthusiasm from various landscape actors are necessary to spur significant changes in the novel cement market landscape.

Barriers

Key barriers deterring actors from pursuing novel cements from the demand-side include:

- Risk aversion relating predominately to 1) safety and liability concerns and 2) long-term durability
- Substantiated and unsubstantiated concerns regarding material characteristics and performance, benign differences
- Potentially higher prices of novel cements
- Lack of inclusion of novel cements in standards, codes, and specifications
- Lack of awareness of technology existence, options, and how to pursue
- Demand-side implementation/logistical challenges
- Lack of existence or awareness of demonstration/pilot projects (especially older ones)
- Insufficient research and product-vetting funds of demand-actors
- Competition with other green cement/concrete products
- General lack of incentive to switch from proven, familiar, inexpensive products when lacking drive for unique properties or sustainability.

Results stressed the interconnected and reinforcing nature of certain demand- and supply-side barriers necessitating consideration of certain supply-side concerns as well. Some key supply-side barriers include:

- Financing, implementation costs, and operating costs
- Supply-side implementation/logistical challenges

- Material availability and pricing
- Stranded asset potential
- Lack of incentive to change, specifically for larger companies with existing business models; potential undermining of these proven models.

The prominence of certain barriers can be very context-specific, although, risk aversion, concern with performance characteristics, and standards/specifications were discussed most universally. Consensus underlined that diminishing barriers will not necessarily generate demand. Further, demand may not even facilitate novel cement dispersion, as supply-sides need to be able to profit in producing these products.

Niche Targeting

Research findings supported initial targeting of niche market segments to incubate, develop, and commercialize novel cements as a means of propelling these products. Unanimous consensus, however, that novel cements can achieve wide-spread commercialized success beyond niche applications was not attained. Ideal niches to focus on for initial targeting and success were classified by three categorizations: manufacturing techniques, applications, and customer segments. Once novel cements have proven viable in these niches, and demonstrations of successful applications become increasingly available and visible, potential risk aversion levels may decrease, and demand for these niche applications or willingness to experiment with novel cements beyond these niches could increase. And so, niches can serve as a foothold for these products to develop further, become commercialized, and more widely implemented.

Propelling Novel Cements Forward

Results brought various strategies and changes forth that may help to accelerate development and commercialization. The range of proposed actions from a variety of actors may underline the importance of transforming the industry landscape from several directions. These key actions were identified and are categorized below.

Business strategies that manufacturers can utilize to help propel demand include:

- Service-based business models; with the possible addition of risk adoption services
- Targeting niche applications
- Heightened marketing and customer engagement.

Public policy options can also be implemented by governments at various levels. Though these actions focus on policies propelling novel cements, penalizing the use of OPC is another mechanism, unexplored in this research, that may also indirectly increase novel cement demand:

- Requirement of EPDs for all cement, concrete, and/or building material products
- Procurement requirements or incentives (e.g. focusing on decreased clinker content, use of green cements)
- Implementation of raising of carbon-pricing schemes
- Increased resource allocation for research/testing of novel cements.

Collaboration of key actor groups can also help to achieve common goals in pooling resources, knowledge, and efforts:

- Awareness boosting (e.g. trainings, conferences, webinars, symposiums)

- Industry groups' services (e.g. trainings, awareness building, resource/information sharing, specification modification services, policy lobbying, provision of industry baselines, promotion of and EPD services)
- Information and research sharing
- Pooling of research resources and efforts through research symposiums
- Various actors lobbying together for standardization change or creation including or permitting novel cements.

Miscellaneous potential actions include:

- Modification of standards or project specifications permitting novel cements
- Inclusion or magnification of green cement criteria in sustainability certifications
- Goal setting surrounding normalized embodied carbon levels or clinker content.

Implications for a Greener Cement Industry

Replacing a sort of 'silver bullet' technology in most aspects except sustainability like Portland cement will likely necessitate the employment of various cement technologies as the development of a new 'silver bullet' technology, one with widespread, inexpensive material availability, similar performance characteristics to Portland cement, and more, is unlikely in the near future. In the scheme of this necessitated technology mix, potential competition between novel and blended cements arises. As many blended cements have similar emissions reduction potentials to novel cements, from a sustainability-driven demand-side standpoint, incentives to choose novel cements over other green cements are lacking, especially given the more 'tried-and-true' reputation of blended cements. While degrees of underlying opposition may derive from competing for material resources and sustainability-driven demand, these various products might also assist one another in boosting awareness of green cements as a whole and strengthening supply chains and material know-how. From a sustainability perspective, competition is not necessarily bad, as all products can serve a role in a greater technology mix. However, from a long-term perspective, early development of novel cements can help them gain a head-start in their development and demand generation as a part of this greater technology mix.

Within the wider categorization of novel cements, there is also likely to be no 'silver bullet' technology. Material availability and costs, standard differences, and policy divergence in various regions each incentivize different sorts of cement chemistries and manufacturing techniques. This suggests that perhaps novel cements should be developed and optimized to fit their local markets and other niches to expedite expansion. On the other hand, focusing on more widely applicable technologies would be preferential in terms of transferability. Regardless, proven novel cement demonstration in one context can help encourage adoption and further market expansion, and several novel cements catered to different needs do and will likely continue to exist on markets simultaneously. Adoption of novel cement products, in general, may create additional transaction costs and complicate procedures like procurement, implementation processes, and operations. Accordingly, buy-in and enthusiasm from actors along demand-chains can help surpass these barriers and help products to succeed and expand. In order to achieve significant changes in the industry landscape, committed actors or groups will be necessary to push for drivers like policy and standard changes, pilot projects, and experimentation with new business strategies. Accordingly, the importance of committed human capital throughout the industry should not be underestimated.

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Abbreviations

ACI – The American Concrete Institute

B2DS – IEA's Beyond 2°C Scenario

CCS – Carbon Capture and Storage

CCU – Carbon Capture and Utilization

CDRAs – Cooperative Research and Development Agreements

CO_2 – Carbon Dioxide

CSI – Cement Sustainability Initiative

EPD – Environmental Product Declaration

EU – the European Union

FHWA – The U.S. Federal Highway Administration

GHG – Greenhouse Gas(es)

GGBS – ground granulated blast furnace slag

GWP – Global Warming Potential

IEA – International Energy Agency

kg – kilogram

LCA – Life-Cycle Assessment

LEED – LEED Green Building Certification

NRMCA – National Ready-Mixed Concrete Association

OPC – Ordinary Portland Cement

RQ – research question(s)

RTS – IEA's Reference Technology Scenario (RTS)

R&D – Research and Development

SCMs – Supplementary cementitious materials

SME(s) – small- and medium-sized enterprises

WBSCD – World Business Council for Sustainable Development

2DS – IEA's 2°C Scenario

1 Introduction

Comprising approximately 8% of global annual CO_2 emissions (Lehne & Preston, 2018), the cement industry produces around 3 billion tonnes of CO_2 annually (van Ruijven et al., 2016). Despite this large proportional make-up of global emissions, the cement and concrete industries receive relatively little attention in public discourse surrounding climate change (Beyond Zero Emissions, 2017). Yet steps have already been taken to reduce emissions in this sector~~,~~—primarily through energy efficiency improvements, alternative fuel use, and clinker substitution~~s~~ (Beyond Zero Emissions, 2017); and according to one source, almost all concretes produced today incorporate some type of innovative or decarbonizing technology (Lemay & Thompson, 2020). However, cement manufacturing cannot meet global climate goals on its current technological trajectory (van Ruijven et al., 2016). Novel cements are an innovative solution that can help mitigate greenhouse gas (GHG) emissions that cannot be accounted for by more traditional solutions like energy efficiency improvements or alternative fuel use. These are cementious products that do not prescribe to traditional cement constituents or manufacturing processes, several of which are said to be able to achieve lower emissions intensity than traditional cements with some even claiming 'carbon negativity'. Most novel cements, however, have failed to reach or sustain commercial viability thus far with even fewer having achieved mass production (Imbabi et al., 2012; Lehne & Preston, 2018).

1.1 Background

Understanding baseline industry emissions and industry status-quo is essential in grasping potential benefits and roles of novel cements in achieving deep decarbonization within the sector.

1.1.1 Industry Baseline

Today cement-based concretes are the most used synthetically-produced substance by weight in the world (Biernacki et al., 2017) and the most widely used construction material (The Concrete Centre, 2014) with global production of Portland cement over 4 billion metric tonnes per year (Lehne & Preston, 2018). While cement production has been in a recent state of plateau, by 2050, production is expected to increase between 12 and 23% by some estimates (International Energy Agency, 2018a) or reach between 3.8 and 5.5 billion tonnes by others (Jahren & Sui, 2014). India and China are currently the largest cement producers comprising a respective 7 and 60% of global production (International Energy Agency, 2018b), with U.S. and European markets having relatively stable, plateaued consumption and demand (Jahren & Sui, 2014). China's demand is expected to plateau or decrease over the coming decades (Fernandez Pales et al., 2019) while major demand increases are anticipated to arise in developing countries like India, Indonesia, Brazil, and in other South East Asian markets (Beyond Zero Emissions, 2017; Fernandez Pales et al., 2019; Lehne & Preston, 2018), overcompensating for the potential decline from Chinese markets as illustrated in Figure 1-1.

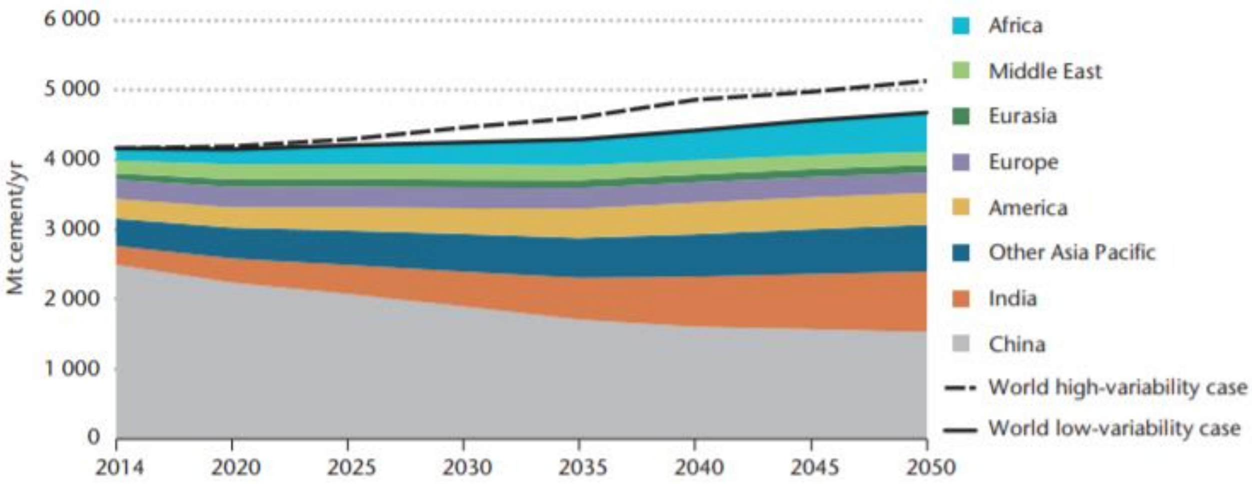

Figure 1-1. 'Cement production by region'.

Source: International Energy Agency (2018b).

When combined with water and aggregate cement works as a binding agent that can be used to make primarily concrete and mortar, as well as screeds, stucco, coatings, soil stabilizers, and more (Imbabi et al., 2012; Rootzén & Johnsson, 2016). Ordinary Portland Cement (OPC) or 'Portland cement' is by far the most widely used classification of cement comprising the binder in over 98% in global concrete and is produced through 'traditional' cement manufacturing processes (International Energy Agency, 2018b). OPC consists predominately of a material called clinker produced from the crushing and grinding of raw materials, primarily limestone, in addition to sand, clays and other constituents, and their subsequent heating in rotary kilns at temperatures above 1400°C (Huntzinger & Eatmon, 2009). Around half of globally produced OPC is used to produce 11 billion metric tonnes of concrete, with the remainder being used for mortars and other applications (Imbabi et al., 2012).

Concrete — the main cement application that will be discussed in this paper — is a widely-used material with unique properties used in the majority of all structural applications. This material has high strength and durability attributes, is resilient (e.g. fire resistance), impermeable, efficient, versatile in that it can be molded into different shapes and reinforced, and can be installed relatively quickly with less labor input than most other structural materials (International Energy Agency, 2018b; Scrivener, 2014). Concrete is also relatively affordable or inexpensive as compared to other building materials (International Energy Agency, 2018b). Due in part to the abundance of limestone and other constituents in most parts of the world, it is used so widely that is currently the only material with the material availability to supply materials to meet the demand for low-cost housing, buildings, and infrastructure (Scrivener, 2014).

1.1.2 GHG Impact

While cement makes up a small portion of concrete by mass, it comprises the majority of its GHG footprint as seen in Figure 1-2 (The Concrete Centre, 2014).

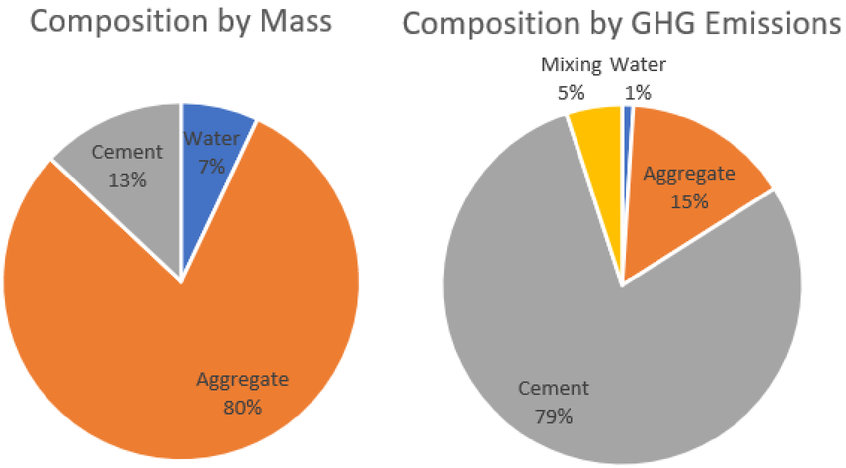

Figure 1-2. Concrete Composition by Mass and Emissions (using OPC cement).

Source: Adapted from Peng (2020).

In terms of GHGs, concrete has significantly lower embodied CO_2 emission levels, or 'embodied carbon' (amount of CO_2 released through production and supply chains), from a lifecycle perspective than other building materials (Scrivener, 2014). With this and irreplaceably high output levels that other building materials would struggle to replace, the CO_2 footprint of concrete must be improved to address both this sector's and the building/construction sector's emissions (Fernandez Pales et al., 2019).

With the use of concrete in buildings and infrastructure projects, the concrete and cement sectors work closely with the construction industry. While operational emissions have historically been considered to comprise the majority of GHGs over the lifetime of a building, embodied carbon is expected to contribute approximately half of emissions in all new construction between now and 2050 (Architecture 2030, n.d.). Both design and engineering communities have embraced and significantly addressed operational GHGs and energy improvements partly in response to global focus of their necessity, availability of existing technologies, and more recent technology breakthroughs. Historically, policy makers and others within the construction industry have dedicated much less attention towards embodied carbon issues (Peng, 2020). However, this is beginning to shift, and if this topic receives similar levels of attention as operational carbon, similar progress trajectories may be possible.

Clinker production constitutes over 90% of this sector's GHG emissions (Lehne & Preston, 2018). Approximately 40% of the sector's emissions are attributed to energy use in clinker production, primarily in heating kilns to temperatures over 1400°C, largely through the burning of fossil fuels. An additional 50% of the sectors emissions are 'process emissions' from the manufacturing process or the calcination in the chemical reaction combining and heating calcium carbonate (limestone) and silicon oxides (sand) in clinker production releasing CO_2 (Imbabi et al., 2012b) as seen in the basic chemical equation below:

$$3CaCO_3(calcium\ carbonate) + SiO_2(silicon\ oxides) + heat \rightarrow Ca_3SiO_5 + 3CO_2$$

The outstanding 10% of emissions are associated with transportation and front-end production processes (Imbabi et al., 2012).

As shown in the equation above, for every molecule of limestone used, one molecule of CO_2 is released. The production of one kilogram (kg) of cement, containing 90% Portland clinker yields

0.93 kg of CO_2 on average (i.e., for every tonne of OPC produced, nearly 1 tonne of CO_2 is emitted) (Lehne & Preston, 2018). This, however, represents the emissions intensity of cement with 90% Portland clinker. In reality clinker-ratios and emissions intensities vary significantly by region (Andrew, 2018), with a global average emissions intensity of 0.87 tonnes of CO_2 per ton of cement due to the utilization of low-clinker technologies (Beyond Zero Emissions, 2017). High-clinker cements continue to dominate global markets with OPC (typically containing >75% Portland clinker) used in >98% of concrete production (Lehne & Preston, 2018).

Despite emissions reductions required to meet commitments of the Paris Climate Agreement and increasing technology efficiency within the cement sector, a Reference Technology Scenario (RTS) created by the International Energy Agency (IEA), anticipates a 4% rise in GHG emissions from this sector by 2050 (International Energy Agency, 2018b). Conversely, if current cement production methods continue, the proportion of this industry's impact on global GHG emissions is expected to rise to around 26% by 2050 (Fernandez Pales et al., 2019).

With the continuation of current production methods, growth in GHG emissions is expected largely due to process emissions (Imbabi et al., 2012) (i.e. if net-emissions reductions are to be achieved, process emissions need to be significantly addressed). To meet the goals set out by the Paris Climate Agreement's 2 Degree Scenario (2DS), this sector needs to reduce net emissions by at least 16% by 2030 (Lehne & Preston, 2018). Accordingly, emissions intensity reductions will need to be even greater than 16% – steep enough to overcompensate for anticipated production increases (i.e. decoupling growth and emissions). Given the 2DS's perceived insufficiency by many in effectively mitigating severe climate impacts, reductions may need to be even higher (Lehne & Preston, 2018). For instance, the IEA's Sustainable Development Scenario cites an annual decline in emissions intensity of 0.7% to meet 2030 GHG goals in this sector (Fernandez Pales et al., 2019).

1.1.3 Emissions Reduction Strategies

Novel cements can achieve lower emissions intensity than OPC through either reduction or elimination of calcination emissions and/or being less energy intensive. Some claim to achieve emissions reductions high as 90% or to be even 'carbon-negative' sequestering more emissions than released in production. However, most novel cements have failed to reach or sustain commercial viability thus far with even fewer having achieved mass production (Imbabi et al., 2012; Lehne & Preston, 2018). With the exception of 'CSA' cements, that have been on Chinese markets since 2014, low-carbon novel cements are either used only on limited scales or are currently in development or piloting stages (Imbabi et al., 2012). Novel cements have also been developed for reasons external to low-carbon benefits relating to unique physical properties of some of these technologies as compared to OPC. A synthesized list of various novel cements and other green cement/concrete start-ups can be seen in Appendix A.

In addition to novel cements, five other categorizations of emission reduction technologies within the cement and concrete industries can be classified as: energy efficiency, alternative fuel use, clinker substitution, carbon capture and storage (CCS), and carbon capture and utilization (CCU) technologies. While many of these emission reduction techniques are widely used, they are not necessarily implemented across the board (e.g. the European Union (EU) utilizes a much higher proportion of alternative fuels than most countries) (Scrivener, 2014). Clinker substitution and CCU will arise in following chapters as they play significant roles in the novel cement landscape. Basic industry statuses surrounding these other technology categories are described in Table 1-1.

Table 1-1. Decarbonizing Technology Categorizations.

Technology	Description
Energy efficiency	Significant efficiency improvements have been made over the last few decades having decreased emissions intensity by 18% since 1990 (Lehne & Preston, 2018). Remaining improvement opportunities are now limited as many efficiency gains have already been made (Fernandez Pales et al., 2019).
Alternative fuel use	Typical fossil fuel use (primarily coal) in manufacturing can be replaced with alternative fuels mostly derived from biomass or industrial wastes with sometimes lower emissions outputs (Beyond Zero Emissions, 2017). Demand for biomass/biofuels is expected to increase in the future making them more expensive and/or potentially unavailable. According to one source, remaining emission reduction opportunities relating to the use of biofuels are around 8% (Fernandez Pales et al., 2019).
Clinker substitution	Reducing the quantity of clinker utilized in cement is the only way to directly reduce OPC process emissions. Accordingly, significant efforts and progress have already been made in reducing the clinker to cement ratio. One means of this is through 'blended cements' in which replacement materials, also referred to as supplementary cementitious materials (SCMs) (Schneider et al., 2011), are added to clinker. This is one of the fastest-growing technology areas within the industry (Lehne & Preston, 2018) and is utilized in several regions. SCMs like fly ash (coal burning byproduct), ground granulated blast furnace slag (GGBS) (iron manufacturing byproduct), and silica fumes (silicon manufacturing byproduct) are all in prevalent use today (Imbabi et al., 2012), and other SCMs can also be utilized in cement manufacturing. Substitution ratios can be higher than 70% offering substantial emissions reduction potential (Lehne & Preston, 2018).
CCS	CCS can offset process emissions helping to indirectly mitigate their impact and can theoretically be applied to cement factories capturing these emissions. Other than Project LEILAC, a collaborative pilot, and some experimentation in the Nordics, CCS has not been implemented in the industry thus far with technology not being fully developed (Schneider et al., 2011; *The LEILAC Pilot Plant*, n.d.). Success of CCS methods is heavily reliant on storage technologies external to the cement sector in addition to the sector-specific separation technologies (Naranjo et al., 2011). Accordingly, viability of CCS in general is controversial despite historic mass financial and research investments.
CCU	As opposed to CCS in which captured emissions are stored, in CCU they are repurposed as additive components to various products (Baena-Moreno et al., 2019). Some of the product enhancements possible within these industries include carbon-curing technologies in which CO_2 is injected into aggregates or concretes both sequestering emissions and increasing strength (Blue Planet, n.d.; *Recycling CO2 to make simply better concrete*, n.d.). These carbon streams can originate from other industries or from the cement industry itself.

In comparison to other technology categories, novel cements have one of the highest theorized decarbonization potentials as demonstrated in Figure 1-3, with some novel cements even claiming to be carbon negative. Despite this, no studies were found systematically examining novel cements from a non-technical standpoint; alternatively, they are mostly mentioned in industry reports discussing all decarbonizing technologies.

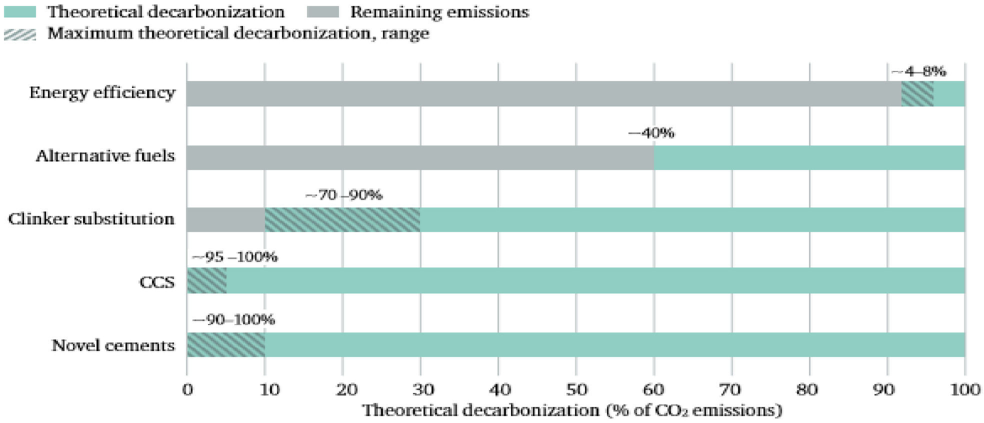

Figure 1-3. Theoretical decarbonization of different technology classifications.

Source: Lehne & Preston (2018).

1.2 Problem Definition

With necessitated deep emission cuts and given anticipated rise in global cement demand, steep emissions intensity reductions are required. According to Lehne & Preston, "although efforts have been undertaken to decarbonize the cement and concrete sectors, most relatively straightforward gains have already been made," mainly in energy efficiency, alternative fuels, and SCMs, and "the next phase of decarbonization will require more ambition and faster action than efforts to date… It will be impossible to even get close to B2DS[1] without also achieving radical changes in cement consumption and breakthroughs in the development of novel cements" (2018). Accordingly, reaching deep reductions necessitates additional development of emerging, but not yet commercial technologies (Beyond Zero Emissions, 2017). The focus on novel cements was chosen as they have one of the highest theorized decarbonization potentials, receive significantly less resource and literature attention, and are one of these aforementioned innovative yet not commercialized technologies. Figure 1-4 illustrates a proposed pathway to reach the 2DS scenario reiterating the importance of innovative technologies like novel cements in achieving these goals. Given that CCS technological advancement is lagging behind anticipated progress (Lehne & Preston, 2018), novel cements may need to compensate for even more of these reductions than implied in this illustration.

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[1] Beyond 2 Degree Scenario (B2DS) referring to a more ambitious emissions reduction scenario than the 2DS as many feel the latter is not sufficient to mitigate severe climate impacts

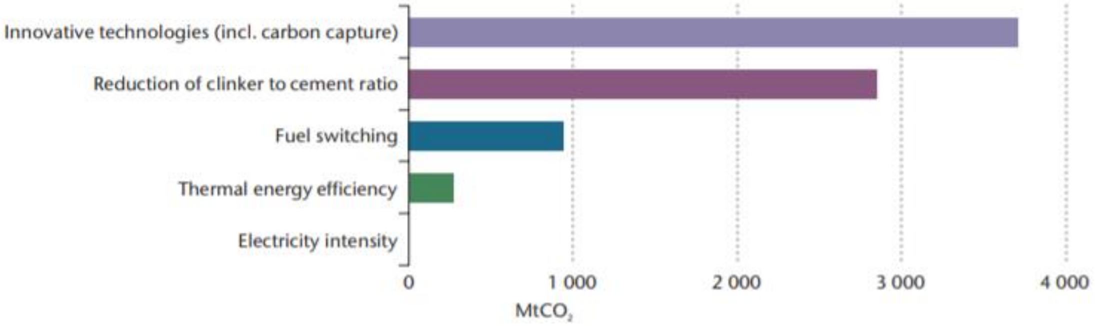

Figure 1-4. Cumulative emissions reductions pathway towards 2DS in the cement industry.

Source: International Energy Agency (2018b).

Demand for cement and concrete in the construction sector drives emissions in the cement industry while providing opportunity for the commercialization of novel cements (Fernandez Pales et al., 2019). For mitigation impacts of novel cements to be realized, demand for these products needs to exist and spur their adoption. Accordingly, the investigation of the demand landscape within this sector, specifically pertaining to novel cements, can help increase understanding surrounding potential future acceptance of low-carbon cement technologies and corresponding strategies to exploit these demand factors and achieve wider commercialization.

While 'novel cements' comprise a range of significantly differentiated products, some likely to be currently undiscovered, they will mostly be discussed collectively despite unique challenges in wide-scale implementation and differing decarbonization potentials. This is partly due to lacking research surrounding individual technologies and partly due to a desire for wider exploration of commercialization that could apply to any of these technologies as many are and will be pursued simultaneously. Through this more general approach, conclusions may become more widely applicable. While some novel cement technologies examined have much lower decarbonization potentials than those theorized in literature, hopefully demand-side landscapes of novel cements portrayed in this research will have similarities and parallels applicable to all decarbonizing cements, particularly those with higher reduction potentials.

1.3 Aim & Research Questions

The aim of this thesis project is to contribute to improved understanding of how commercialization of decarbonizing cement manufacturing methods, specifically those within the novel cement space, can be propelled to help achieve deep emissions cuts within this sector. As novel cement technologies have received perhaps the least research attention of the aforementioned categorizations of decarbonization technologies and have one of the highest theorized decarbonization potentials, they will comprise this project's focus. Demand-side factors present significant barriers to wide-spread commercialization. As demand is a principal driver of market existence and success, obtaining a greater comprehension of the extent of and approaches to overcome these demand-side barriers may help advance understanding of which strategies and/or technologies can be leveraged in propelling these technologies. To achieve this aim, the following research questions (RQs) are being pursued:

> RQ1: What is the demand-side landscape surrounding novel cements?
>
> RQ2: What are the demand-side barriers and drivers to commercializing decarbonizing novel cements?
>
> RQ3: How can the pursuit of niche markets help to propel these technologies?

RQ4: Which strategies can be used to address demand-side barriers and leverage demand-side drivers to increase uptake and commercialization of novel cements?

1.4 Scope

References to and definitions of novel cements, SCMs, blended cements, and other 'green' cement/concrete products are not consistently distinguished or defined within the sector's discourse and are sometimes referred to by the same terms. For the sake of this paper, 'novel cements' will refer to non-clinker-based[2] cements or those made using unique manufacturing methods as compared to OPC with lower carbon footprints. While these products are sometimes also referred to as 'alternative cements', 'green cements', or 'innovative cements', for the sake of clarity, they will be exclusively referred to as 'novel cements' in this thesis. In hopes of minimizing confusion, other 'low-clinker' or 'blended cements' utilizing SCMs will be referred to interchangeably while 'alternative' and 'green' cements will refer collectively to novel cements and blended cements. CCU technologies, however, will not be referred to as novel cement technologies, as the cement product used in these concretes is typically unchanged. While the focus of this paper and research aims surround novel cements, blended and other green cements are still relevant in the market landscape and may exhibit parallels surrounding demand and other aspects of the novel cement landscape. Accordingly, they will be included in some parts of discussions surrounding demand factors, acceptance, barriers, and market penetration.

Where specification is necessary, this study will focus on cement applications in the concrete sector, as this constitutes the majority of cement use, as opposed to those in mortars or other smaller sectors utilizing these binders. As some novel cement technologies and corresponding concrete technologies are closely related, the two industries and applications will in some cases be consolidated or referred to interchangeably.

While the geographic scope of this project initially strived to be global, due to language barriers, resource access, and interviewee responses, European, North American, and Australian markets together comprise the significant majority of information represented. While some parallels from this research can likely be used in other markets, findings will be most relevant to these three regions. Geographic differences and limitations are discussed further in later sections.

This paper will not focus specifically on given novel cement technologies, as those on the market are subject to change and as this research aims to be applicable to many novel cement products. Finally, while the initial focus of this thesis surrounded private actors and markets, policy implications arose frequently in interviews and literature and will accordingly be discussed as they also make up a part of the wider market and technical landscapes.

1.5 Ethical Considerations

No compensation was received as a part of this research. Upon request, interviewees could choose to remain confidential or refrain from being directly cited. While none opted for anonymity, one asked for direct citations to be approved before publishing which was observed. For assistance in interview note-taking, interview recordings were performed with permission from subjects. Academic integrity was maintained throughout the duration of the project with deliberate avoidance of plagiarism and efforts to ensure validity of findings through triangulation or disclosure of potential subjectivity or bias. Biases and additional limitations are further discussed in the 'Methodology' and 'Discussion' chapters to account for additional partiality.

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[2] Clinker referring to limestone-based clinkers

1.6 Audience

The intended audience for this research includes actors interested in or within the cement and concrete industries and their associated demand chains, down to end-users of these products, along with others interested in more general industry decarbonization. From an industry standpoint, this research may help cement and concrete manufacturers understand the landscape of demand-side barriers to better optimize strategies for commercializing these products in addition to understanding their potential value addition. From an end-user perspective, it can assist prospective novel cement customers in attaining a better understanding of the industry status as well as technology and business-model options to enhance customer decision-making processes surrounding green cement/concrete adoption. This research can further be used be academics or policy makers in the construction material, cement, and concrete realms to enhance comprehension of the demand-side of the business landscape and help conceive how these technologies can be propelled in the future to achieve deeper emission reductions. This paper has a geographically and technologically broad scope, and audiences are not expected to be intimately familiar with novel cements or to have a robust chemistry or materials background. However, basic familiarity or quick grasp of concepts and terms pertaining to these industries may be beneficial for prompt comprehension.

1.7 Disposition (Outline)

The introduction or Chapter 1 of this paper has identified novel cement commercialization as a potential solution to help achieve necessitated emission reductions within the cement industry. Chapter 1 further described the utility in obtaining a greater comprehension of demand-side factors to better understand how commercialization can be accelerated. Chapter 2 will provide a description of the full methodology utilized along with a depiction of the conceptual frameworks used to guide the research. The literature review in Chapter 3 will synthesize findings from academic and grey literature pertaining to the four RQs. Chapter 4 will build off the findings from the literature review with those from industry actor interviews. Findings from the literature review and the data collection will be synthesized and analyzed together in Chapter 5 to obtain a more holistic understanding of novel cement demand-side factors. This chapter will also discuss the applicability and reliability of the results found. Finally, Chapter 6 will summarize the findings of this research in relation to the thesis's RQs and their wider implications. Due to the substantial number of themes within this thesis resulting from the broad and exploratory nature of this project, significant overlap exists between many topics, specifically within Chapters 3 through 5.

2 Methodology

2.1 Research Design & Approach

As there is little academic research pertaining to these subjects, this thesis is exploratory in nature to enhance comprehension surrounding the research problem (Blaikie, 2010). To answer the RQs posed in Section 1.3, a qualitative, inductive approach is taken in which a literature review and series of expert interviews strive to contribute to the understanding of the industry's demand-side landscape and how demand-side barriers and drivers can be addressed and employed. A triangulation approach attempts to enhance the validity and credibility of the findings from these two practices. The questions and topics for investigation posed in the RQs are distinct yet addressed through the same methodological approaches and overlapping research methods. RQ1 is considered through examination of value chains in both the cement and construction industries along with a broad investigation of the industry landscape. Expert perspectives and literature are synthesized to tackle RQ2 and RQ3 utilizing strategic niche management theory in addressing RQ2. Finally, actions stimulating wider novel cement dispersion, both those that can be utilized by industry actors and others, are examined considering technological transition theory that in turn serves to answer RQ4.

2.2 Conceptual Frameworks

Two main conceptual frameworks were used to frame the research design and findings of this thesis based on literature surrounding: technological transition pathways (Geels, 2002) and strategic niche management (Kemp & Schot, 1998). These theories were consulted to help comprehend trends enabling and surrounding major technical shifts and technology adoption to understand potential trajectories for novel cements as an emerging technology. Key framings presented in literature surrounding these two theories were utilized to help structure the remaining methodology (i.e. literature review and interview strategies).

2.2.1 Technological Transitions

Research surrounding technological transition theory works to understand sociotechnical systems and how radical changes within these systems can come about. In his research, Geels outlines extreme difficulties in sociotechnical reconfiguration due to interlinking components (e.g. regulations, infrastructure, user practices, maintenance networks) of prevailing regimes serving to 'lock-in' existing configurations that are aligned to current technologies (2002).

Geels describes the settings surrounding various technological innovations through a multi-level perspective (2002). A multi-level perspective helps to allow for inclusion of complexities of real-world markets and technology spaces. Through this perspective, three aligning and interacting levels are described: socio-technical regimes or current, self-reinforcing structures enabling and restricting various activities surrounding a technology; the broader landscape in which socio-technical regimes and other external factors interact; and niches where radical, innovative technologies can be developed and bred in more controlled incubation spaces. As new innovative technologies are developed, they are nurtured in niches and may eventually enter the wider socio-technical regime where they will both be shaped and will in turn shape regime-level elements (e.g. industrial networks, policy, infrastructure, etc.). While many of these technologies will fail, those that persist or are 'selected' by the socio-technical regime will alter various aspects of prior socio-technical regimes, eventually influencing the broader socio-technical landscape. (Geels, 2002)

Two mechanisms described for technologies to break out from small niches to a regime level potentially applicable to novel cements arose. First niche-cumulation in which technologies are continuously developed and grown through numerous, different niche applications gradually increasing their applicability, performance, and viability while gaining minor market share and recognition. Another mechanism is hybridization in which newer technologies are paired with compatible incumbent technologies, often to solve bottlenecks. In this sense, new technologies do not compete with existing ones, rather symbiotically work in parallel (e.g. plant retrofitting). (Geels, 2002)

Landscapes of technology adoptions are described to incorporate numerous aspects beyond producers and adopters including infrastructure, industrial networks, policy, other actors, 'cultural discourse', suppliers, end-users, financial networks, research actors, and more (Geels, 2002). Accordingly, research methods were designed to incorporate as many of these aspects of wider landscapes as possible to maximize comprehension of real-world implications (e.g. wide range of interviewees selected).

While major cement transitions may not fit perfectly in this framework, as cements may be more accurately classified as a material or commodity rather than a new technology, and novel cement adoption would likely not significantly change the way society functions, this framework is still useful as it outlines many of the relevant and applicable barriers and drivers for innovative change.

2.2.2 Strategic Niche Management

Strategic niche management was described by one author as a means to help facilitate sustainability regime shifts and technological transitions (Kemp et al., 1998). Kemp et al. describes that despite identifications or conceptions of which technologies may be able to provide more sustainable long-term solutions, absence of these products on markets and other barriers to implementation inhibit their pursuit (1998). Strategic niche management is modeled as a means to both get these technologies/products to markets and to foster development, improvement, and success of these products within more protected incubation. Within these niches, technologies have the opportunity to optimize costs, demonstrate viability, build awareness and customer bases surrounding their products, establish financial stores for future development and expansion, and build constituencies of actors familiar with these technologies that may play various roles in larger regime shifts later on. Upon success in niche markets, technologies will be more developed and accordingly more prepared to enter and succeed in more diversified markets further increasing their dispersion. This strategy has been exemplified to help expedite regime shifts and technological transitions (Kemp et al., 1998).

One specific barrier described by Kemp et al. in technological transitions towards more sustainable products surrounds demand factors (1998). Demand hinderances described include customer risk aversion, strong user preferences, and price sensitivity/lack of financial incentives. Accordingly, manufacturers are greatly discouraged from pursuing these technologies due to perceptions that demand cannot be easily changed or influenced by suppliers. However, these suppositions are described to be false, and the interrelatedness between all barriers, demand-based and otherwise, is emphasized (Kemp et al., 1998).

2.3 Research Methods

A literature review and expert interviews are the two methods used to inform the results of this thesis. As they were performed concurrently, findings from each were able to inform and enhance the other. For example, interviewees may have cited or suggested key literature for inclusion in the literature review, while the literature review may point to new concepts to bring up in interviews. This dynamic approach helped to blend findings from the two different methods while allowing for further expansion or enhancement of topics found later in the research process.

2.3.1 Literature Review

The literature review in this thesis utilizes academic literature, reports from research institutions and other organizations within the cement and concrete industries or 'grey literature', company websites, popular science articles, and industry webinars. Despite the focus of the paper on demand-side aspects of novel cements, the literature review incorporates a wider swathe of topics within the cement and concrete industries as demand drivers and barriers within this topic are intricate and span across all segments of the industries, and as there is little literature specifically concerning the demand landscape.

The literature review was initially driven by keyword searches on academic databases like LubSearch and Google Scholar. Supplementary grey literature was then sought on major industry organization websites (e.g., Portland Cement Association Library, World Business Council for Sustainable Development's (WBSCD) Cement Sustainability Initiative (CSI), etc.). Examples of query topics include novel cements, cement and concrete sustainability, cement and concrete innovation, names of novel cement companies, novel cement technology types, novel cement demand, sustainable cement demand, etc.. Later these initial resources were largely supplemented by literature suggestions from interviewees and other correspondents. Additional resources were also discovered through citations of the aforementioned sources. Company websites and popular science articles were also consulted, predominately for information pertaining to descriptions of available technologies, development/commercialization status, sustainability claims, and portrayals of various products as several were not found in academic or other literature. The literature review was performed until subject matter and argumentation sustained a level of saturation and was also performed concurrently with the interview process. Accordingly, interviews helped to shape the literature review, and vice-versa, as both progressed.

Sources of potential bias may relate to types of resources analyzed. While academic literature is typically thought of as containing lesser bias, the inclusion of non-peer reviewed sources like company websites, popular science articles, or even grey literature can be viewed as having greater potential for partiality or ulterior motivation. While there may be greater risk for bias, company sites provide advantages in representing more primary perspectives, and resources like grey literature can potentially be more abundant. In dealing with a topic like this that lacks representation in academic literature, grey literature helped to compensate for data and information lapses comprising the majority of resources examined (Blaikie, 2010). To minimize potential biases, only grey literature from reputable organizations was utilized in the literature review, and company websites were only consulted for claims about their own organizations and products.

2.3.2 Interviews

Nine semi-structured, expert interviews were performed with a diverse set of industry actors to obtain multi-perspective findings. Actors from different positions within the cement demand chain, within the cement industry, academics studying cement industry innovation, and industry group members were chosen as interviewees to attain a holistic grasp of the demand-side landscape relevant to the RQs. An interview guide was developed for each interviewee to steer the interviews to the most relevant and pertinent issues within this topic. In accordance with the exploratory nature and methodology of this project, the interview guide was adjusted somewhat and tailored specifically for each interviewee based on their stakeholder type and specific experience within their position(s). Interviews were kept relatively flexible to allow for open discussion and inclusion of unforeseen variables within the industry landscape. Yet general topics and some questions were kept consistent, especially for those within the same stakeholder group, to ensure some level of consistency and foster better triangulation. As interviews went on, interview guides were continuously adjusted to enhance relevance of lines of questioning and further optimize triangulation. Examples of interview questions found in some of the various interview guides can be found in Appendix B.

Both cold-emailing individuals or organizations found online and snowball sampling were the two tactics used to acquire interview subjects. In finding potential interviewees, thirteen novel cement companies, three larger cement and concrete companies, four academics, and five industry groups were reached out to via email or online messaging services. These sets were selected to represent the industry-side of the value chain with the underlying assumption that these groups would have knowledge of demand-side aspects as demand considerations are necessary in ensuring revenue. On the demand-side, six demand-side actors including developers and construction companies, transportation agencies, and members working on this topic from an academic position were also approached for interviews or potential interviewee contacts. The snowball sampling method was also largely utilized in finding interviewee subjects, particularly from those within academia as this was an easy starting point for a student with no industry connections. A full list of interviewees is found in Table 2-1 below:

Table 2-1. List of Expert Interviews.

Name	Position	Interview Date	Interview Method	Interview ID #
Jannie Van Deventer	Chief Executive Officer: Zeobond Group	2/27/2020	Video-Conferencing	1
Paul Sandberg	VP: Calmetrix; Prior VP materials Science: CarbonCure Technologies	2/28/2020	Video-Conferencing (Voice Only)	2
Johan Rootzen	Researcher: Chalmers University of Technology; focus in CCS within Swedish cement industry	3/16/2020	Video-Conferencing (Voice Only)	3
Terrence Profita	IKEA: Real Estate, Construction – Engineering Group (Malmö, Sweden)	3/24/2020	Video-Conferencing	4
Tristan Nilumol & Alana Guzzetta	U.S. Concrete – National Research Lab: Research Representative & Technical Manager	3/26/2020	Video-Conferencing (Voice Only)	8
Richard Meininger	US Federal Highway Administration (US Department of Transportation): Pavement Materials Team	3/27/2020	Phone	7
Zihui (Lance) Li	Caltrans Concrete Materials Testing Branch	4/1/2020	Video-Conferencing (Voice Only)	5
Dr. Wolfgang Dienemann	HeidelbergCement Technology Center: Director Global R&D	4/7/2020	Video-Conferencing	9

Lionel Lemay	National Ready-Mixed Concrete Association: Executive Vice President, Sustainable Development	4/9/2020	Video-Conferencing	6

The nine interviews were performed from February 27–April 9. Excluding one phone interview, interviews took place over Skype or other video-conferencing tools and lasted between 30 and 80 minutes. With the permission of subjects, interviews were recorded to enable more dynamic conversations between the two parties from decreased focus on note-taking and transcription. Upon request, interviewees were provided a final draft of this thesis prior to final publication to ensure the exclusion of any sensitive information from the interviewees' perspectives and to ensure their opinions have been properly represented. ID #s are used in the results section to reference interviewees.

2.4 Limitations

The potential for the presentation of biases or misrepresented information may appear in this paper as partiality from the author may arise through iterative representation of information after performing, transcribing, and summarizing interviews along with various rewritings. Further, interviewees' understandings are likely subject to their own contextual, subjective experiences. For instance, while an interviewee may provide information representative of their own experiences, the same sentiments may be less applicable or inconsistent in other contexts or markets (e.g. in another country, relating to a different technology, etc.). Having just one respondent representing some industry actor groups can also present limitations as the communicated experiences of one individual likely fail to fully represent trends felt throughout their entire group. Finally, certain actor groups may exhibit inherent biases. For instance, research groups trying to attain carbon-neutrality may speak more optimistically about the feasibility of green technologies, as it is in their best interest for this to be the case.

Biases and limitations, in addition to those already discussed, are related to the broad scope and nature of this project. While focus on markets in China, India, and other developing countries would be ideal due to their majority share in both current and anticipated production and demand (Beyond Zero Emissions, 2017), the defacto geographic focus of this thesis surrounded North America, Europe (especially Scandinavia), and Australia due largely to accessibility of interviewees and research availability in the author's main language (English) in hopes that many findings will be applicable to this wider geographic range. However, given significant market and contextual differences, all findings need to be viewed critically in their wider application.

In addition to the expression of potentially anecdotal or subjective perceptions, interviews and some sources consulted through the literature review, like company websites, may reflect potentially 'motivated' communications. Due to the rapidly developing field of green cement and concrete technologies, many literature sources may also now be out of date, particularly academic sources written over a decade ago. However, lack of academic literature discussing market aspects of this sector made this hard to overcome. Additionally, for some smaller cement and concrete companies investigated, it is sometimes difficult to ascertain the current status of these businesses, particularly when contact information is out of date, as they can often change hands or go out of business without much associated publicity. Finally, the diverse and sometimes off-script nature of interviews led to a lack of consistent discussion types. As interviews were relatively short, and this project includes so many subtopics, interviewees were often not given the chance to fully elaborate or answer follow-up questions pertaining to certain topics due to time constraints limiting both full comprehension of interviewee perspectives and triangulation.

The aims of this research surround lowering GHG emissions to reduce contributions to climate change. Accordingly, the term ‘sustainability’ in this thesis generally refers to low-emission technologies and practices. However environmental sustainability is much more complex than this singular issue requiring consideration of other environmental factors. The neglect of consideration of these other issues is a further limitation of this research in advancing what are touted as ‘sustainable’ technologies.

3 Literature Review

3.1 Industry Landscape

Often producing over one million tonnes of product annually, cement plants are typically mass manufacturing sites. Plants costing in the range of hundreds of millions of dollars with additional maintenance costs in the range of tens of millions of dollars make these facilities massive infrastructure investments, and in combination with their high capacities lead to a globally limited number of plants (e.g. only ten in Australia) and accordingly localized industry. (Beyond Zero Emissions, 2017) In these localized markets, plants are usually built close to raw material sources and rarely face cross-border competition as cement is inexpensive but heavy and accordingly costly to transport (Beyond Zero Emissions, 2017; Fernandez Pales et al., 2019; Lehne & Preston, 2018). For instance, cements and SCM markets typically surround manufacturing plants in a 200–300 kilometer radius (CEMBUREAU, 2017).

Cement plants can be integrated, combining clinker production and cement grinding, or stand-alone mills (International Energy Agency, 2018b). Some clinker is sold directly from plants, but most is ground, mixed, and turned into cement on-site. OPC is stored in silos, then either bagged or sent out in bulk with most sold to either concrete manufacturers or contractors (Rootzén & Johnsson, n.d.). OPC usually contains > 90% clinker by mass, while blended cements have lower clinker to cement or 'clinker' ratios (Beyond Zero Emissions, 2017). While cement can be viewed as a commodity (very little product differentiation competing mainly on price) (Lehne & Preston, 2018), concretes are typically available for purchase in a range of specifications (Beyond Zero Emissions, 2017). Over the past several decades, previously more prevalent small- and medium-sized enterprises (SMEs) cement companies were purchased and consolidated into larger ones. In addition to independent concrete manufacturers, some cement and concrete companies are vertically integrated. Many cement producers are subsidiaries to larger multi-national, vertically integrated organizations like HeidelbergCement or LafargeHolcim (Rootzén & Johnsson, 2016).

Generally spatially confined markets allow for varying input and delivery costs in different markets and regions. Materials and transportation typically comprise the majority of operating costs (at least in Nordics) (Rootzén & Johnsson, 2016). Economies of scale in this industry apply not just in optimizing manufacturing and in operating at capacity, but also surrounding logistical coordination (e.g. delivery optimization) (Hortaçsu & Syverson, 2007). More recent decelerating economic growth and development in China have helped transition the industry into a 'global cement glut' (Lehne & Preston, 2018). Additionally, disproportionate production capacity and demand in European markets along with increasingly high-performing plants in emerging markets have further contributed to a period of financially challenging market conditions for manufacturers (Soliman & Fruitiere, 2016).While the concrete sector is in some ways its own non-competitive sector, in others it also competes with other building materials.

Historically, innovation and change have occurred incrementally in this sector, not through radical breakthroughs, with most research surrounding improvements in OPC- or 'clinker-based' cements, not novel cements (Lehne & Preston, 2018). Most novel cements remain in various phases of Research and Development (R&D) and piloting and while their use remains limited in most Nordic countries, for instance, (with Denmark as the exception), it is expected to increase over time (International Energy Agency, 2018b; Nielsen & Glavind, 2007). Despite some novel cements being in more advanced stages of development, very few are actually made readily accessible to concrete producers to use or test (*European standardisation of new and innovative cements*, 2016).

One patent analysis demonstrates the range of solutions being pursued to be targeted towards several applications, rather than attempted development of a 'silver bullet' technology. (Lehne & Preston, 2018). Several SCMs already cost less than OPC in several regions helping certain novel cements become cost competitive with OPC. In South Africa geopolymer cement is already cheaper than OPC because of this. Wider adoption and larger production scales are likely to further increase the economic viability of novel cements through economies of scale (Beyond Zero Emissions, 2017).

Cement's end-use (considering only concretes) are described by Rootzén & Johnsson to be between civil engineering (e.g. transport infrastructure, hydraulics, other infrastructure), non-residential building, and residential building sectors (2016). Three main classifications of concrete applications will be referred to in this thesis: ready-mixed, precast, and dry bagged. Differences in these classifications have implications on the viability and feasibility of various novel and green cements. These are described in greater depth below, and an example of supply-side material flow (in Nordic markets) can be exemplified in Figure 3-1.

Ready-mixed: Ready-mixed or pre-mixed concretes are typically delivered from their conception at centralized plants to work sites in 'transit mixers' in which they are semi-liquid and mixed during delivery to minimize application times at work-sites. Pre-mixing before delivery allows for greater precision in measurement, potentially resulting in higher quality than on-site mixing. Pre-mixed concretes with more specialized mixes can also be tailored to clients' specifications. It is important that ready-mixed products can be mixed at plants then transported to sites while remaining semi-liquid, and traditionally, setting times of cements used in ambient temperatures need to be similar to those of OPC. (Beyond Zero Emissions, 2017)

Precast: Precast products are concretes mixed, poured, and hardened off-site in precasting facilities producing products like panels, pipes, bricks, blocks, tiles, and beams. Due to their manufacturing in controlled factory conditions by trained staff, precast products can be made with more complex processes facing additional challenges like lower workability, longer hardening times, and toxicity that may be too difficult to manage on construction sites. Precast manufacturing enables faster, more precise construction as concretes have already hardened upon reaching sites with factory settings minimizing errors. This has led to increases in their proportional makeup of concrete use in places like Australia. (Beyond Zero Emissions, 2017)

Dry, bagged cement/concrete: These products are sold in powdered form, often in 20 kg bags. Their assumed uses are mostly in small-scale applications (e.g. concrete in small renovation or landscaping projects), and in making mortars for bricklaying and masonry block laying. Simplicity, ease, and clarity of instructions in mixing dry-bagged cements are critical as they are used on-sites, often by those without associated training. Reasonable setting-times of these products are also essential. (Beyond Zero Emissions, 2017; Rootzén & Johnsson, 2016)

The proportional makeup of these types of cements and concretes can differ significantly by region. For instance, of ready-mixed and precast, in the EU 49% of concretes are ready-mixed (European Ready Mixed Concrete Organization, 2015), whereas in Australia, 70% is ready-mixed, 20% precast, and 10% dry bagged (Beyond Zero Emissions, 2017). In several developing countries, however, bagged products comprise the largest share (Scrivener et al., 2018).

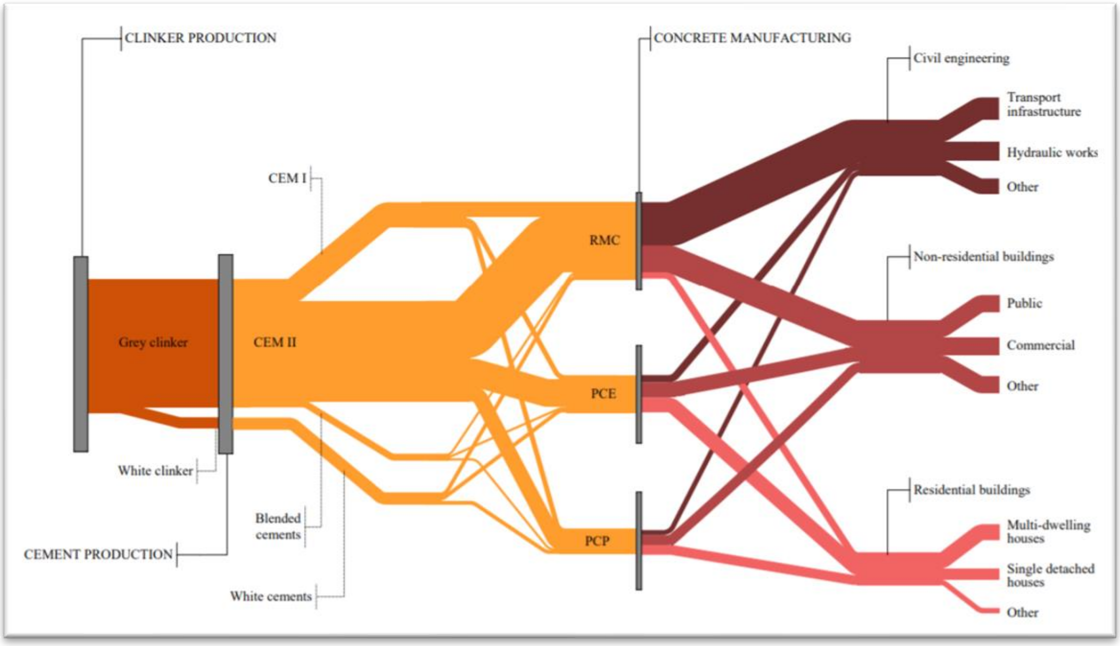

Figure 3-1. Supply-chain cement material flow (Nordic markets).

Source: Rootzén & Johnsson (2016).

Various types of industry actors were found throughout literature in relation to the existing novel cement landscape and corresponding paths to wider commercialization:

> **Supply-side:** large, incumbent cement and concrete manufacturers; innovative novel cement SMEs; other green cement/concrete start-ups; and associated supply-chain actors
>
> **Demand-side:** end-users/customers; building developers; architects/designers; engineers; contractors; site-workers; and consultants
>
> **Other:** policy makers; academia; financing actors; research institutions; industry groups and trade associations; standards organizations; sustainability certification bodies; and sustainability organizations

Sustainability prioritization was described to vary significantly across the sector. A limited number of demand-actors and end-customers are motivated by sustainability commitments and comprise a group of potential novel cement early-adopters. Increasingly, some customers are setting embodied carbon targets in construction projects and supply chains. For instance, at least 39 building firms have set or expect to set science-based emission reduction targets (Lehne & Preston, 2018). On the supply-side, one described the management of multiple cement and concrete companies as having genuine sustainability interest (Burris et al., 2015). However, various cement producers have substantially different emissions intensity levels, reduction targets, and overall sustainability commitments. Exemplifying this, is major incumbents' use of significantly different internal carbon prices. Further, while sustainability pressure in this sector has significantly increased, several incumbents still do not follow guidelines surrounding climate risk exposure (Lehne & Preston, 2018).

3.1.1 Supply-Side Actors

Supply-side actors are comprised predominately by cement and concrete manufacturers in addition to those within material constituent supply-chains. This industry is described as having generally low R&D capacity, typically following incremental innovation pathways. As noted by one source, most companies have few resources dedicated to R&D, excluding LafargeHolcim (Lehne & Preston, 2018).

Manufacturers can be classified into two main groups: large incumbents, and start-up like SMEs. SMEs were cited to not significantly collaborate with other industry actors in pursuing cement innovations (van Deventer et al., 2012). Manufacturing in the cement sector is concentrated to a few large producers. Accordingly, a limited number of incumbent actors have high levels of influence over several industry aspects (e.g. creation and content of industry roadmaps and guideline setting, influence over standards committees, lobbying power) (Lehne & Preston, 2018). Generally, incumbent manufacturers are cited as being incentivized to maintain the status-quo and have innovation within the sector limited to their own internal operations (Wesseling & van der Vooren, 2017). In this sense, technological innovations are often channeled through incumbents who can influence their dispersion and surrounding political lobbies according to their own interests (Lehne & Preston, 2018). While this can limit novel cement dispersion if not deemed to be in the best interest of large actors, on the other hand, once decided to be in their best interests, technologies have the potential to be widely implemented and dispersed very quickly (Lehne & Preston, 2018). There are large differences between individual cement incumbents in terms of innovation capacity and support of various emissions-reduction regulations (Soliman & Fruitiere, 2016). Despite perceptions describing large incumbents to be unincentivized to pursue novel cements and other innovative technologies, outside of China, LafargeHolcim and HeidelbergCement are the two biggest contributors to alternative cement patents. LafargeHolcim is also cited to work closely with Solidia, a green cement SME (Lehne & Preston, 2018).

3.1.2 Demand-Side Actors

The multi-actor, disjointed demand chain within the construction, building development, and infrastructure sectors corresponds with non-linear, inconsistent decision-making processes concerning material consideration and adoption (Renz & Zafra Solas, 2016). Accordingly, for the uptake of novel cements to occur, buy-in from numerous demand-side actors is required. Cement or concrete manufacturers often interact with the demand-side at the contractor or subcontractor level, typically after material selections have already been made (Lehne & Preston, 2018). A more detailed outline of the value chain within the construction sector can be seen in Figure 3-2 highlighting four actor groups with strongest influence over potential novel cement selection: architects, end-customers, contractors, and structural engineers. Other sources reiterate designers' significant influence on sustainability-related material decisions (Lemay & Lobo, 2020). More direct collaboration and interactions between demand-side actors and manufacturers before material specification could help increase uptake (Lehne & Preston, 2018).

Demand-actors, specifically end-customers, strongly committed to sustainability have significant influence over innovation processes and demand trends. This can come from both public and private actors and can take the form of green cement endorsement or activism, for instance. Governments particularly can help drive change as they have such high construction spending (e.g. in the U.S., 32%, of construction spending comes from the public sector) (Lehne & Preston, 2018). Major, influential end-customer firms setting ambitious emissions reduction targets and working with construction companies, designers, developers, and other demand-chain actors to procure low-carbon cements could also be extremely influential in shaping both demand and industry experience surrounding these products.

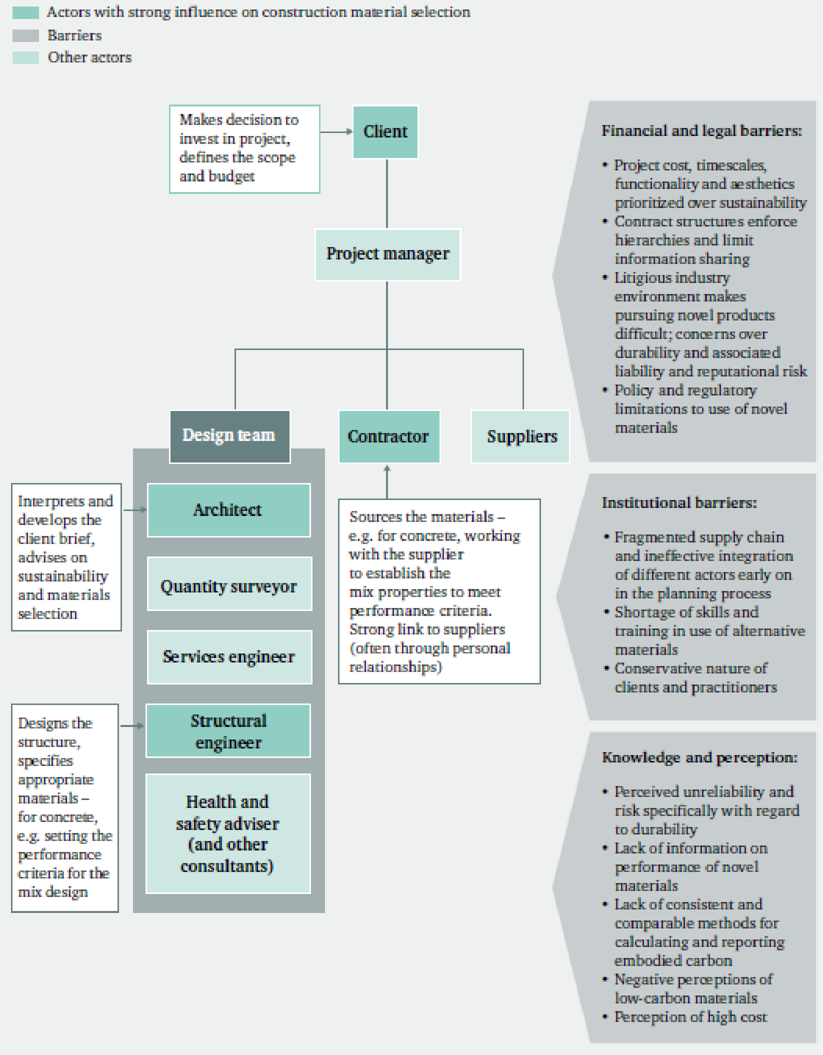

Figure 3-2. Construction demand-chain actors.

Source: Lehne & Preston (2018).

Transportation organizations are an example of a highly influential sub-sectors, some of which have already taken actions in adopting and widening adoption of novel cements. This can be seen in the example of the U.S. transportation sector who actively and increasingly investigate novel cements for applications in infrastructure, often in urban areas, largely for their unique properties (e.g. higher strength and durability, faster setting times decreasing road closure times). These unique benefits and properties were cited to outweigh any potential challenges or cost increases in using these products. Some research teams aim to develop guidelines and recommendations for testing new alternative cement products including performance criteria to integrate in specifications, with another having identified a group of alternative cement products for further testing with aims of scalability (International Energy Agency, 2018b).

3.1.3 Other Actors

Governments and policy makers (from municipal bodies to supranational organizations), academia, industry groups and trade associations, financial actors, insurers, climate action and research organizations, standards committees, and sustainability certification groups were all mentioned in literature as playing various roles in shaping the larger demand landscape. The roles of these actors will be described in following discussions surrounding both barriers and 'Paths Forward'.

3.2 Novel Cement Technologies

While novel cements are mostly discussed collectively in this research, in reality, several distinct technologies with varying chemistries, material constituents, manufacturing techniques, performance characteristics, and more comprise this broader grouping. Some basic novel cement categorizations found in academic literature as part of a pre-study for this thesis were compiled in Table 3-1. This list is by no means exhaustive, especially given the constant evolution and development of these technologies. Additional descriptions of a select, limited set of these technologies/categorizations developed in the same pre-study can be found in Appendix C. Further, companies and research bodies developing a particular novel cement technology often derive their own specific formulations. Accordingly, several novel cement categorizations are closely related and share varying degrees of similarities. Due to the continuous development of these technologies, not all novel cements are yet found in academic literature. Other technologies not found widely throughout literature can discovered through some of the green cement SME company and product names found in Appendix A. While there are currently no publicly available comparative life-cycle assessments (LCAs) of a wide range of novel cements (Beyond Zero Emissions, 2017), the claims in Table 3-1 should be viewed subjectively and not well suited for direct comparison.

Table 3-1. Synthesis of select novel cement technologies and attributes.

(Note: Numeric codes (1-11) refer to citations listed below)

Technology Name	**Development Phase**	**Developer(s)**	**GHG Mitigation Potential**	**Generalized Cost Comparison**	**Material Availability**	**Application**	**Standardization Coverage**	**OPC Plant Retrofit Ability**	**Sources Referenced**
CSA (calcium sulphoaluminate)	Commercialized (1) ; Commercialized in China, used since 1970s (2)	Lafarge, BRE (2)	50% (1); 20% (2)	Higher (1,2)	Limited (1,8)	Niche (1)	Covered in some Chinese standards; European standards under development (1)	Yes (2)	1,2,8
BYF	Demonstration (1); early development (4)	Aether (4)	>20% (1); 10% (4)	Higher (1)	Variable (1)	Niche, theoretical wide range (1)	Covered in some Chinese standards; European standards under development (1); largely covered (4)		1,4
Calcium aluminate/calcium alumina silicate				Higher (2)					2
Geopolymers/alkali-activated binders	Commercialized (1,2); Demonstration (10)		90% (1); 95% (2); 65% (10)	Similar (1,2)	Variable (1)	Wide range in Australia (1)	Limited coverage (Beyond)		1,2,6,8,10
Super-sulfated cements				Higher (2)	Limited (1)				1,2

Magnesium-based cements	Research (1); commercialized (2); lab testing (3); pilot stage (10)	US Gypsum's 'Grancrete'; Chinese wallboard companies; Argonne National Labs 'Ceramicrete'; TecEco, Novacem; Eco Cement (2,3,8,10)	>100% (1); carbon negative (2,8,10)	Unsure (1)	Variable (1), high global availability but not evenly distributed (2,4)	Unsure (1), unique qualities useful in building applications (2); broad range (3)			1,2,3,4,8,10
Calera Cement	Advanced development stages (2); pilot plant now closed (3)	Calera Corporation	>90%, carbon negative					No (1)	1,2,3
Carbonation hardening based on calcium silicates	CO_2 curing in precast concrete piloted, not yet fully commercially viable (1); development (10)	Solidia	>70% (1); >50% (10)	Similar (1)	High (1)	Currently limited to precasting (1)	Precast covered by local technical approval (1)	Same kiln as OPC (1)	1,10
Calcium silicate hydrates	Pilot plant (3)	Celitement (3,8); Schwenk Group (3)	>50% (1)	Similar (1)	High (1)	Wide range (1); Same as OPC (3)	Not covered (1)	Yes (3)	1,3,8

(1) (Lehne & Preston, 2018); (2) (Imbabi et al., 2012); (3) (Ulrich Dewald & Achternbosch, 2016); (4) (Ellis Gartner & Hirao, 2015); (5) (Huntzinger & Eatmon, 2009); (6) (Maddalena et al., 2018); (7) (Schneider et al., 2011); (8) (Naranjo et al., 2011); (9) (Jang et al., 2016); (10) (Hasanbeigi et al., 2012); (11) (E Gartner, 2017)

As closer look at one set of novel cement technologies, geopolymers, is examined below helping to illustrate the significance of technology-specific attributes in shaping effective strategies for commercialization and their role in the wider landscape.

Geopolymers – A Closer Look

Alkali-activated cements or 'geopolymers' are described to be well-developed yet commercially limited (Beyond Zero Emissions, 2017) having increasingly gained popularity in recent years (Maddalena et al., 2018). They have been explored since the 1970s as one of the most widely known and researched novel cements (Lehne & Preston, 2018). These binders are made when aluminosilicate materials are combined with an alkali activator. Prominent geopolymers are typically classified as either alkali-activated fly ash cement or alkali-activated slag cement. Mixtures of the two, both with and without OPC, are used (Imbabi et al., 2012). While most geopolymer formulations utilize fly ash and GGBS (Lemay & Thompson, 2020), many other materials with a minimum aluminosilicate content can also be used. Some of these less explored materials include waste glass, volcanic ash, certain clays, and red mud (Beyond Zero Emissions, 2017). Use of different materials, however, can affect physical properties of geopolymers and other novel cements. For instance, calcined clay-based geopolymers can have higher strengths and different coloration than more standard ones (International Energy Agency, 2018b). Current reliance on materials used in many blended cements (e.g. natural pozzolans, GGBS) makes most geopolymer viability dependent on regional material availability (Beyond Zero Emissions, 2017). Large production scales of certain geopolymer facilities are also described. For instance, Banah UK was set to open a factory with a capacity of 200,000 tonnes per year in 2017, with other companies expected to significantly expand manufacturing in the near future as well (Beyond Zero Emissions, 2017).

Their limited commercialization includes markets in Australia, Brazil, Canada, China, Czech Republic, India, Netherlands, Russia, South Africa, Ukraine, United Kingdom and the U.S. (Provis, 2018). One source describes geopolymers to be 'tried and tested' in a range of applications in both infrastructure and building sectors (e.g. multi-story buildings, precast panels, airports, sewer pipes, curb sides, pavements, and railway sleepers). There are some geopolymer-based buildings in the world over fifty years old and still in use demonstrating potentially successful long-term durability. Geopolymers have one of the largest portfolios of demonstration projects of any novel cements. However, despite this, perception of their proven viability is still lacking. (Beyond Zero Emissions, 2017)

Estimated emissions reduction potential ranges from 65% (Hasanbeigi et al., 2012) to 95% (Imbabi et al., 2012), with one geopolymer technology (Ceratech) even claiming carbon-neutrality (Beyond Zero Emissions, 2017). While geopolymer manufacturing enables lower manufacturing temperatures, most associated emissions come from generally very carbon-intensive alkali activator production. Wide ranges of activator use and mix designs decrease the applicability of established average emissions reductions potential. Over the past few decades, however, amounts of activator required in production have decreased from 40% to 5-15% with additional reductions likely still possible helping to lower some of these impacts (Beyond Zero Emissions, 2017). Activator reduction remains a current focus of academic research (Lemay & Thompson, 2020).

Geopolymer concretes were described by one source to meet the **performance** of OPC cements (e.g. strength, durability, hardening times) (Beyond Zero Emissions, 2017). Some potentially superior traits cited include faster strength gains, lower dry-shrinkage, improved durability, enhanced fire resistance, higher flexural tensile strength (greater ability to bend without cracking), and acid, salt, and chloride resistance (Lemay & Thompson, 2020)(Beyond

Zero Emissions, 2017). On the negative side, some evidence suggests that these products can carbonize more quickly potentially accelerating steel corrosion in reinforced applications. Particular advantages associated with geopolymers are found in hostile or extreme environment applications (Beyond Zero Emissions, 2017).

Many geopolymers can be produced at similar **costs** to OPC (Imbabi et al., 2012; Lehne & Preston, 2018) with some cited to be less expensive in some markets (Beyond Zero Emissions, 2017). Geopolymer plant installation is described to cost less than 10% than that of an OPC plant (due in part to lack of kilns), however, the expensive and energy intensive nature of activator production associated with geopolymers diminishes this benefit (Lemay & Thompson, 2020; (Beyond Zero Emissions, 2017). One geopolymer product in South Africa (from Murray and Roberts) is cited to be 30% cheaper than OPC in that region, due in part to large supplies of fly ash and slags (Beyond Zero Emissions, 2017). Another geopolymer group (NuRock) whose bricks and blocks are described to be half the cost of standard industry prices. Further, another geopolymer-based concrete (Wagners' Earth Friendly Concrete), while 10-15% more expensive than traditional concrete, is less expensive than the specialty cements/concretes it more realistically competes with (e.g. high-acid resistance, off-white coloring specialty cements) (Beyond Zero Emissions, 2017).

A unique challenge presented by geopolymers relates to their generally high levels of alkalinity posing potential **safety risks** in working with them. The caustic nature of the activators used can be corrosive and accordingly need to be dealt with in controlled environments (e.g. temperature control) (Lemay & Thompson, 2020);(Beyond Zero Emissions, 2017). Accordingly, construction sites may be less conducive to direct mixing of these products, while more controlled factory environments would minimize some of these risks. Lowering the pH of activators, in the long term will help minimize these concerns which some are already pursuing. For instance, Murray and Roberts has developed a geopolymer with a pH lower than that of OPC. Another, developed by Banah, is classified as only an 'irritant' by European standards (Beyond Zero Emissions, 2017).

Niche applications most optimal for geopolymer use may include precast products due to aforementioned safety concerns, potentially longer setting times, and more precision and training required in mixing. Pre-mixed concretes, on the other hand, typically need to be able to cure at ambient temperatures. Many geopolymers are heat-treated to accelerate hardening which can only be done in factory settings. Some applications in which geopolymers are described to have superior performance characteristics to OPC involve those needed in more 'extreme' conditions including: piping exposed to acidic and high-sulfate conditions (e.g. sewers), foundations in acidic or high-chloride soils, marine environments (e.g. in harbors and ports), applications with needs for high levels of fire-resistance (e.g. road and rail tunnels), 'extreme' environments like chemical tanks and processing structures, petroleum applications, acid-exposed trenches, jet engine test pits (for heat resistance), and other high stress or toxic environments. They may also be preferential in road surfaces, building foundations, and other precast applications as higher strength levels of some of these products may decrease the need for steel reinforcement. An example of a geographic niche that may be well suited for geopolymer use is in parts of the Middle East where higher sulphate and chloride conditions may make geopolymers' unique properties more desirable. (Beyond Zero Emissions, 2017)

Lack of widespread inclusion of geopolymers in national **standards** has been described to inhibit uptake. Some groups (e.g. Standards Australia) are working to widen standards to become more inclusive of or explicitly include geopolymers. Despite standardization barriers, a few organizations (e.g. some within the Australian public sector) have specified geopolymers as equivalent products to OPC for certain applications (Beyond Zero Emissions, 2017).

3.3 Barriers

While the focus of this research initially exclusively surrounded the demand-landscape, the literature review illuminated the interconnected and reinforcing nature of both supply- and demand-side barriers as manufacturers and other actors play major roles in shaping demand and creating awareness and understanding of novel cement technologies and as emergence of demand can help shape new business models and incentivize investment by manufacturers (Lehne & Preston, 2018). Accordingly, certain supply-side barriers are discussed in relation with demand-side barriers.

The barriers discussed below and the magnitude to which they inhibit novel cement commercialization can differ significantly based off the specific novel cement technology in discussion along with other regional differences (International Energy Agency, 2018b). For instance, geopolymers may be cost- and performance-competitive with novel cements in a certain context but face regional material shortages in another (van Deventer et al., 2012).

3.3.1 Risk Aversion & Product Quality

Risk aversion is attributed in literature to both lacking knowledge surrounding actual durability and long-term performance of these products (International Energy Agency, 2018b) as well as unsubstantiated perceptions of products being more risky and having lower performance (Lehne & Preston, 2018). Lack of actual or visible demonstrations of these products in action, especially in varying conditions and from long-term perspectives, can deter novel cement consideration, especially in structural applications (Burris et al., 2015). Some of this risk aversion, however, can be attributed to substantiated differences between novel cements and OPC. For instance, physical attributes increasing difficulty in application (e.g. poor flow, non-smooth finishing), differing setting times and early-stage strength development, and variable durability are some attributes met with aversion (Lehne & Preston, 2018). In novel cement testing and use, mixed results regarding performance have been attained: the positive ones encouraging further use and experimentation, the negative ones potentially disincentivizing continued use and experimentation (International Energy Agency, 2018b). One source cites these concerns with technology performance as the most prominent barrier facing novel cements (Beyond Zero Emissions, 2017).

Lack of performance testing or widely available testing data can reinforce risk aversion and performance-based barriers while available, positive results can increase certainty and understanding surrounding these new products diminishing barriers (Lehne & Preston, 2018; van Deventer et al., 2012). As long-term performance and durability, for instance, cannot be precisely modeled with current short-term testing extrapolations (although this may soon change), perceived uncertainty concerning long-term performance is reinforced (Lehne & Preston, 2018; Wray, 2012). Finally, most resources allocated towards research are used in enhancing OPC-based products rather than novel cements (Snyder et al., 2013).

Lack of long-term demonstration projects and lacking ‘in-service’ testing results further reinforce risk aversion (Lehne & Preston, 2018). As research and testing performed through predictive modeling are currently still met with substantial skepticism (Giesekam et al., 2016), advances in testing technologies and their efficiency could help decrease this skepticism of lab-based testing (Lehne & Preston, 2018). These improved testing mechanisms with corresponding increased confidence in results could further help transitioning towards performance-based standards (McCarter et al., 2015) and help accelerate the development of new standardizations in general (van Deventer et al., 2012). In addition to improved lab testing, enhanced and more user-friendly in-situ testing and monitoring mechanisms may further help garner more confidence in novel cements (Giesekam et al., 2016). Finally, sharing of this testing data is critical in maximizing its value and garnering wider understanding and confidence (Lehne & Preston, 2018).

3.3.2 Standards, Codes, and Specifications

Literature finds a variety of barriers concerning standards with several sources describing standard restrictions, for both cements and concretes, as main barriers to alternative cement proliferation. Standards in general are set and followed to help safeguard quality, functionality, and safety of widely adopted products (International Energy Agency, 2018b). Accordingly, high levels of risk aversion and safety concerns found across the construction sector are reflected in cement and concrete standardizations and specifications. In these ways, current standards both reinforce and reflect low demand for green cements (Lehne & Preston, 2018). Many current cement and concrete standards do not explicitly exclude novel cements, but rather implicitly encourage the use of OPC-based cement (Beyond Zero Emissions, 2017). Standards not directly referencing novel cements can make it more difficult for engineers to specify and get approval for their use; accordingly, having standards and specifications specifically for novel cements would be helpful (International Energy Agency, 2018b). According to the EU, standardizations can help spur innovation and competition by increasing market access to more products, enhancing user protections, and decreasing risk aversion for customers (*European standardisation of new and innovative cements*, 2016). In shifting to a market with a wider assortment of cement products, standardizations need to become more broadly inclusive as opposed to their current revolution around variations of one product (OPC). Standard changing processes, however, are generally very slow, taking as long as decades for new ones to be implemented (Lehne & Preston, 2018).

Two main types of standards and specifications are described in literature: prescriptive ones providing details about mixture composition, and means and methods for how cements/concretes should be mixed (e.g. content limitations, fuel use, etc.); and performance-based ones defining attributes and performance qualities necessitated by products. Prescriptive standards are described to be more widely used than performance standards, yet, many are a hybrid of the two in reality. Risk aversion and concerns with physical properties generally encourage prescriptive philosophies as more straightforward guidelines can be perceived to be less risky (Lehne & Preston, 2018). Although they may be more straightforward to follow, performance and quality metrics in prescriptive standards are not specified and mixture optimization for certain features (e.g. low emissions) is not really enabled (Lemay & Lobo, 2020). Many of these standards essentially require similar performance characteristics to OPC even in applications for which this is unnecessary (e.g. most standards require carbonation resistance, even though this only necessary in reinforced concretes, about 25% of all concrete (Lehne & Preston, 2018; Scrivener et al., 2018). Further, widely used prescriptive standards do not account for regional variations (e.g. soil and climate differences) with some standards being too conservative in certain local applications (Lehne & Preston, 2018). Accordingly, the need to transition towards more performance-based standards more specific to the applications to which they will be applied is often discussed, and even performance-based standards will require drastic reform (Biernacki et al., 2017). Establishing performance-based testing methods and parameters required for this transition can be quite challenging though (Lemay & Lobo, 2020). Performance-based standards necessitate testing to demonstrate achievement of performance criteria. While these exist for more traditional cements, these methods may not be yet developed for novel cements, increasing challenges in the inclusion in standards (*European standardisation of new and innovative cements*, 2016).

In addition to standards, many companies and organizations have their own specifications based on other standards or tailored to their more specific needs and philosophies. Specifiers and designers typically define these performance requirements while producers and contractors ensure appropriate mixes are designed to meet these criteria (Lemay & Lobo, 2020). Like standards, specifications need to meet traditional performance and durability requirements while incorporating other sustainability factors yet should not be restrictive when it comes to optimizing for sustainability (e.g. restrictive limiting of admixtures) (Lemay & Lobo, 2020). Encouraging specifiers to specify non-OPC cements, especially for large projects, is cited to lead to great mitigation opportunities (Peng, 2020), and ideally, both standards and specifications would permit low carbon novel cements in all applications in which their performance characteristics are sufficient (Lehne & Preston, 2018). Including clinker substitution thresholds, on the other hand, does not suit well to optimize sustainability and performance as suitable substitution rates vary significantly in their appropriateness for different applications (Lemay & Lobo, 2020).

In addition to cement standards, concrete standards and other building codes play similar roles in the consideration of novel cement adoption. Accordingly, similarly enabling guidelines need to be set in all for optimal impact. If cement standards open, but concrete standards do not, the standard modifications will have a diminished impact. In Norway, for example, only cements with >95% OPC are permitted in most concrete standards (Müller, 2012).

Standards and specifications help shape conduciveness for novel cements. Novel cements are included in some standard regimes and not others (e.g. China's inclusion of CSA clinkers) (Lehne & Preston, 2018). Australian standards are described to be more enabling to non-traditional cement designs than many other countries' (e.g. no limits on fly ash or GGBS use), for instance, but still require changes to enable greater implementation. Clinker ratios are sometimes specified in standards and can also vary significantly by region (Beyond Zero Emissions, 2017). European and North American standards can further be very influential in outlining those of other regions'/countries' (Lehne & Preston, 2018).

In addition to significant regional variability, standards have different implications for specific novel cement technologies and changes for some are moving faster than others. For instance, belite-based cements are incorporated in many standards (Ellis Gartner & Sui, 2018). Geopolymers are specifically referenced in various standards and specifications in several countries and can be used under certain performance-based ASTM standards (Beyond Zero Emissions, 2017). Many standards influence the potential of various novel cement inclusion through limitations on SCMs or on specific SCMs. For instance, some standards allow for the use of certain fly ash and GGBS but restricts others (International Energy Agency, 2018b).

Inclusion in standards and specifications will not necessarily enhance novel cement uptake but can help in diminishing demand barriers (Lemay & Thompson, 2020). While some existing standards are more inclusive to novel cements (e.g. ASTM C595 and ASTM C1157 hydraulic cements), they need to be included into organizations specifications in order to be used and contribute to emissions reductions (Lemay & Thompson, 2020). Further, cements need to be readily available on markets in order for them to be adopted. For instance, European standards categorize five main cement types (CEM I-V) (The European Cement Association, 2012). CEM I consists of general OPC (>95% clinker) while CEM II groups Portland-composite cements (65%–94% clinker content) (*European standardisation of new and innovative cements*, 2016). Specifications may call for Type I cements, but if they are not readily available demand-actors may divert to Type II cements instead, negating impacts of standards changes. Other specifications specify the use of locally available materials (e.g. aggregates) in concrete which can be further limiting not allowing for optimization of concrete blends (Lemay & Lobo, 2020).

Further, while standards are widely followed and can provide specifiers with greater confidence in decision-making, they are not necessarily definitively restrictive (Lehne & Preston, 2018). Some applications, like certain precast concretes can be sold with local technical approval, and do not require strict standard adherence (*European standardisation of new and innovative cements*, 2016). For several specialty cements (e.g. those with rapid strength gain or acid resistance), standards may not be deemed necessary (Lehne & Preston, 2018). In Europe, manufacturers have mechanisms to independently validate and assess novel cements not covered by standards with special permission (Beyond Zero Emissions, 2017). Some organizations utilize novel cements changing their internal specifications despite exclusion in standards (*European standardisation of new and innovative cements*, 2016). However, when standards are not followed, viability of novel cements often must be proven on case-by-case bases, replicating demonstration and testing efforts (Provis, 2018).

Several actions to support standardization and specification changes arose in literature. In some cases, standardization changes originate from the bottom-up by specifiers, while in others, they can derive top-down by regulators (Beyond Zero Emissions, 2017). Certain groups are actively working to change standards. For example, 'Standards Australia' is currently working with another sustainable construction group to develop a Geopolymer Concrete Handbook, that aims to help concrete users understand their options and make it easier for them to specify geopolymers while encouraging the adoption of new standard specifications allowing geopolymer concretes (Athena Sustainable Materials Institute, n.d.). Industry groups, like the National Ready-Mixed Concrete Association (NRMCA), can offer guidance in improving and opening specifications, providing one-on-one support to members in doing so reviewing new specification language, for example (Lemay & Lobo, 2020). Digital tools (e.g. Athena's Impact Estimator for Buildings) provide basic LCA tools that can help create project-specific specifications optimizing sustianability considerations (Lemay & Lobo, 2020; (Beyond Zero Emissions, 2017). One source describes standardizations as reflections of industry confidence in technical performance (*European standardisation of new and innovative cements*, 2016). Accordingly, increasing testing and improving procedural reliability can help boost confidence in the viability of new cements encouraging their inclusion in standardizations (Lemay & Lobo, 2020). Certifying testing labs could be one way to help increase this confidence (Lemay & Thompson, 2020). Finally, in genearting new standards, manufactuers' engagement and industry collaboration from the beginning of the process can help acclerate the development of more widely-satisfactory results while pooling resources can help minimize duplication of efforts (Lehne & Preston, 2018; Scrivener, 2014).

3.3.3 Resource Availability

While several novel cements do not face significant material constraints, many do, and one source cited material availability as perhaps the most limiting and important aspect of advancing novel cements (International Energy Agency, 2018b). Most materials potentially suitable for creating novel cement chemistries are not nearly as widely available and accessible as limestone. Resource availability for many SCMs and other novel cement constituents can be very regionally specific (Rootzén & Johnsson, 2016; Scrivener, 2014). This regional availability plays a major role in determining product costs, quality, and which novel cement chemistries are feasible (Lehne & Preston, 2018).

A few large cement manufacturers have integrated supply-chains for clinker production, but for most others, availability and material quality are not within their direct sphere of influence (Scrivener, 2014). Further, stocks of some currently available and often economically feasible

SCMs for use in blended or novel cements, like GGBS and fly ash, are expected to decline in both certain regions and globally, making them more expensive and potentially inaccessible in the future (Lehne & Preston, 2018). While fly ash availability is expected to drop in many regions like Europe due to decreased coal consumption (Alberici et al., 2017), in Australia, for instance, it is currently widely available with domestic stockpiles over 400 million tonnes (cited to be able to produce an approximate twenty years supply of materials for novel cement, particularly geopolymers, in local markets) (Beyond Zero Emissions, 2017). More generally availability of many waste products is expected to decrease due to streamlined waste efficiency in other sectors (Energy Agency, n.d.).

However, once these stocks run out, shifts to other materials, like metakaolin-based cements, limestone fines, calcined clays, and pozzolans are expected to be needed (International Energy Agency, 2018b) and could accordingly help emissions reductions reach much wider scales (Beyond Zero Emissions, 2017). Other potential SCMs include gypsum and natural volcanic material (Scrivener, 2014). Calcined clays were referenced as the only material with potentially high enough material availability to continue drastically reducing emissions in blended cements once currently used SCMs run out (Beyond Zero Emissions, 2017). Some countries import waste products (e.g. Australia with slags) (Lehne & Preston, 2018), however, shipping costs can drastically increase material prices for these imports that may be otherwise inexpensive if locally sourced (Scrivener et al., 2018). Less traditional SCMs should be developed and scaled up immediately to address longer-term needs of this sector. Increases in patenting around volcanic rocks and ash and calcined clays may indicate promise in these materials eventual wide uptake as SCMs or novel cement materials (International Energy Agency, 2018b).

Novel cements may also compete for material needs with other green cement technologies. The materials used to make many geopolymers, for instance, are often the same SCMs that go into blended cements (e.g. alumino-silicate materials) (International Energy Agency, 2018b; Scrivener, 2014). If SCMs contribute to performance in proven, viable blended cements already, multiple authors cite that they should be used in these applications before taking risks and prioritizing their use in unproven applications like certain novel cements (Scrivener, 2014). Some research has demonstrated, for instance, that it is both more economically and environmentally optimal to use certain SCMs in blended cements as opposed to geopolymers (Gauthier, n.d.; Provis, 2018). The cement industry also competes with other industries for waste products as many have other economic applications in separate industries as well. For instance, waste products from aluminum, like bauxite, used in CSA novel cements, are also sought by many other sectors leading to increased material costs (Scrivener et al., 2018).

Waste material markets are not necessarily well developed and can present difficulties for cement and concrete companies in utilizing SCMs or waste materials even if they are available. Challenges in acquiring long-term contracts, for instance, can deter cement companies from wanting to invest in facilities to store and handle these materials in making novel cements due to increased uncertainty. Accordingly, valuable waste products, like fly-ash, often go unused. (International Energy Agency, 2018b). Polices could be developed to incentivize industries with waste products to find markets and sell them (e.g. incentivizing sale of fresh and stockpiled fly ash) (International Energy Agency, 2018b). This could take the form of financial incentives, penalties, bans in stockpiling or disposing of waste materials, or incentives to recover waste materials like fly ash, waste glass, red mud, bagasse ash, and more (Lehne & Preston, 2018). As fly ash and GGBS stocks in the U.S. are decreasing due to shifts in other industries, policies will likely not drastically improve the quantity of SCM availabilities, but may rather help to recover these products from disposal sites (Lehne & Preston, 2018). However, in countries like China and India where there are large underutilized supplies of these materials, those sorts of policies could make sense. Policies enabling more international trading of SCMs was also posed as a potential mechanism to assist with these shortages. While cement and SCM sourcing is generally highly localized, this has somewhat changed recently with slags and fly ash. Classifications of these substances as materials vs. waste products can influence trading abilities, for instance. In 2008 in the U.S., for example, the U.S. Environmental Protection Agency considered reclassifying fly ash as a hazardous waste which decreased fly ash use significantly despite its not being passed demonstrating substantial policy influence. On the other hand, bans on fly ash disposal and concrete in landfills has helped encourage and increase fly ash use in the Netherlands along with collaboration between waste and cement actors (Lehne & Preston, 2018). LCA assessing the net carbon footprint of this trading would need to be assessed, but initial estimates suggest that emissions impacts are beneficial. Trade would decrease limitations due to limited material availability of these SCMs in the U.S. and Europe. As many of these imports would likely come from China and India, better supply chain and distribution systems would need to be established. Even within larger countries, trade implications in shipping SCMs can be applied as some areas within a country have sufficient supplies while others do not (Moon, 2013).

3.3.4 Costs

In the absence of additional financial incentives, novel cements need to be cost-competitive with OPC to be economically viable and desirable for manufacturers to produce while also being affordable for consumers as well (Lehne & Preston, 2018; Rootzén & Johnsson, 2016). Accordingly, having comparable or cheaper production costs and ability to retrofit existing plants and infrastructure as opposed to building new ones can help boost the viability of a novel cement technology (Scrivener, 2014). Novel cements, like belite, CSA, BCSA, and CACS clinkers, for instance, can all be produced in OPC factories by merely altering raw consistent mixes (Lehne & Preston, 2018; Rootzén & Johnsson, 2016). Accordingly, technology and material costs were cited by one source to be a main barrier of wide commercialization from the supply-side (Ellis Gartner & Sui, 2018). Finally, utilizing economies of scale may help decrease costs of novel cement production (Lehne & Preston, 2018).

From the supply-side, transitioning to new technologies or systems can generate substantial capital costs from new infrastructure, equipment, or storage infrastructure, and can alter material and energy costs (International Energy Agency, 2018b). However, in building new plants or production facilities, those of novel cements can be cheaper than those of OPC plants. Geopolymers, for instance, do not require kilns in their manufacturing making capital costs of new plants relatively low. While one source cites standard cement clinker plants to cost around $400 million, they cite geopolymer plants to cost less than $40 million (Beyond Zero Emissions, 2017). However, in this example, other high capital costs concerning activator manufacturing, for instance, diminish the initial cost benefits (International Energy Agency, 2018b; Provis, 2018). Producing multiple cement types within a specific plant can also add infrastructure costs (e.g. requiring more storage infrastructure) (Lehne & Preston, 2018). These financial impacts are dependent on the novel cement technology in question and regional characteristics like material availability and pricing (International Energy Agency, 2018b). Multiple sources cited supply-side costs to generally be closed related to material availability (Lehne & Preston, 2018). While some SCMs or clinker substitutes may be more expensive than OPC constituents, others like fly ash, slags, and limestone can sometimes reduce costs (Lehne & Preston, 2018) or be on par with OPC (Beyond Zero Emissions, 2017). However, while these transition costs are significant, they could be considered as a 'future-proofing' business strategy (Peng, 2020). Another cost consideration mentioned concerned labor costs. Particularly in high-wage countries, labor costs can be much higher than material costs and can outweigh any material savings. Accordingly cements and concretes that require more workers to implement (site workers) or produce (plant workers) can become more expensive (International Energy Agency, 2018b). One source cites that supply-actors will need to pass down costs greater than those of OPC to customers in order to profit and be commercially viable (Rootzén & Johnsson, 2016).

From the demand-side, pricing comes into play when considering competition with other green cement technologies like admixtures and blended cements with more innovative technologies, often being more expensive (Lemay & Thompson, 2020). One study examined how costs from more expensive decarbonizing cement technologies are passed through the value chain (in the context of residential buildings). The findings indicate that costs decrease significantly down the chain by each actor or 'transformation level'; nearly doubling cement prices would only increase the building's total cost by only 1% (Rootzén & Johnsson, n.d.). This indicates that from the demand-side cost increases may not be as important to end-customers. From the demand-side, mere perceptions of higher costs can also generate significant barriers in novel cement consideration (Lehne & Preston, 2018).

3.3.5 Implementation and Logistical Factors

Logistical challenges in addition to the mere perception of these challenges serve to inhibit the adoption of novel cements (Beyond Zero Emissions, 2017). Differing physical properties of novel cements (e.g. low early-strength gain, longer setting times) can create logistical issues or necessitate process changes. For instance, contractors often cast concretes in the afternoon and demold in the morning. Certain novel cements with different hardening times could require scheduling restructuring and other changes (Snyder et al., 2013). Other examples include: some novel cement pavements requiring surface grinding to attain proper finishing, difficulty in using traditional transportation methods, short workability windows, seasonal availability, and higher variability in composition and quality of end-products (Beyond Zero Emissions, 2017). Some of these performance properties can be especially sensitive to material inputs in novel cements, according to one source, and material characteristics can accordingly differ from batch to batch (International Energy Agency, 2018b). In addition to distant material availability potentially increasing prices of novel cements, non-localized transport can also pose logistical transportation challenges (Beyond Zero Emissions, 2017). Further, some novel cements can be more sensitive to contamination by OPC that could be found in manufacturing facilities or on-sites, making use by construction workers more burdensome or challenging (Scrivener, 2014). Personnel that are familiar with using OPC will have much higher confidence in dealing with and applying OPC as opposed to other novel cement-based concretes. This necessitates the need for additional training and confidence building that could be additionally burdensome (Burris et al., 2015). In addition to potentially drastic transition cost implications, pursuing novel cements that can already be made with existing plants and infrastructure helps to lower a number of logistical barriers as well (Beyond Zero Emissions, 2017).

3.4 Paths Forward

In addition to strategies propelling widening of standards and specifications and policies to enhance testing availability and increase greater material accessibility, other 'paths forward' to diminish barriers and stimulate drivers relating to demand are discussed below. These strategies serve to both help upscale and promote more advanced novel cement technologies and develop new novel cements as a portfolio of technologies is expected to be needed to achieve deep emissions reductions.

3.4.1 Business Strategies

Developing business strategies can both generate new value from redefined or supplementary business models, while potentially helping companies minimize financial risk associated with increased climate concern and action (Fernandez Pales et al., 2019).

Transitioning cement sales to a more **service-based model** is discussed as a means to provide additional value to customers as a means to drive additional demand. These services can include increased marketing or enhanced customer service and product-tailoring. Additional service provision helps to distance cement from a commodity market potentially reducing price sensitivity that disadvantages many novel cements helping to reduce barriers in product consideration (Lehne & Preston, 2018).

Targeting initial novel cement development and deployment towards niches most conducive to market success is a currently utilized and often discussed strategy (Beyond Zero Emissions, 2017). An example of **niche targeting** to optimize the benefits and circumstances of a specific technology towards niche applications, manufacturing methods, customer groups, and geographic regions can be seen in the case of geopolymers above. As novel cements are increasingly piloted in niche applications and/or projects, once demonstrated to be viable, risk aversion may decrease helping to spur more adoption of cements in these niches and potentially beyond (Lehne & Preston, 2018).

Commodity products typically do not have as sizable, influential marketing departments as many other industries. However, as novel cements are differentiated products, **marketing** specific product benefits to customers may help significantly increase their consideration and uptake. In addition to individually-driven marketing, collaborative awareness building through the efforts of trade associations or through action plans could help increase awareness of the existence of these products—an important first step in driving demand (Beyond Zero Emissions, 2017).

The development of novel cement technologies (along with complementary technologies and products) have intellectual property value themselves, around which business models can be created. Patenting profiles can help attract investments and ultimately technology adoption by incumbent manufacturers. Solidia and CarbonCure are examples of green cement technologies that do not sell their own cements or concretes, but rather **provide technology services** to existing companies (Lehne & Preston, 2018).

3.4.2 Financing and Funding

Finance and investment in both alternative cement technologies' research and deployment are crucial to have the capacity to meet demand for these products, despite cement innovations having failed to attract significant venture capital thus far (Lehne & Preston, 2018). Accordingly, taking advantage of private-public investment opportunities is critical (Beyond Zero Emissions, 2017). Governments can play a role in helping stimulate this financing. Policy models governments have put in place concerning clean and renewable energy stimulation could be copied or combined with those for cement innovation. For example, allowing preestablished financial organizations (e.g. Australia's Clean Energy Finance Corporation) to invest in commercial, green cement production or demonstration projects as a part of their energy investments could help utilize preexisting mechanisms (Beyond Zero Emissions, 2017). Accordingly, rerouting or widening existing funding pools to be inclusive of novel cements may help as well. For instance, CCS demonstration has historically received funds from energy and power financing programs. If these energy and power programs were restructured to include industrial facilities, perhaps more funding could be attained by cement plants as well (Beyond Zero Emissions, 2017). These strategies can be pursued not just by national governments, but also by international foundations who often have finances to direct in supporting technology innovation, implementation, and demonstration. Examples of potentially influential international organizations include the UN's Green Climate Fund and the Mission Innovation initiative aiming to amplify investments in clean energy R&D. Organizations like Horizon 2020 and the Innovation Fund in the EU can also help attract private investors while helping reduce investment risks for other actors (Beyond Zero Emissions, 2017).

In addition to direct financing covering capital and operating costs, investment into research is also essential. Thus far most research in alternative cements has been executed by a limited number of companies and academics (International Energy Agency, 2018b). Governments, manufacturers, and academia can promote research and testing for new novel cements, support more demonstration projects, and help in developing and accelerating standard inclusion to help accelerate commercialization of novel cements (Beyond Zero Emissions, 2017). Research surrounding these products that helps to increase understanding and confidence in using new products should be upscaled to significantly accelerate the development of these products. (Beyond Zero Emissions, 2017; Lehne & Preston, 2018).

Research should not just surround novel cement technologies, but also optimization of green cement manufacturing, implementation, and other co-technologies like admixtures, dispersants or different grinding mechanisms to help optimize characteristics and ease of application of novel cements and concretes (Rootzén & Johnsson, 2016). Targeting research resource allocation towards technologies that have demonstrated promise should be prioritized. (Beyond Zero Emissions, 2017). Similar to financial resources, restructuring existing research bodies (e.g. clean energy organizations) to become inclusive of cement innovation could help similarly redirect existing research resources towards this sector (Lehne & Preston, 2018). Incubators and accelerators can further help to increase innovation operations (e.g. LafargeHolcim developed a start-up accelerator for these reasons) (Global Cement staff, 2017).

3.4.3 Policy Options

Many governments have begun to and are increasingly embracing sustainability (Beyond Zero Emissions). Targeting various actors, incentivizing novel cement use, and generating awareness and increased comprehension of novel cements are some ways that policies can help propel these products. These policies can take more prescriptive forms like restriction setting or softer ones like credible goal setting (International Energy Agency, 2018b). When implementing policies, however, it is important to not too greatly hinder industry actors and maintain domestic and regional industry competitiveness. For instance, although cement markets typically do not face cross-border competition, ensuring policies do not disadvantage green early-movers in competition or trade-exposure with external markets is important for manufacturers (Rootzén & Johnsson, 2016).

In addition to relating to some of the aforementioned strategies and barriers discussed so far (e.g. India's current pursuits in widening standards for new composite cements by order of government) (Rootzén & Johnsson, 2016), policy options relating to novel cements found in the literature review broadly include those discussed below.

Carbon Pricing Schemes

Carbon pricing is often discussed as a potential major driver for change in this sector (Lehne & Preston, 2018), yet current schemes are insufficient to incentivize novel cement adoption alone (Rootzén & Johnsson, n.d.). For instance, one estimates carbon pricing in Australia, for instance, (23 AUD/tonne of CO_2) to increase concrete costs by 0.13%-0.23%, negligible in incentivizing change (Rootzén & Johnsson, 2016). Another trading scheme in India (the Perform, Achieve and Trade scheme), however, was cited by one source to have already achieved some positive results in the cement industry (Lehne & Preston, 2018). The EU ETS, on the other hand, has also been and will likely continue to be unsuccessful in driving change and innovation in the near future (Scrivener, 2014).

In creating incentivizing emissions pricing or trading schemes, strong price signals need to be sent. In the EU ETS, since 2013, prices often fluctuate between €4/tonne and €8/tonne. If these prices were five to ten times higher, for instance, currently available novel cements may become cost competitive (Ellis Gartner & Sui, 2018). Strong price signals could be assisted by lowering emissions caps or creating price floors. Additionally, excessive allocation of free emissions allowances can undermine incentives of scheme (Lehne & Preston, 2018) by in some senses subsidizing larger cement producers, encouraging lock-in of certain emissions levels, and diminishing competition forces (Global Cement staff, 2013). While free allocation can generally help protect countries within the scheme to not face external competition (further helping to prevent carbon leakage), the applicability of these concerns are debatable given the highly localized nature of the sector (Neuhoff et al., 2014). Output-based allocation, inter- or multi-national pricing schemes, or inclusion of carbon pricing on imports may help mitigate concerns of carbon-leakage and competitive disadvantage (Beyond Zero Emissions, 2017; Lehne & Preston, 2018). Finally, some stress the importance of application of any carbon pricing or trading schemes to all competing CO_2 intensive building materials to be further non-discriminatory (International Energy Agency, 2018b; Neuhoff et al., 2014)(International Energy Agency, 2018b). Clarity and predictability of these schemes are also important to increase actors' confidence and certainty to better incorporate these schemes into their business considerations (Neuhoff et al., 2014). While these pricing schemes can theoretically be very effective in incentivizing change, they may become more advantageous to larger producers as they can be more capable of dealing with administrative and mitigation costs and better connected with scheme planners (Global Cement staff, 2013).

Research by Rootzén and Johnsson suggests that industry CO_2 compliance costs (internal abatement plus emission allowances costs) have the potential to significantly impact manufacturers' production costs and pricing (2016). Despite differences in various building projects and local industry and market conditions, according to their research, passing on these CO_2 compliance costs would only generate minor price increases on the final construction costs as cement and concrete generally comprise a very small proportion of construction and infrastructure projects' total costs (Beyond Zero Emissions, 2017). Accordingly, policies or business strategies passing down these CO_2 abatement costs to end-customers, would not drastically affect end-users' project costs. Ideally, mitigation expenses could be shared amongst actors along the value-chain and encourage manufacturers to pursue more innovative change (Lehne & Preston, 2018). If some of these schemes are implemented, one source argues that it is feasible that provision of low-carbon cements and concretes will gain competitive advantage justifying higher mitigation costs (Beyond Zero Emissions, 2017).

Regulatory Approaches

Some bills (both passed and unpassed) surrounding embodied carbon in the U.S. construction sector represent potential regulatory policies that could encourage novel cements. These include 'Buy Clean' laws that typically require governments to solicit Environmental Product Declarations (EPDs) measuring embodied carbon of materials in the bidding process of public projects. Global warming potential (GWP) thresholds, for instance, may affecting bid rating and granting. California has implemented one of these laws, however, it does not currently extend to cements and has been delayed due to implementation difficulties. More have been proposed in other states including cements but have not been passed. Concerns were raised by industry groups relating to imposing embodied carbon thresholds requirements, even as prequalifications or considerations in bidding. Most concrete mixes and schedules are not determined before bidding with projects often not commencing until a year and a half after the bidding process. Accordingly, material selection and scheduling are highly subject to change making selection of materials during the bidding process unrealistic. Another policy proposal example includes mandated technology adoption. In 2018, Hawaii had a bill mandating the use of mineralized (by post-industrial CO_2) concretes, yet this did not pass due to lack of local testing and proprietary implications. New York state, on the other hand, successfully passed legislation for 'Low

Embodied Carbon Concrete' in 2019 in which 'Buy Clean' concepts are combined with tax incentives for green concrete products. (Peng, 2020)

Other legislation has been passed imposing maximum clinker content or embodied carbon thresholds. While this can be effective in encouraging the use of novel cements, NRMCA opposes this due to concerns that restrictions can be too harsh on certain cements while too lenient on others as performance requirements for specific applications within a given project can vary significantly necessitating cements with different footprints. In terms of both application and project type, material choices are highly specific. Accordingly, regulations guiding and incentivizing decision-makers to choose low emissions products rather than restricting them are described by NRMCA members to be most appropriate (Peng, 2020). Working with insurance companies to align policies with novel cement specification without drastically increasing rates is another action policy makers could pursue in lowering demand-side risk aversion. Tax cuts or incentives for projects achieving embodied carbon thresholds or those using low-carbon cements could also be implemented (Beyond Zero Emissions, 2017). Additional concerns about command-and-control regulation expressed by NRMCA include those involving anti-competitiveness (Peng, 2020). If regulations only apply to cements or concretes, unfair competitive advantages for other building materials are speculated. Accordingly, perhaps legislation could be applied to all building materials. Policies necessitating local or national procurement are also cautioned due to potential price increase concerns by NRMCA (Peng, 2020). Finally, as manufacturers tend to know material and supply-chains best, engaging them or letting them lead in regulation creation may help ensure that regulation is not too limiting for industry producers (Peng, 2020).

Public Procurement

As governments purchase large amounts of cements and concretes for applications from buildings to infrastructure, public procurement standards promoting or requiring the use of green cements could significantly increase demand for these products. Further, these policies may increase the number of demonstration projects, potentially helping accelerate adoption further and increase industry experience in working with these products (Beyond Zero Emissions, 2017).

Some procurement incentives and requirements concerning both green and novel cements are already in place. For instance, requirements to reduce OPC use by a product average of 30% and other similar goals are in place within transportation authorities or specific projects in Australia (Beyond Zero Emissions, 2017). Mandatory or voluntary targets concerning embodied carbon, clinker ratios, and OPC reductions could be more widely implemented in green cement procurement (Lehne & Preston, 2018). These standards could be set similarly to existing clean and renewable energy standards that many governments have (Beyond Zero Emissions, 2017). Another type can be seen in the Netherlands where suppliers' bids are adjusted in price comparisons favoring greener products which has been successful in generating demand, and could be adopted by others (Kemp et al., 2017). While requiring this sort of information in bidding processes has been proposed by several, one source cites that this is too logistically burdensome on manufacturers (Peng, 2020). Another option is for public authorities to specify or even require the use of novel and green cements in low-risk, non-structural applications. For instance, the United Arab Emirates requires all major infrastructure projects to use cements with >60% GGBS or fly ash (Edwards, 2016). Additionally, where novel cements lend explicit benefits due to unique physical properties, they can be specified specifically for these specialty applications (e.g. geopolymers in acidic environments like sewers) (Lehne & Preston, 2018). Some of these policies would also encourage data and information accumulation in requiring bidders to calculate embodied carbon (or other relevant metrics) of their products. More broadly, consideration of LCA of construction materials in general could also help increase the deployment of novel or other green cements (Lehne & Preston, 2018). Mandating, paying for, or subsidizing LCAs in various projects could be another way that governments could encourage the use of novel cements and information collection (Peng, 2020).

While public procurement is discussed as a powerful tool in boosting novel cement demand, it can be challenging to outline and implement (Beyond Zero Emissions, 2017). One concern raised in target or threshold setting (e.g. maximum clinker content restrictions, emissions reductions targets) is that the high number of variable properties and requirements of concretes in various applications makes realistic emissions reductions difficult to compare and highly dependent on project context. Best available technology estimations tailored to specific projects where material selection is optimized to the products available meeting necessary property requirements would be more ideal. Accordingly, wider, universal emissions thresholds may also not be optimal. Therefore, project specific goals/requirements or decision-making/process requirements may be more realistically suited to meet emissions reductions and less restrictive. Finally, examining clinker-reductions or novel cement use from a project average level rather than impositions upon all products may be more fruitful (Peng, 2020). Specifying cement services rather than specific products may be strategy aligning to this perspective as well (Beyond Zero Emissions, 2017).

Informational Tools

In catering to sustainability-related demand, consumers and other industry actors should have accessible emissions-related information and metrics to enable decision-making (de Wolf et al., 2017). Further, actors need to understand what these indicators actually represent and how to measure them. Universal indicators and widely applicable LCA methodologies for product comparison are also lacking with significant inconsistencies in current data communication of climate-related and other green attributes (Giesekam et al., 2016). An example of an existing policy relating to this is the publication of standards surrounding performing LCAs for buildings by the European Standards Committee (de Wolf et al., 2017).

EPDs are documents produced by manufactuers measuring environmental footrpints of products through the use of third-party verified LCAs. Some projects (e.g. those with sustainability goals, those applying for green certifications) require manufactuers to submit EPDs to verify green attributes (Lemay & Lobo, 2020). EPDs can be both industry-wide (providing average baselines applicable to an included list of companies) and product-specific (based on mixes from a given facility). Plant- and product-specific EPDs provide more precise information in decision-making processes (Lemay & Lobo, 2020). While several national EPD databases exist, benchmarks are often not globally comparable, and data submissions are typically voluntary. Enhanced informational tools and policies may accordingly help mitigate some of these information-related barriers. Embodied carbon can be one lens through which to communicate cement emissions, as this is often used in the wider construction industry. The process of creating EPDs in itself can also help increase manufacturers' understanding of their own products footprints which can then be shared in communications with customers (Peng, 2020). An industry group, NRMCA has generated industry-wide EPDs and offers several EPD related services to its members (Lemay &, 2020). While requiring EPDs in bidding processes has been discussed in some policy discussions, one trade association describes this to be too logistically burdensome (Peng, 2020).

Additionally, accounting tools and centralized databases can help both supply- and demand-side actors understand and compare impacts of various products. For instance, increasing discussion surrounds software tools like building information modelling (BIM) that can be in helping in measuring and optimizing attributes (e.g. embodied emissions) on complicated projects and communicating these results to decision-makers. Online tools are also available to help compare

EPDs. Other building materials can also even be compared against cement/concrete products in tools like Skanska's 'EC3' (Peng, 2020)(*Skanska Conceives Solution for Calculating Embodied Carbon in Construction Materials, Announces Transition to Open-Source Tool*, 2019). Further, labeling carbon-footprints of products could also help increase awareness and understanding of products' and wider industry impacts (Lehne & Preston, 2018). More directly mandating labeling of some of these green indicators or mandating measurement of these indicators on certain products may also help to increase information availability (Scrivener et al., 2018). Support in executing some of these information-based policies could be provided by policy actors through trainings or other resources, for example, to help ensure successful execution (Beyond Zero Emissions, 2017).

Green Certification Programs

Green certification programs can help incentivize adoption of novel cement technologies. LEED Green Building Certification (LEED) and BREEM in the U.S. and the Infrastructure Sustainability Council of Australia's Rating Scheme and Green Star in Australia are examples of popular rating systems continuing to gain popularity that can encourage the use of these products (Beyond Zero Emissions, 2017).

The success and implementation of green cement incentives in some of these systems indicate how they could be widened or focused more specifically on novel cements. For example, in Green Star, points are offered for clinker content reductions of 40 percent or more (project average). Others offer points for replacing OPC with other cements, acknowledging both SCM use and geopolymers, for novel cement use, or for those produced in plants with emission reduction technologies or processes. (Lehne & Preston, 2018). Points could even be allocated for the use of cements produced at green certified plants (e.g. NRMCA Green-Star Plants) (Lemay & Lobo, 2020).

More broadly incentivizing novel cements through points in lowering embodied carbon levels of building materials could also be conducive to their propulsion of novel cements. The 'Living Building Challenge', on the other hand, requires certification recipients to purchase carbon offsets to compensate for embodied carbon also helping to incentivize low-carbon cements (Beyond Zero Emissions, 2017; *Living Building Challenge 4.0 Basics*, n.d.).

Education, Training, and Human Capital

Most concrete production and application in emerging markets is performed by personnel who do not have training or specialty knowledge pertaining to non-OPC cements (Beyond Zero Emissions, 2017). Accordingly, actors may struggle to apply novel cements that necessitate more complicated implementation (e.g. use of additional grinding equipment or admixtures). Increased training and education for engineers, contractors, architects, and designers surrounding low-carbon cements and concretes, in which applications they are most appropriate, and how to use them may significantly help overcome related logistical, awareness, and risk aversion barriers (Ulrich Dewald & Achternbosch, 2016). This could also take the form of incorporation in higher-education classes, specifically geared towards engineering students as they are typically not taught about alternative cement products and accordingly become more naturally inclined to work with OPC upon entering the sector (Lehne & Preston, 2018; Rootzén & Johnsson, 2016). These initiatives could also be applied in other various professional development programs within the sector. Familiarizing themselves with novel cements could also help building/construction firms assisting them in providing client recommendations and requesting appropriate products from concrete/cement manufacturers (Beyond Zero Emissions, 2017).

The cement sector also struggles to attract and recruit material scientists and engineers (Lehne & Preston, 2018; Scrivener, 2014). This provides a barrier to pursuing major industry change. Further, as having qualified, knowledgeable personnel is essential in executing novel cement application, providing qualifications for completing various trainings could help incentivize actors to work with or undergo education surrounding novel cements (Lemay & Lobo, 2020).

3.4.4 Actor Collaboration

Resources cite a general lack of collaboration between manufacturers, due in part to historical issues with antitrust legislation (*European standardisation of new and innovative cements*, 2016; Lehne & Preston, 2018). Increased collaboration can help generate understanding for all actors through knowledge and experience sharing, provision of mechanisms to pool resources to diminish barriers, and potential acceleration of standardization and specification widening. It is especially important that manufacturers participate in collaborative efforts as they hold much of the technical knowledge in this sector (International Energy Agency, 2018b).

Several collaborative actors can help propel technology development and deployment further. Collaboration with end-users can increase customers' understanding surrounding different technologies and how to use them. Patenting pools, cross-licensing, and restructuring patent legislation can help encourage information sharing while maintaining some incentives from competitive advantage (International Energy Agency, 2018b; Lehne & Preston, 2018). Manufacturers can work more directly with legislators and specifiers to push for more incentivizing policies and encourage specification inclusion (Peng, 2020). Thorough, independent, publicly available LCAs or other comparative analyses of alternative cement products are lacking and could be solicited or produced through collaborative efforts (Lehne & Preston, 2018). Collaboration between standard organizations, testing facilities, and universities could also help accelerate testing processes and technologies needed to provide evidence of novel cement viability to standards boards. Online and other digital tools can further help increase this information accessibility (International Energy Agency, 2018b). Nanocem is an example of a research consortium between industrial and academic actors that pools resources to increase understanding surrounding cement chemistries (*Our Research*, n.d.). Creation or enhancement of these collaborative research networks can help propel technology development further (Lehne & Preston, 2018). Industry groups, trade associations, and other independent institutions providing data sharing, trainings, and stakeholder engagement can further play a major role in accelerating these products (Beyond Zero Emissions, 2017). For instance, NRMCA, a trade association, may be more qualified in writing legislation language than policy makers due to their greater understanding providing significant value to propelling decarbonizing technologies (Peng, 2020).

In addition to cross-actor collaboration, several sources cite the importance of international collaboration (International Energy Agency, 2018b). One reason is to help prevent asymmetric policies and carbon leakage (Beyond Zero Emissions, 2017). Setting and aligning international targets and establishing widely accepted frameworks within cement, concrete, and construction sectors can also help to support R&D capacity (International Energy Agency, 2018b; Lehne & Preston, 2018). International knowledge and resource sharing platforms pertaining to both private and public sectors could also be valuable. Major international initiatives and organizations (e.g. IEA, CSI, C40, and the Global Cement and Concrete Association) can play major roles in fostering these collaborative efforts (*Cement Sustainability Initiative*, 2020; Global Cement staff, 2018; Lehne & Preston, 2018). Competition concerning intellectual property rights can serve to discourage potential collaboration and lead to potentially monopolistic behavior. However, according to one source, this has not been exemplified so far with novel cements, as companies have gained little strategic or monetary advantages from patenting novel cements thus far (Lehne & Preston, 2018). Finally, with their significant collective purchasing power, major demand-actors could also come together in committing to lowering embodied carbon footprints (International Energy Agency, 2018b).

3.5 Wider Implications

Literature described the need for both radical and incremental innovations in achieving deep decarbonization within the cement and concrete industries (Scrivener, 2014). The pursuit of a technology mix was described by several as essential in significantly addressing these issues (Lehne & Preston, 2018). More readily available cement technologies need to be increasingly disseminated (e.g. blended cements), while others in earlier stages of growth and market penetration, 'high-hanging fruit', like novel cements need to be increasingly and continuously developed (Lehne & Preston, 2018). This can help accelerate transitions in long-term emissions reductions, as readily available technologies all have limited mitigation potential, limits to growth, and potential for drastic market changes to undermine their future viability (i.e. diversification needed to account for disruptive market changes). Further, many innovative cement technologies can be employed simultaneously in the same project (International Energy Agency, 2018b).

In addition to affordability, solutions also need to be tailored to specific markets in which they will be disseminated to be most successful. This includes optimizing technology selection and development to the most conducive materials (available and affordable), local policies, standards, financing access, market context, local environmental conditions, and more. On the other hand, tailoring technologies to be transferrable to several markets or some of the most influential ones (e.g. China and India) could help maximize impacts of development efforts and provide further financial incentive through potential technology sales (Wray, 2012). In this sense, tailoring products to specific markets may enhance individual success while broadly applicable ones may have greater breadth of impact (Beyond Zero Emissions, 2017).

Replacing OPC with low carbon cements in combination with other market forces will likely lead to a significantly higher number of products on the market (Lehne & Preston, 2018). Transitioning from an industry focused around one core product to a more diversified market will inherently increase its complexity. Acceptance and use of the most common blended cements were cited to have taken over thirty years. Given the necessitated greater number of products and the underlying urgency of climate change, long testing periods, standards changes, and other necessitated market adjustments need to be drastically accelerated. Systemic and widespread understanding of novel cements across a broad range of industry actors may help to hasten these changes. (Wray, 2012) It is perhaps both too early and challenging to anticipate which specific novel cement technologies should be pursued (Rootzén & Johnsson, 2016). Despite wide-spread identification of novel cement technologies as playing potentially major roles in decarbonizing this sector, some are skeptical that novel cements will ever achieve significant penetration or contribute to significant emissions reductions (International Energy Agency, 2018b; Lehne & Preston, 2018).

As sustainability urgency increases and begins to increasingly shape the cement industry landscape, shifting to low-carbon cements and concretes may potentially offer enough competitive advantage to account for any price and logistical burdens posed by innovative technologies in the future (Beyond Zero Emissions, 2017). The mass outputs of this industry mean that even incremental reductions in emissions intensity will have large impacts in net emissions outputs if widely implemented (Scrivener, 2014). Further drastic improvements made at individual plants can also substantially impact net-emission reductions within a certain region as there are so few plants (Beyond Zero Emissions, 2017).

4 Results

The results presented in this section are comprised of interviewees responses.

4.1 Industry Status: Sustainability & Demand

General pressure facing the industry concerning both sustainability and embodied carbon was brought up by many interviewees, despite one's portrayal of a relative lack of climate focus as compared to other sectors [9]. Several described a current industry shift within the construction and building sectors from a focus on energy efficiency and operational emissions to embodied and material emissions [2,8,9]. Despite popular discourse surrounding embodied carbon, many emphasized the need to approach material selection from a more holistic sustainability lens (i.e. imperative to factor in durability and longevity) in decision-making and consideration of other topics like standardizations [8]. Accordingly, while concerns and criteria surrounding sustainability have increased, others are as important as before, and actors are not willing to compromise any previous performance attributes [6]. In commenting on how most other sectors have successfully achieved substantial GHG and energy efficiency improvements while the construction sector has not [2], respondents stipulated this could be partly due to expensive housing costs in North America and Europe and the widely-felt effects of these impacts [2]. Multiple interviewees stressed a relatively lower emissions intensity of concrete as compared to all other major building materials from an LCA perspective [9].

4.1.1 Demand Status

Interviewees described current levels of demand for novel cements somewhat differently. Some illustrated customers as willing to accept new green products presented to them (not actively seeking them out themselves), as long as they are not more expensive and have comparable performance characteristics [8,9]. Most customers were described as unwilling to pay premiums for sustainability attributes, with only a small portion willing to accept price increases [8]. Demand was depicted as coming from both top-down (i.e. manufacturers suggesting these products to customers) [8] and bottom-up (i.e. customers requesting greener products from manufacturers) [8,10]. Several described demand as currently existing only for niche applications [1]. (Note: in some conversations, interviewees diverted back to discussing other green and blended cements despite the focus of this thesis.)

Some respondents also noted divergence in demand-levels pertaining to geography [8]. For instance, the west coast of the U.S., particularly the San Francisco Bay Area, was described as having higher demand levels within design communities and generally more interest than on the East Coast where the topic is a newer [8]. Other major metropolitan areas, highly populated regions, and areas of influence of 'big tech' companies were also described having higher levels of demonstrated demand in the U.S., while other regions (e.g. Texas) have exhibited little interest in these products [8,10]. Other locations with high levels of sustainability interest, like Sweden and the Nordics, were cited to have potentially higher demand levels relating to sustainability as well [4,8].

One respondent shared an interaction with another industry actor from a company with a strong sustainability focus. This actor had been on the receiving end of advocation for and assistance in specification change, yet despite the sustainability focus and expressed intention to implement change had not done so [6]. This could demonstrate potential willingness to change, but lack of sufficient drive to take initiative in doing so (what one respondent called 'inauthentic demand'). Those that initially pursue novel cements will be those on the cutting-edge of sustainability action, yet this minority group can grow over time [6].

4.1.2 Decarbonization vs. Performance Benefits

The extent to which decarbonizing features of novel cement both drive development and demand for these products varied somewhat according to each respondent. One working in the novel cement arena communicated that while novel cement development has been occurring for decades, he noticed CO_2 emissions becoming a consideration and driver around 1994, despite lacking wider consideration of climate change at the time [1]. Several respondents discussed growth in demand relating to products' decarbonization attributes over the last five years, also associated with a growing awareness and consensus surrounding the need to pursue emissions reductions in this sector [2]. More specifically, one interviewee described inexistent demand and lacking incentives and development concerning green cements in Sweden five years ago. This has changed with interest in decarbonizing cements now extending to the CEO-level in Sweden. They now see this as the future and are actively interested in this arena, however, generally do not understand barriers surrounding these products or implementation according to this respondent [2]. The significance of decarbonization benefits is present not only in the cement and concrete industries, but in the broader construction sector as well.

Significant proportions of demand for novel cements were echoed by many to come not from decarbonizing features but rather from unique physical and performance properties [2,7]. The balance between green attributes vs. physical properties as the leading demand driver varied by respondent, with some stating that demand is almost solely driven by unique features often not influenced by green features at all [2]. While unanimous consensus was not reached concerning lead drivers for novel cements, many respondents noted decarbonizing features as dominant drivers for other green cement/concrete technologies. For instance, multiple interviewees pointed to carbon curing, specifically CarbonCure, as an example of a commercialized green concrete service company with largely sustainability-driven demand. One respondent cited this technology as having attained a sizable market with steady demand, having attracted customers predominately through green benefits, proving existing environmental market forces and demonstrating actual demand for green cement/concrete products [2]. Several respondents noted considerations of other sustainability factors in weighing the decarbonizing benefits of green technologies [2,7], for instance, consideration of concrete longevity as this affects other sustainability concerns from a life-cycle perspective.

4.1.3 Awareness

Demand is necessitated first by awareness of novel cements themselves and of their benefits. Accordingly, some interviewees were asked about awareness levels within various actor groups. Lack of awareness of novel cement products was cited by one respondent as being one of the leading contributors to lacking demand [3]. Others cited awareness of these products as having increased significantly over the last four to five years [8]. It is important to note that increased awareness, however, does not necessarily translate directly into active demand [3].

While respondents cited general awareness surrounding sustainability, necessity of decarbonization, and other environmental concerns, several noted that this does not necessarily translate into novel cement awareness [7]. For example, many actors may be familiar with high-blend or low-clinker products, but not novel cements [7]. Some respondents cited a prior lack of discussion or reporting on these topics, as having contributed to this historic lack of awareness while noting that this has changed over the last couple of years [8]. Campaigns and industry plans or roadmaps, even those outside of the construction sector, (e.g. Fossil Free Sweden Initiative), have helped to boost awareness [3]. NRMCA, a trade association, has exemplified significant efforts and success in increasing awareness of both necessity of decarbonization and innovative green cement technologies through education campaigns and other programs [8,10].

The existence and awareness of other non-novel green cement and concrete technologies can help boost awareness of decarbonizing needs and indirectly of other green cement technologies as well. For instance, one respondent mentioned CCU technologies (e.g. CarbonCure, Blue Planet) as bringing more awareness to other opportunities for embodied carbon reduction potential [8].

4.1.4 Green Cement Action Thus Far

One interviewee described most novel cements in use thus far as those in 'show-off', or sustainability demonstration projects [3]. Others described more mainstream applications of novel cements as deriving predominately from demand relating to their unique physical characteristics. An example of this is the use of novel cements for faster hardening times to decrease road closure times in California highway repairs which have been used for some time [7]. Another example includes the U.S. Army Corps of Engineers and U.S. Navy researching specialty cements primarily due to interests in unique properties like rapid repair [7].

Other green cement technologies' use and status within the industry were also mentioned. For instance, IKEA has considered CCU and concretes with higher carbon absorption (this however has not moved far beyond discussion phases) [4]. Caltrans has already developed criteria to authorize fly ash and slags in cement use and currently uses SCMs in all applications in which they exhibit superior performance qualities [5]. IKEA has also used slags in a couple of projects, but these experiences were not totally satisfactory [4].

Several respondents discussed their own research and testing surrounding green cement and concrete products. The U.S. Federal Highway Administration (FHWA) reportedly has significant GHG concerns and accordingly has a sustainable pavements program covering asphalt, concrete, and pavements. The interviewee described the organization as focusing primarily on low-clinker and blended cements, having only really worked with two novel cements, one of which being Solidia [7]. While the FHWA has yet to greatly explore novel cements, they engage in sustainability forums, for example both presenting and participating in webinars surrounding new, green technologies [7]. They have also helped create a Sustainable Pavements reference guide, a manual with information to help users consider implementing green pavement options [7]. Another group, Caltrans, is looking into using higher blends than previously permitted [5]. One interviewee mentioned the state of California, several universities, and internal management [5] looking into CCU technologies developed at other labs to verify product claims. After a successful verification process these technologies can be piloted, and if the pilots prove successful, the product(s) can be adopted into specifications for general use at Caltrans [5]. Caltrans researches a range of innovative technologies like titanium oxide use and emissions absorption within mixing vehicles [5]. While many novel cement applications have been successful, they require more upfront engineering and testing to ensure mixes continue to work in field conditions as these products are less understood and less 'tried-and-true' [7].

Some actors (in addition to green cement SMEs), have made sustainability a key part of their business strategy. For instance, starting about twelve years ago, Central Concrete has engaged with numerous sustainability issues, for instance, incorporating sustainability considerations into their product offerings, marketing green products, becoming a founding member of groups like the Carbon Leadership Forum, and working with others like the Embodied Carbon Network and Architecture 2030 to push for increased sustainability within these sectors [8]. Increasing trends for some projects on the U.S. east coast including setting embodied carbon targets [8] while in some west coast markets nearly all cement and concrete producers all have EPDs [8].

4.2 Industry Landscape & Actors

According to one interviewee, most customers do not care where their cement comes from [1]. With OPC constituting the vast majority of total cement produced globally; the cement industry is in many ways that of a commodity [6]. The extremely inexpensive nature of cement, competitive nature of the market, and slim margins make this sector difficult to make money in having significant implications on the potential commercialization of novel cements [1].

4.2.1 Supply-Side Actors

Decades ago, the industry used to be comprised of more mid-sized companies, however, since then these were mostly bought by larger organizations leaving a relatively small number of big producers to control the market with most small firms having exited [7,10]. Currently rather than trying to compete with larger incumbents, SMEs focus primarily on niche markets [2].

Some concrete manufacturers are vertically integrated with cement companies, while a few others remain independent [1]. A few producers attempt to distinguish themselves based on sustainability [8], and several actively focus on mitigating emissions and other environmental impacts. A large incumbent HeidelbergCement, for instance, was described to be "keenly aware" of its environmental impacts and as having experience in mitigating other sustainability issues in the past, (e.g. biodiversity). This experience was described to have helped equip them with some skills and alignment and in pursuing other sustainability issues like GHG emissions [9].

Green cement SMEs and start-ups on the other hand have not achieved widespread commercialization. One interviewee portrayed them as sometimes lacking business planning to successfully commercialize these products. However, they were also described to typically have much stronger marketing and branding than incumbent producers, removing cements from their typical commodity mold [6] and some SMEs citing close collaboration with developers interested in green buildings [1].

Large incumbents are in the position to address both large volume and niche product market segments [9]. For economic reasons, infiltrating large volume production and markets will be extremely difficult for start-ups, with practically no one having successfully done this, according to some respondents [2,9]. An example of a specific challenge SMEs may face is difficulty in affordable material acquisition. With the expensive nature shipping and port occupancy, small production scales increase marginal shipping costs [1].

Incumbents were also described as not being sufficiently incentivized to pursue disruptive technologies [1]. Many are publicly traded, risk averse, and may not have the R&D appetite leaving major innovations to come from SMEs [6]. In many other sectors, most innovation derives and develops in small start-ups. Following success, they are eventually purchased by larger companies that can divert significant capital towards their up-scaling [2,6]. SMEs may also be more agile than bureaucratically driven incumbents allowing them to potentially shake things like standards up [1].

Some discussed suspicions or rumors of large incumbents having developed novel cement technologies without commercializing them and 'keeping them in their back pockets' while others expressed skepticism towards this claim [1,3]. If this is true, incumbents may be waiting if/until it becomes economically sensible to diverge from traditional business models, potentially creating stranded assets, to pursue these technologies [2,10]. According to one interviewee from HeidelbergCement, R&D is not the most expensive part of pursuing new technologies. Rather change is more contingent on when to execute new technologies and investments, waiting until it becomes competitively advantageous rather than disadvantageous. If there is enough societal and political will to make radical change, then large cement companies will likely fall into line in pursuing more expensive strategies for strategic reasons [9].

An anecdote was shared by one interviewee in which several industry actors lobbied to open up a standard, and essentially succeeded in incorporating more types of slags than before. However, a larger incumbent, that was financially struggling at the time, successfully lobbied to have it changed back [1]. An additional example of influence of incumbents surrounds how many academics and other research bodies are often funded by larger incumbents who may accordingly exert influence on research and testing decisions [1]. Suspicion of similar sorts of competition within U.S. markets was expressed by another interviewee [6].

4.2.2 Demand-Side Actors

End-users/customers, architects, contractors, site-workers, engineers, consultants, and building developers were the main demand actors discussed in interviews. Within the construction sector, architects were described by multiple respondents as those to typically drive novel cement consideration due to heightened sustainability concern and are accordingly typically the easiest for producers to target [1,2,8]. However, they do not necessarily have the background to sufficiently advocate for these changes (e.g. technical know-how). Engineers, particularly structural engineers, are described as being the most difficult to convince and most risk averse as they maintain some liability in the event of structural failure [1]. Material decisions are often left to structural engineers; however, most are not trained in material decision-making according to one interviewee [2]. Structural engineers were cited to be often hesitant in trying new products, especially those without performance history [2]. Contractors may be less driven to pursue novel cements without direct customer requests with otherwise limited incentives and perceived risks associated with experimentation [2]. Contractors, engineers, and architects were described by one as butting heads over decisions concerning novel cement inclusion due to initial exclusion of novel cements in bidding, pricing, and scheduling and inexperience working with these products. Sometimes other actors like consultants or manufacturers can help bridge the gaps between the actors in being able to answer technical or logistical questions that others may not be able to, for instance [8].

Larger companies soliciting building projects may have several internal actors who may share responsibility in considering novel cements. For example, within IKEA decision makers were described to lie most directly in local teams working on specific projects, on its global team, and within a separate sustainability group [4]. Progressive consultants can also drive consideration of novel cement inclusion [8] while also serving as an intermediary between end-customers and developers or within the wider construction industry. A respondent from IKEA cited consultants as being the main party that has raised consideration of novel cements within new construction projects (in this case, BREEM associated consultants) [4].

Worldwide, about half of concrete goes into infrastructure and the other half into buildings [2]. Accordingly, the building sector and transportation sectors are major demand actors. Landscapes of these sectors can vary significantly given regional context. In Europe, for example, transportation sectors typically operate through national organizations, while in the U.S. several, disjointed transportation agencies exist [7]. The transportation sector is a major consumer of cement/concrete products, and given its large size and public sector position, this sector may be slower and more difficult to promote change in. Smaller contractors and building developers, on the other hand, were described as moving faster that public sector actors [3].

4.2.3 Other Actors

Policy makers, industry groups, finance providers, trade associations, and sustainability organizations were all mentioned as relevant actors in shaping the demand landscape of novel cements. Policies can play major roles in shaping demand, yet one noted that countries like Sweden, Germany, and Spain, while allocating substantial government resources and money towards environmental issues, do not really act on or execute drivers to achieve improvements within the cement industry (e.g. no steps to address standards and codes) [2]. Leadership from certain politicians or other policy actors can play significant roles in supporting or hindering green cement products. One interviewee gave the example of a mayor in Houston publicly denouncing fly ash for us in concrete. While this example served to decrease demand for green cements, this could potentially work in the other direction and demonstrates the influence of leadership, at least in certain contexts [2]. Trade associations and industry groups serve several roles for their members, generally aiming to increase representation in policy, code, and standard generation in addition to providing additional business opportunities to members. In the cement industry this can take the form of education programs and promotion or marketing of certain products, especially more ‘cutting-edge’ ones [6].

Challenges in retaining qualified, knowledgeable personnel was cited as a challenge in testing arenas (at least within transportation agencies) with recent difficulties in retaining experienced technicians. Accordingly, testing and quality control and assurance are becoming increasingly contracted out within U.S. transportation agencies to engineering consultancies [7].

4.3 Barriers

As several indicated, there is no single barrier preventing accelerated development and commercialization of novel cements, rather several interrelated ones [4]. Further, diminishing barriers will not necessarily spur demand. As one interviewee mentioned, supply-side factors are very closely intertwined with demand-side considerations and in possibilities of connecting demand with actual products [1]. If supply chains cannot be optimized and manufacturers cannot be incentivized to pursue novel cements, producers will have no way to make money off novel cements and will accordingly not pursue them [1]. Therefore, some supply-side barriers are discussed in conjunction with demand-side ones.

4.3.1 Risk Aversion & Product Quality

Risk aversion was agreed to be a leading barrier by several respondents [1,3,4,9,10]. This can take the form of general safety concerns and/or associated legal, financial, and performance risks. Interviewees described the construction sector to typically be very risk averse with a general focus on risk minimization. These characteristics are not expected to change, making transition in this industry more challenging [9]. According to one respondent, not all novel cements currently meet performance expectations or live up to their stated benefits [6], and so both founded and unfounded skepticism pose significant barriers to novel cement adoption.

Despite promising lab results simulating long-term structural performance through advanced modeling [1], there is a lack of actual buildings or demonstration projects utilizing novel cements that have been in place for long periods of times. This reinforces perceived uncertainty about novel cements’ long-term performance and viability, especially as many customers expect performance to last for very long periods of time, beyond a century in some cases [1,4]. One interviewee claims that current testing methods are sufficient, and common perceived uncertainty regarding testing is essentially unfounded; that is, they are quite accurate and should be met with more trust [1].

Relatively benign property differences can also deter demand. For example, IKEA’s display floors contribute to the company’s signature brand aesthetics, and so the company has specific specifications for display flooring [4]. Despite potentially equal and sufficient performance characteristics of certain novel cements, minor aesthetic variations, like different finishings, could potentially jeopardize their appeal [4]. Dissimilarities in aspects like workability in differing weather conditions are also other relatively benign considerations that merely require adaptation and increased experience to mitigate [7].

Generation of negative publicity or discourse surrounding product dissatisfaction or failures can heighten risk aversion, decreasing market interest and uptake of novel cements or other green products in the future [2,3,7]. On the flip side, however, shared positive experiences may have the opposite effect and negate risk aversion [2]. Risk aversion does not just affect product demand but can also reinforce other barriers. For instance, risk aversion combined with lacking demand was cited to drastically decrease testing activity of novel cements in Sweden [3].

4.3.2 Standards, Codes, and Specifications

Standards are normally conservative, providing strict criteria to address concerns with structural safety, however, often have unintended consequences [5]. Once in place, they can be very hard to get around [2], and engineers are unlikely to take risks on new products outside of standards without anything to fall back on in the case of product failure [8]. They are valuable to demand-side actors in that they help eliminate most liability in using cements and concretes while providing straightforward guidelines to assist in material selection [2]. For these actors, codes and standards influence which products are tested and adopted [5]. According to multiple respondents, altering and expanding standardizations to be more conducive and inclusive in permitting novel cements would help decrease both experimentation and adoption barriers (e.g. risk aversion, authorization barriers, legal concerns) [4,7,9]. Some referred to standards restriction as the leading or ‘top-two’ barrier [1,2], while others noted their expansion will not directly accelerate or allow for product adoption [7]. With changes, respondents can foresee demand-chain actors becoming more willing to consider their adoption [2], as this would increase their legitimacy [4]. While becoming more inclusive of green products, standards also need to maintain prioritization of safety and longevity considerations [8]. In addition to standards, other guidelines like organizations’ specifications and local building codes play similar roles. Accordingly, in addition to widening standards, specifications and other codes may need to be similarly widened [2]. Like standards, specifications are comprised of a list of clauses essentially giving permission to use products adhering to these criteria. In this sense, they are not directly prohibitive of certain products, but rather indirectly imply which products can be used (e.g. defacto prohibition) [7]. In developing specifications, companies or organizations may use those that only permit OPC, and if novel cements are not included, they can be very hard to use. Certain specifications and standards permitting novel cements may not be appropriate for all applications. Accordingly, creating new standards and specifications as opposed to merely widening existing ones should be pursued. Reaching out to architects, engineers, and specifiers who have influence over specifications may help to promote change.

Two main classifications of standards were described by one respondent: prescriptive and performance-based [1]. Prescriptive standards are more descriptive of how to make cements or concretes (e.g. inclusion of mixing ratios). One described these to be associated with lesser liability [1]. Performance-based standards, on the other hand, outline performance thresholds and characteristics required by end-products requiring testing to verify achievement of these attributes [1,7]. Historic resistance to performance-based standards, is beginning to shift by some actors as these are generally thought to be more conducive to novel cements [1,7].

Countries typically utilize their own standards, with actors within a given country even using various sets of standards in many cases. For instance, in the U.S., many follow both ASTM and American Concrete Institute (ACI) standards in addition to many actors utilizing their own personalized specifications (or those of an umbrella group, e.g. American Association of State Highway and Transportation Officials) [7]. Standard changes in one country can encourage and influence similar shifts in others to some degree [2]. For instance, several African and Asian countries copy European standards almost identically [9]. One respondent noted that while standards changes would help minimize barriers significantly in many 'western' countries, this effect may not be globally applicable. For instance, places like India and China already have relaxed regulation and standardization from the perspective of some multi-national companies who already perform additional testing and inspections to compensate for these perceived deficiencies. In these cases, opening up standards may not help significantly accelerate novel cements [4].

Differences in standards landscapes amongst various countries were also portrayed. Some described differences between the availability of more inclusive novel cement standards in the U.S., Australia, and Europe along with differences in actual specification and adoption of these more inclusive standards [2,9]. One described U.S. standards to be generally more prescriptive, however with existence of one open standard more conducive to novel cements, for instance [1]. European standards, on the other hand, were described to be largely coordinated by the EU Commission [9] and harder to infiltrate [1,2]. Yet once adjusting them, there are fewer other barriers like local codes to overcome within the EU [2]. In the U.S. you may have state- and locally- specific codes and maybe even corporate codes in addition to basic standards that may need to be followed [2]. However, one described various codes and standards within the U.S. to be similar at the end of the day, perhaps just more advanced or expansive at state-levels or in populous areas [7]. Despite these levels of 'strictness' described, willingness to change was also portrayed within U.S. standards boards like ASTM, for instance, being comprised of driven people willing to change standards, while this is not the case in other places [1]. In some countries, like Sweden, companies can use novel cements not covered by standards if assuming liability for them [2]. In other European markets, opportunities also exist to use alternative cements if strict certification processes are undergone. However strict national European codes make this exceedingly difficult [2].

The process to change standardizations can be quite slow, even with desired change, resulting in delays in accelerating novel cements [7,8]. Some respondents cited an average three to five years in getting a new standard implemented (with three years being relatively quick) [7,8] with changes taking ten years or longer in other cases [8,9]. The volunteer nature of member committees on standards bodies responsible for these changes is likely not conducive to quick changes. For example, state highway officials in the U.S. used to attend ASTM meetings and contribute to the standard creation processes, but travel restrictions and other resource restrictions largely deterred maintaining high levels of participation [7,8]. Accordingly, this volunteer nature can make involvement, time allocation, and commitment highly dependent on individual productivity and implementation [8]. Further, efficient implementation of changes is aided when those participating understand material science behind cement products [2]. In one U.S.-based anecdote, lots of expertise has been lost (at least within transportation infrastructure) due to significant retirements, experienced talent relocating to the private sector, and corresponding losses of experienced human capital [7]. While previously-mentioned rumors described incumbents exerting lobbying power to retain more restrictive, traditional standards and codes [1,2,3], specific areas (e.g. Sweden), were described as having concrete producers with sincere sustainability drive having accordingly participated in processes widening standards [2]. SMEs and other actors are described as having lobbied for the opening of these standards in some cases. For instance, in South Africa efforts led by one individual led to standards opening up for novel cements [1]. One cited a Swedish start-up-like organization that strives and lobbies for standards changes including more novel-cements in risk free applications. There efforts were described to likely achieve success soon in opening standards for indoor concretes [2]. Political aspects can also impact standardization change. For instance, one interviewee cited European cement standards as being in somewhat of a 'stand-still' due to legal and political differences within the EU Commission, cited to decelerate innovation processes and drivers significantly while also preventing the uptake of green cements [9].

If codes and standards open up, technical guidance documents and testing methods will have to be revised accordingly [7]. Even if codes, specifications, and standards open up, the products local engineers and designers are willing to use can override these expansions [8] as engineers may adopt stricter codes or criteria than specified according to their own design philosophies [8]. This is especially the case in smaller regions that are more dependent on a limited number of local contractors and actors [7].

4.3.3 Resource Availability

Material availability poses significant supply-side challenges in deploying novel and alternative cements on wider scales, particularly given the massive volumes of output necessitated by the industry [3,9,10] and limestone's incredible abundance making it difficult to find such available substitutes [3]. That is, the geographic availability of any potential substitute will almost always be more limited than that of limestone's [3]. These challenges apply not only to novel cements, but also to several other green cement and concrete technologies. Even currently used SCMs (in both novel and blended cements), like fly ash and slags, are already limited and likely to become significantly more expensive and/or inaccessible in the coming decades [9]. Many other SCMs that have not yet been widely exploited (e.g. glass) also have very limited availability in comparison with limestone [6]. Additionally, OPC's supply-chain is highly advanced and has been optimized over decades [6] making it even harder to economically compete with. Calcined clays and fines and paste from recycled concretes are some materials that are being investigated and tested due to their wider availability [2,9]. Once currently utilized waste materials become more expensive and/or unavailable, uptake of other materials will likely accelerate [9]. To widely implement green cement technologies, materials need to be not only widely available, but also cost-competitive and scalable [2,9]. While many plants share mix designs, the constituents used in these mixes can differ, often due to local availability, which can sometimes affect performance and economics of concretes [8].

4.3.4 Cost

Interviewees diverged in assessments of the magnitude of economic and cost concerns in inhibiting novel cement propulsion. While some said economics are the main issue [9], others disagreed [3].

From a demand-side perspective, one respondent described price sensitivity of most clients to be very high [9] with some minor exceptions (e.g. Scandinavia due to increased sustainability concern). Cement is very inexpensive, especially as a building material, costing merely ~ €0.04 per kilo of concrete [9]. Accordingly, for there to be demand for novel cements, customers likely need to be willing to pay higher prices in many cases [9]. Purchasers are typically more willing to experiment with new products if there are financial benefits [4], so any green cements offered at a lower cost than OPC could further accelerate their uptake.

While price sensitivity of purchasers may be quite high, end-customers of many development projects are often less price sensitive (with these products) as they typically constitute a small fraction of total material and project costs [3,9]. For instance, in the building sector, this price increase could be less than one percent (less than that of error margin) of total project costs, while in transportation infrastructure it could be closer to two percent [3], as cited by one respondent. Accordingly, from an end-user perspective, increases in cement prices, even doubling, should be usually easily digestible. According to an interviewee, if end-customers drive investments in these products, costs will pose much less of an issue. However, when construction companies drive decision-making, this is much less likely, as they typically focus heavily on their margins and perceptions of material prices [3]. Accordingly, pushing these costs down the demand-chain can be more challenging in reality.

If certain sustainability goals (e.g. carbon-neutrality by 2050) are taken seriously and actively pursued, it is feasible that implementing necessary technologies to achieve these goals could double the costs of cement and concrete [9]. Accordingly, one respondent sees the doubling of the cement and/or concrete prices as a potential reality that could be realized quickly with major market shifts, for instance, through the drastic raising of carbon prices [9] and customers' price sensitivity would accordingly be forced to adapt. Doubling of costs was cited to likely not decrease viability or competitiveness of cement and concrete significantly as compared to other construction materials because it is regarded as such a uniquely valuable, 'irreplaceable' material [9].

From a supply-side perspective, it is very challenging to replace OPC because of how inexpensive it is to produce. Its raw materials are vastly abundant and inexpensive, and its manufacturing has been optimized over a long period of time [9]. Accordingly, developing an alternative product at a comparably low cost will be extremely challenging. One respondent cited the roughly doubled price of geopolymers, for instance, as being the main barrier in its lack of wide-spread adoption [9]. Accordingly, simple economics pose a major barrier in the success of novel cements [8,9].

The cost of various novel cements depends on technologies used. In many places, certain SCMs like fly ash and slags cost less than OPC, so utilizing these materials assist in reaching cost-neutrality or preferentiality, which is achieved already in some blended cements [8]. Notably, however, material pricing can differ significantly by location. Even within the U.S., for example, SCMs and blended cements have been a part of many companies' standard operating procedures for some time on the west coast. Accordingly, slags are less expensive there than on the east coast where they are sometimes more expensive than OPC [8].

4.3.5 Implementation and Logistical Factors

Various implementation and logistical considerations were described as presenting additional barriers on both demand- and supply-sides. From a broader standpoint, some described additional requirements in adopting or manufacturing more cement types to be generally burdensome, complicating things like procurement and implementation [3]. However, another cited that for his company (IKEA), using additional cement products, at least from a procurement standpoint, would not pose significant additional burdens [4].

An example of logistical considerations on the construction side relates to the high alkalinity of geopolymers and corresponding safety concerns necessitating the use of protective gear and other inconveniencing mechanisms to ensure product and site safety [9]. Another example relates to different finishings than OPC produced by novel cements. While not necessarily structurally problematic, different overlays may need to be applied requiring additional time and resources [3,7]. The types of cement or concrete selected for a project can even impact what type of mixing vehicle is required or optimal [7]. Additional operational impacts can be exemplified in slower hardening times of some novel cements as this can lead to significant delays in construction scheduling along with potential impacts on construction loans which can be very financially significant [6].

Existing awareness amongst demand actors of how to work with OPC in various conditions (e.g. warm and cool climates) do not necessarily extend to novel cement products posing additional learning and implementation obstacles [5,7]. One interviewee suggests that these sorts of obstacles can be mitigated through more upfront technology trials or testing with actual mixes and materials. Respondents noted differences in lab testing vs. real-life application, however, not all companies may have the resources to perform this additional testing [7]. Further, if a company is interested in working with novel cements, but no one on their team of engineers, contractors, or construction crews has experience working with them, it may become too daunting to undertake. Accordingly, trainings, education, and design and construction guidance (e.g. manuals) could help diminish these barriers [5,7].

Significant implementation barriers also relate to infrastructure and existing facilities [7,8]. One example concerns material storage requirements. In using a new cement constituent powder (e.g. SCMs like fly-ash or slags), an additional silo or other large storage infrastructure (e.g. bins) is likely needed. Many smaller companies only have one to two silos posing a significant barrier in offering new blended or novel cements with more powder constituents. Installing this new infrastructure is associated with high capital costs which for budget-strapped or spatially confined plants can be significantly limiting. Other new systems necessitated in novel cement transitions would all pose significant capital costs. If these costs are too high, and the products cannot be sold for a high enough premium, they are essentially not economically viable from a manufacturer's standpoint [7]. Utilizing technologies that can be produced at existing cement plants may be much more feasible from both logistical and capital investment standpoints [6]. For instance, while geopolymers essentially require constructing a new plant, the limestone-based Solidia may be much easier to adapt existing facilities to [6].

4.3.6 Financing

Insufficient financing and funding can also pose major challenges to supply-side economics. It can be very difficult for novel cement start-ups to obtain sufficient financing. Up-front full-time financiers typically demand most decision-making power in this sector, which is unappealing to several companies [1]. Conversely, the availability and characteristics of financing options in some locations can help increase attractiveness and preferentiality of certain regions in building novel cement start-ups. For instance, according to one interviewee, the U.S. venture capital market is more mature and likely more inducive to cement start-ups than many other countries [1]. On a separate note, financial backings of SMEs are sometimes relevant to demand-chain members. In taking risks adopting new products, customers may wish to ensure producers have the financial backing and ability to mediate or compensate for product deficiencies in the event of product failure [4].

Financing in the form of government funding can also pose issues on the demand-side. For instance, funding to large, public cement and concrete consuming organizations can accelerate or limit the amount and speed of testing in vetting new cement products [7]. Lack of funding can further increase difficulty in establishing new programs, while budget cuts can further inhibit or delay other programs surrounding novel cement consideration and development [7].

4.3.7 Competing with other Green Cement/Concrete Technologies

From a sustainability-driven demand standpoint, novel cements can be seen as competing with other green technologies. Some interviewees agreed that from a customer standpoint, there are often no major differences in sustainability advantages between blended and novel cements, especially when emission abatements are comparable [3,9]. However, for sustainability leaders like IKEA, some actors may not consider the use of waste products in cements to be charging the forefront of sustainability while the use of novel cements would be [4]. From a demand perspective, in the short term, it can be challenging for novel cements to out-compete proven, readily available, and potentially more affordable products like blended cements [2].

However, as long-term material availability will be a major issue for blended cements [2], novel cements that utilize other materials could provide unique value and become more attractive in the long-term. Yet while greater resource availability was cited by multiple respondents as being a potential benefit of novel cements over blended cements, another noted that several material constituents used in novel cements without immediate, significant resource concerns (e.g. calcined clays) can potentially also be developed into SCMs for other blended cements [9].

From another perspective, SCMs and blended cements can be seen as a 'lower-hanging fruits' and more short-sighted solutions [2] while novel cements could be a solution to be implemented once CO_2 reductions from blended cements begin to saturate. In this sense, one respondent described blended cements as a potential first step towards more complex or expensive novel cements [6].

While HeidelbergCement has historically performed research surrounding novel cements, more recently they have shifted their focus to other decarbonizing technologies [9]. This include focusing on decarbonizing input materials (e.g. use of concrete wastes) and exploring CCS projects [9]. To help formulate R&D program priorities and key performance indicator setting, HeidelbergCement performed an intensive strategic analysis surrounding potential decarbonizing technologies as described by one interviewee. Through this they evaluated both potential emissions intensity reductions and marginal abatement costs of these potential reductions for various green cement and concrete technologies. These exercises placed novel cements within the higher tiers of marginal abatement costs (i.e. more expensive to reduce footprint) compared to other green cement technologies like blended cements and CCS. Accordingly, the interviewee from HeidelbergCement suggested that many of these other non-novel cement technologies are better solutions, and that novel cements may only make commercial sense in specific niche applications [9].

4.4 Paths Forward

Many interviewees were directly asked or independently commented on potential business model, policy, and other strategies and drivers to create a more conducive industry landscape to propel novel cements.

4.4.1 Service-Oriented Business Model

The concept of a more service-oriented business approach was raised in the first interview and presented to other interviewees in subsequent interviews. It was initially described broadly as providing cement and/or concrete to end-customers through more of a direct service rather than the traditional, more linear chain. This could look like manufacturers working directly with end-users, developers, or other decision-makers in selecting optimal materials to meet project needs as opposed to more traditional material selection without interaction between manufacturers and demand actors during planning phases.

This more direct service could include supplemental value addition in cement or concrete producers sharing or adopting financial and/or legal risk of their products. This would help reduce aversion to novel cement adoption from these types of risk [1,2]. Cement providers could additionally be responsible for maintenance for a certain period and/or replacement in event of failure [1,3]. Companies being able to provide these services may necessitate further vertical integration for companies to be logistically able to internalize risk and provide these services [1].

This ‘risk-adoption service’ does not necessarily need to derive from manufacturers but could also originate from other demand-actors (e.g. developers, contractors) [3].

Several interviewees were familiar with this concept before, however, few were aware of any cases of this strategy in action [2,3]. According to Zeobond’s CEO, Zeobond has implemented it and it tends to work [1]. General feedback highlighted the importance of this strategy that was met with some enthusiasm [3,4], even highlighted as a top-two solution to widely commercialize novel cements [1]. However, some raised financing concerns with this strategy, for instance, SMEs or start-ups not having sufficient financial backing or permanence or the perception of lacking financial backing to adopt risk in the case of failure. Experiences like this with other SMEs in different sectors have been experienced by some businesses potentially deterring them from entering these sorts of agreements in any sector [4].

Vertical Integration

As mentioned above, vertical integration could assist in providing more service-based approaches to customers while allowing manufacturers to promote sales of their green products first-hand. Some respondents added that stronger vertical integration could further assist in passing mitigation costs down the value chain to end-customers [9]. Novel cement SMEs were described by one as needing an independent supply-side with vertical integration potentially helping achieve that [1]. On the other hand some noted that in places with vertically integrated concrete and cement companies, there may be less incentive to reduce amounts of OPC in mixes and adopt green cements, as cost-efficiently running cement production typically requires maintaining high output volumes [8]. Another commented that while vertical integration may intuitively seem to increase control over which mixes and blends can be produced due to greater buy-in, this may not actually be the case. This is partly due to that the nature of the industry in which concrete companies are sometimes forced to buy cements from competitors instead of their own vertically integrated cement company due to volume and geography restrictions. Accordingly, it is more difficult for parent companies to force their subsidiaries to purchase their own products [6] potentially negating this intuitive greater decision-making power.

4.4.2 Niche Targeting

Several respondents supported the concept and strategic benefit in focusing on development and commercialization of novel cements within strategic niches. Once novel cements have been successfully proven in specific niche applications, this could help widen acceptance and decrease risk aversion for applications beyond those specific niches over time [2,4]. These niches can be classified in different ways, and several niche applications can exist within the same project [6]. Several respondents commented on which niches make the most sense for initial pursuit.

Manufacturing Techniques

Many commented that pre-cast products probably present the most, early opportunities for manufacturing of the three main categorizations of concrete products [2,5,7,10]. However, the ideal manufacturing techniques depend significantly on the specific novel cement technology in question and other market context [5,8].

Pre-cast applications are manufactured in factories as opposed to on sites [2]. As factories are more controlled environments, products tend to have greater uniformity with less opportunity for error [2] and can output thousands of units [4]. Further, factory environments allow for better optimization of resources and can more easily handle complicated material processes. All of these factors help enable pre-cast novel cement products to have advantages over ready-mixed and dry-bagged in novel cement manufacturing [2,10]. Specific low-risk, easier to implement pre-cast applications mentioned by respondents included all sorts of non-structural aspects with pre-cast slabs highlighted as a specifically low-risk application [5]. However, selecting ideal niche products depends largely on the novel cement technology and project-specific risks or concerns [7,8]. Pre-cast slabs, concrete blocks, bricks, and even floor elements are examples of already manufactured novel cement applications, some of which are beginning to be commercialized by Solidia [7]. Further, a respondent mentioned that certain green pre-cast products (specifically carbon-curing blocks) can be used immediately if they meet their current specifications [5] demonstrating potentially lower standard/specification barriers as well.

Other manufacturing methods also pose benefits for niche prioritization. For instance, ready-mixing allows for alteration of concrete formulas on the fly without retooling production facilities while other methods require retooling of a plant to significantly change product formulation [6]. Additionally, some novel cement technologies may be tailored better to some techniques than others. For instance, ready-mixed concretes must remain perishable for longer periods of time than in precasting. Accordingly, novel cements that stay perishable for longer could be better suited for ready-mixed applications [6]. While differences may make certain manufacturing techniques more ideal, that does not mean they cannot also be used in other types of products. Self-consolidating concretes, for instance, work better in precasting than ready-mixed products. Nonetheless, these concretes' acceptance is growing within the ready-mix realm being used more and more [6]. This could be analogous to novel cement technologies, perhaps gaining initial traction in the pre-cast arenas while expanding slowly into others.

Applications

In general, non-structural applications were endorsed for initial market focus as they are likely to be met with less risk aversion [4,8]. Applications requiring superior physical attributes to those of OPC can also be good niches for initial development [7,9]. Rapid setting novel cements, for instance, can be ideal in certain applications like highway repairs to ensure timely road re-openings [7]. Geopolymers on the other hand have advantages like acid resistance that are ideal for some sorts of applications and very applicable in niche markets [9]. Aesthetic differences can also play significant roles for some customers. For instance, using concrete slabs with different aesthetic features would likely be more feasible in an IKEA warehouse than an IKEA showroom [4]. Accordingly, slabs that are often covered up by flooring, or other less exposed features can serve as more attractive niche application [3,8]. Some interviewees also highlighted the importance of finishings in some contexts [5]. Lightweight applications were highlighted as potential bad niche application as they do stand up to finishing, for example [4]. Slabs, wall applications, sidewalks, parking areas, and sleepers in train tracks (for which there are potential large demand volumes) are other specific applications that were mentioned as potential initial niche applications [3,8].

Customer Segments

Targeting certain customer groups and/or tailoring products towards these groups' needs may help optimize demand. For instance, customers soliciting building construction for their own use will adopt both the low-carbon benefits and risks of using novel cements themselves, potentially appealing to their own sustainability interests. On the other hand, from a builder perspective, adopting liability relating to any corresponding failures without demand for implementation of green features is not incentivizing [2]. On a separate note, some customers may be more able or agile in adopting novel cements. For instance, smaller contractors and building developers can potentially move faster in adjusting specifications than large or public organizations [3]. In-house capabilities of public clients in advancing new structures is not very sufficient, as a lot of it is now lies in consulting firms [3] as noted by one respondent.

Infrastructure vs. Building Sector

Interviewees did not reach a consensus on one sector as more ideal for initial focus, however, different implications for the transportation and infrastructure markets vs. the building sector were identified with niche opportunities highlighted in both sectors [3]. Respondents cited potentially higher levels of risk aversion in the transportation and infrastructure sectors as projects may have more catastrophic consequences associated with structural failure [2]. Additionally, in the building sector there are typically less structural failures that could occur in the first place [2]. On another note, different conditions create slightly different needs between products for the two applications. For example, risks associated with salt-scaling need to be considered in infrastructure applications that are far more exposed to the elements than most indoor concretes in housing applications [2]. Additionally, as transportation and infrastructure projects are almost always regulated by government agencies, they may be inherently slower moving in adopting new products in addition to often being more resistant to change [6]. While these responses highlight challenges novel cements may have in infiltrating the transportation sector, two transportation agencies indicated that they already use novel cements in certain applications and suggested opportunities for expansion of their use [7]. The sheer size of demand for concrete products and influence over other public agencies in some regions can make the transportation industry a highly influential sector to change [3].

Geography

Features of certain geographies were also discussed to be more conducive to certain niche novel cement penetrations. Unique physical features of certain areas can necessitate specialty products. For example, one respondent mentioned differences in soil chemistries. In Texas, for instance, concretes require better vapor barriers to account for the expansion of soils while in other soils, more corrosion resistant cements and concretes may be required [4]. On a separate note, some countries use more pre-cast manufacturing and products than others. For example, is Sweden projects are built with lots of pre-casting while in the U.S., more pour-in-place is used [4], potentially creating different demand for various product types. Some countries were also discussed to potentially be more immediately conducive to novel cement SMEs. For instance, once noted that North America may be the most conducive start-up environments [2] while the Nordics may be the most conducive for piloting [4].

4.4.3 Marketing

Marketing can serve to better promote novel and green cements. CarbonCure, a CCU technology, for instance, has done a great job of marketing their technologies. They perform a lot of outreach to various concrete makers and have been successful in growing a sizable client base. One respondent noted their opinion that this approach could work for novel cements too, it would merely require greater effort [2]. Many novel cement start-ups do a great job at marketing these products while others have a way to go [6]. Some companies ask industry groups to in some ways market these products for them, but according to one respondent, they would likely gain more traction marketing them themselves and this respondent believes they have the financial capacity to do so [6]. Many companies keep their local, original brand-names, and while this provides certain marketing benefits, they may be missing out on associating unique value of some of these green products and brand recognition and loyalty [6]. A part of marketing efforts may include customer outreach encouraging them to change specifications to permit more novel or green cements which could further enable effectiveness of more traditional marketing techniques once specification barriers are diminished [6].

4.4.4 Policy Options

Despite lack of inclusion in initial research scoping, several policy options arose in discussions to help promote demand or diminish both demand- and supply-side barriers.

Leadership

Government leadership can both help spur demand and action in implementing novel cements [2]. Some politicians may also have significant influence over changing local codes allowing for the inclusion of more novel or green cements. However, this potential is likely more applicable in the U.S. in comparison to Europe, as local U.S. actors may have more power in accommodating these sorts of local requests and may face less political resistance according to one interviewee [2].

Emission reduction targets from both governments agencies and private actors were also cited to serve as a potential drivers for pursuing green cements or other decarbonizing cement/concrete technologies. For instance, California has set the goal of a zero-carbon society by 2040. In response to this, Caltrans's materials testing branch reported having received emails and solicitation from various levels of government, including the governor's office, inquiring about potential technologies and requesting the branch to work towards alignment with these goals. Inquiries were also reported as coming from higher levels of management within Caltrans including some relating to CCS and CCU [5].

Funding

Additional monetary and personnel resources may help to accelerate testing, vetting, and verification processes of novel and green cements used by the government [7]. For instance, in the entire state of California there are less than twenty staff members responsible for researching and testing new cement and concrete products [5]. Additional resources could potentially help to evaluate more products and to do so more quickly [5].

Piloting/Demonstration Projects

Governments could also solicit and pursue more demonstration or pilot projects using novel and green cements [7]. In contexts like the U.S., the federal government could even work with states in piloting these projects with the federal government adopting types of risk so that state governments feel less hindered in pursuing these new endeavors [7]. Governments could also test new, novel cement technologies for use in their own applications. For instance, the U.S. FHWA began to work with Solidia in testing their products, however, budget constraints along with other obstacles halted this process [7].

Piloting and demonstration projects are not limited to just the public sector. These projects, in addition to providing proof of concept of novel cements, also help give contractors experience in working with these technologies making them more likely to obtain approval [4]. Particularly large, leading companies, like IKEA, testing these products paves the way for other companies to follow [2]. According to one interview subject, "the second project is always easiest" [1]. According to another, the "difficult part is to get to the stretch with enough projects to show people it really works" [2]. Finally, it was noted that taking a risk on a 100,000 square meter building (like an IKEA) is very different than on a small building, accordingly the latter may be an easier place to start for pilot projects [4].

Command and control

More specific regulations could also be put in place to incentivize or require the use of novel or green cements. For instance, to obtain a building permit, one could be required to have a levelized embodied carbon level below a certain threshold [4]. Other types of legislation could also help to stimulate demand. However, one respondent highlighted support for incentive schemes as opposed to regulatory mandates [6].

Public Procurement

Public procurement standards can help increase bulk uptake of novel cements while influencing other actors to follow suit. For instance, one respondent cited the Swedish Transport Administration as being the most effective driver of change in the country relating to the uptake of green cements in Sweden [3]. If they altered procurement guidelines to allow for novel or green cements, this would both increase demand for these products significantly and pave the way for other actors to follow suit [3]. For instance, municipalities traditionally follow or consider changes implemented by this group. Accordingly, public procurement change by one actor, could have a domino effect across the country's public sector [3].

Informational Tools

EPDs were described as being like 'nutrition labels for concretes' including material constituents and sustainability characteristics like GWP of certain products, helping customers to understand the environmental impacts of the concretes they purchase [8]. Industry groups can serve to help manufacturers produce EPDs and compile industry average EPDs to serve as baselines in product comparison [6]. In the San Francisco Bay Area market, for example, all concrete companies now have EPDs which can enable more sustainable companies to receive demand-related competitive advantage [8].

Green Certification Programs

Widely used green certification standards were also mentioned as a minor driver relating to decarbonization [6]. Those like BREEM and LEED can help encourage embodied carbon reduction [4] including through novel cement use. One respondent described LEED and Architecture 2030 as two initiatives that have motivated the industry to focus on embodied carbon (at least in the US) [6]. LEED and other certification bodies can also assist in generating demand for EPDs (as these may be requested in submittal packages) [6]. One concrete-selling company assists customers in compiling EPD and submittal packages for these certifications [8] helping sustainably driven customers to reap benefits from adopting greener products. Some states in the U.S. have even adopted policies requiring various green certifications (e.g. Green Building Initiative or LEED) for certain state funded projects [6].

4.4.5 Actor Collaboration

Participation in industry groups, conferences, conventions, research sharing, and working with customers are sources of collaboration cited to help propel novel cements [8]. One actor cited little collaboration amongst green cement SMEs, likely because they are too fragmented and small. However, potential opportunity for them to collaborate in working towards common interests was proposed by one interviewee, especially in North America [2].

Industry and trade groups are also examples of forms of collaboration. Several of these organizations see value in and focus on sustainability. ACI, for example, gives presentations at conventions focusing on various sustainability topics. They also recently formed a subcommittee to develop new code language for reinforced concrete geared towards increasing sustainability [8].

Cement and concrete companies having close relationships with customers can serve to help attain demand for greener products. This enables them to share new technologies with customers, communicate their benefits, and explain how to use them. This can also help gauge interest for new products and help customers in troubleshooting [8]. CarbonCure, although not a cement company, has focused a lot of attention and marketing towards reaching out to head architects specifically. This is described as having been very effective in the U.S. and Canada and could be a potential strategy for novel cements companies as well [2]. Companies like

Central Concrete also do presentations for architects, engineers, and contractors tailored to the specific audience describing concrete sustainability, how to measure this sustainability, and how they can help provide low-carbon concrete products [8]. By getting involved and communicating more intimately with design communities, they can not only increase awareness and understanding of decarbonizing technologies, but also address hesitancies other actors may have [8]. This company considers their commitment to sustainability as a part of their business model, and accordingly sees fiscal value in meeting these niche demands [8]. Some cement and concrete companies also serve roles in larger sustainability-focused organizations. For instance, Central Concrete is a founding member of Carbon Leadership Forum, also working with the Embodied Carbon Network and Architecture 2030 [8].

One cited increased research sharing and accessibility as being a major change that could help further propel these technologies. This would serve to both increase awareness and may even help specification committees open up specifications [7]. Awareness of other pilot projects and research can also be used in others' literature reviews to support changing specifications [5].

Respondents from the public sector also reported similar types and forums for collaboration. The U.S. FHWA, however, described their collaboration with the industry as being limited outside of Cooperative Research and Development Agreements (CRDA)s. In these agreements a federal lab can work with a specific company to evaluate a new product for potential application. There is no monetary exchange and companies are restricted to those within the U.S. in CDRAs [7]. FHWA also described additional collaboration with a Canadian company and a CRDA with Solidia that was formed after repeated outreach from Solidia [7]. Another transportation organization, Caltrans, cited instances of working directly with cement companies, particularly large incumbents, through various partnerships. An example of which is an industry association, the California Nevada Cement Association, in which cement manufacturers members and Caltrans sit on various committees enabling Caltrans to become familiar with new industry products and manufacturers to become aware of new guidelines being put in place by Caltrans [5]. Industry members actively bring new ideas, products, and suggestions for new specifications to Caltrans in these meetings. For example, before 2017, Caltrans had never considered accepting Type 1L cements into their specifications to the interviewee's knowledge. However, after one of these meetings, in which industry members promoted and suggested Caltrans's acceptance of them, Caltrans formed a subtext group and drafted a research proposal for the acceptance of these products [5]. While one respondent echoed the previous notion of the public sector potentially being more risk averse and slow to change, they also noted that because the audience or number of individual actors within the public sector is smaller in this field, it may in some ways be easier to infiltrate or collaborate with, despite aforementioned challenges [6].

4.4.6 Internal Optimization

Increasing and optimizing internal collaboration was also noted as a strategy to increase efficiency and accelerate novel cement adoption on the demand-side. This could take the form of more formalized, new product evaluation systems within a demand actor's organization, with distinct procedures outlined in which responsibilities are clearly delegated to adopt new cement products [5]. Additionally, increased collaboration between research and specification teams within an organization may help generate new, more inclusive specifications more quickly [5].

4.4.7 Literacy and Technology Comprehension

Understanding and experience in dealing with novel cements can also help accelerate uptake. While regular concrete producers and contractors may be aware of these products they may lack any first-hand experience [7]. The more technically aware industry actors are, especially those writing specifications and troubleshooting on sites, the lesser barriers novel cements will face [7]. For instance, in changing standards, one noted when those involved understand material science (e.g. educators), likelihood in achieving standards changes is higher. Many working in the industry understand only rules surrounding cements not the material science [2].

4.5 Long Term Outlook

While one interviewee expressed skepticism of potential wider success of novel cements outside niche applications [9], others were more optimistic of potential success beyond niches. Multiple respondents noted that a combination of technologies will likely be required to achieve emissions reduction goals [6]. Accordingly, novel cements need to be continuously developed so these cumulative emissions cuts can be reached [7]. Within the same project, novel cements, blended cements, and CCU technologies can often be used at the same time as they are not mutually exclusive [6]. Having low carbon footprints for individual concretes within a project should not be prioritized while having low average carbon footprints on project levels should be [6]. This is important to consider as some products or applications are more easily suited for low-carbon technologies.

Multiple actors noted that major landscape changes could potentially spur accelerated change and adoption within the sector. For instance, carbon pricing mechanisms could play a major role if prices become significantly higher than they are right now. Ten to fifteen years ago, solar was not nearly as widely commercialized as it is today, and according to one interviewee, did not take off until utilities started investing in these products. Similarly, one major actor, tried-and-true with a big bankroll like a utility procuring mass amounts of novel cements could help tip the scales and propel novel cements into wider commercialization [4]. In terms of standards change for instance, other major changes like the U.S. Drug Administration’s provision of a fast-track approval system could model a potential pathway this industry could follow if major policies like this were to be implemented [2].

5 Discussion

5.1 Methodology & Limitations

The decision to select interviewees from predominately different actor groups provided a variety of perspectives to enhance demand landscape understanding. However, relying on only one representative's perspective, despite their position as an expert, enhances the anecdotal nature of data potentially heightening bias. Additionally, given the differing market contexts of several interviewees (e.g. geographic location), applicability of insights may be limited to or sounder in their own markets while misleading in others. Having more interviewees from each sector or from a more limited selection of sectors may have helped to enhance credibility or conclusiveness of the results. However, given the aim and necessity of understanding the full landscape in this research, interviewing multiple actor groups may have helped to provide a fuller picture of novel cement progress on a more global basis in combatting the global nature of climate change. Accordingly, many findings should be viewed through an anecdotal lens that is not necessarily inclusive of all markets without many definitive, universal conclusions. With the inductive nature of this project, the research questions are explored rather than definitively answered, especially given divergence in interviewee responses.

While the scope of paper is global, from both production and consumption standpoints, many regions are not well represented in this project (particularly those accounting for the majority of global cement production, like China, India, and other developing countries). Accordingly, findings from this paper may be less applicable to these regions. Though this paper focuses on novel cements, many interviews incorporated more content relating to other green technologies than expected (e.g. blended cements) in parallel, conjunction with, or opposed to novel cements. However, findings applying to other technologies may still have relevance to novel cements, as they are an important part of the greater landscape, have comparable barriers and drivers, and can even be viewed as directly competing with novel cements for green demand. Finally, many aspects discussed are not demand-specific yet have important roles to play in the larger demand landscape, especially as manufacturers from a supply-side need to be able to produce desirable, profitable products for there to be demand in the first place.

Novel cements and green technology developments within this sector are fast moving. This was evidenced by significant amounts of literature published since even the commencement of this project. Correspondingly, implications or conclusions of this report could change quickly with accelerating development in this arena.

5.2 Demand

Historically within the climate discourse, disproportionately lacking levels of attention have been dedicated to the cement, concrete, and construction sectors, but recently, this has begun to change. Despite recognition of these concerns, understandably, building structurally sound, long-lasting structures remains an imperative priority of the industry. So, for sustainability topics to be considered, they must be supplementary to preexisting performance-based criteria.

Descriptions of current demand somewhat diverged with some describing customers as willing to accept green products if pushed by manufacturers, but largely unwilling to compromise performance or higher costs. However, several examples of willingness to accept higher prices were also raised. Demand was described as being driven from both manufacturers to customers and from the bottom-up (customers requesting green products). Novel cements are currently mostly used in show-off projects and niche applications. Given increasing sustainability pressure and more recent awareness generation, current demand levels could rise significantly in the future.

Two categorizations of demand for novel cements were identified: sustainability-driven demand and non-sustainability-driven demand. Customers highly valuing sustainability, willing to extend additional effort to reduce their impacts, and those attracted to these products for unique performance characteristics. In cases with desirable performance characteristics, more expensive novel cements (compared to OPC) may already achieve price-parity with more expensive specialty cements that they more directly compete with, or customers may be willing to pay premiums for unique attributes. According to one respondent, SCMs and blended cements were not initially sought for decarbonizing benefits, but rather unique performance characteristics; they were further met with initial resistance largely due to risk aversion. Now they are not only widely used, but also thought by many to be the most optimal means to achieve carbon reductions. Perhaps, novel cements will follow a similar demand-trajectory. On the other hand, successes and wide-commercialization of products like CarbonCure demonstrate potential for wider scale sustainability-driven demand already.

Breaking down demand barriers will not necessarily create demand. Things like standard and specification changes make product adoption easier if underlying demand already exists but does not generate demand itself. In this way demand drivers and barrier diminishers can be distinguished. Drivers will likely be tied to monetary facets like financial incentives, penalties, or, on the other hand, heighted or widened sustainability concerns, primarily from end-customers, and awareness building amongst those with sustainability interests.

Increasing sustainability demand has manifested in some manufacturers incorporating sustainability into business models. However, this demand for green products may translate into other technologies like blended cements or CCU, not novel cements which was exemplified in several interviews. While awareness of green cement products has risen over the last decades, many within the industry, including some interviewees, are not necessarily well familiarized with novel cements as defined in this thesis.

5.3 Industry Landscape

The industry is dominated by large incumbent actors, many within a small number of multinationals, with the breakthrough of new, small companies being extremely challenging in mass markets. For the most part, production is highly localized and is consolidated into a few large plants. Large production scales complicate economic viability in implementing changes at plants, especially given the industry's commodity nature and already slim profit margins. While parties interested in driving innovative cement adoption exist amongst demand actors (particularly within the design community), the disjointed, multi-actor nature of the demand-chain, specifically within the jostled construction industry, can make collaborative, more complex decision-making and execution more challenging.

As its very difficult for SMEs and startups to gain significant footholds within the industry, widespread commercialization is somewhat at the mercy of large incumbents, at least within the current landscape. The rate at which incumbents choose to significantly pursue green technologies will likely largely dictate the degree to which they will spread across wider markets. As most large incumbents are multi-nationals, they have the potential to help spread technologies across regions that SMEs may have more difficulty in doing. This is not to say, however, that start-ups do not play a role in advancing these technologies. By focusing on niche applications and reaching sizable customer bases, they will help to spread, introduce, improve, and prove novel cement technologies. Driven demand actors can accelerate this by actively collaborating with some of these start-ups. Potentially competitive actions alluded to in this research suggesting that certain incumbents may be or have actively worked against propelling green cement technologies in order to retain favorable status-quo industry conditions, if valid, have the potential to deter long-term proliferation of these technologies in both hindering SMEs and in not acting themselves. Actors are needed to drive some of the ‘paths forward’ mentioned. Enhanced competition between manufacturers as opposed to collaboration could defer if not prevent progress and could shift actors’ attention and resources away from these pursuits.

5.4 Barriers

While opinions of the ‘greatest’ barriers differed, consensus surrounded the prominence of those listed below, and that there is no single barrier preventing novel cement commercialization, but rather several interrelated ones.

5.4.1 Performance

Risk aversion relates to OPC’s greater familiarity and demonstrated reliability than all other products due to its historic, widespread use. While some risk aversion may be merely due to the conservative safety- and performance-driven nature of the construction industry, not all concerns regarding novel cements are unfounded. Performance characteristics and reliability are perhaps the main attributes that customers seek. Accordingly, it is imperative that novel cements have both high actual performance and perception of high performance. While several novel cements have reached high levels of performance and consistency, some have not. For those that have not, further development of these cements or complementary products like admixtures (that can help mitigate some of their differences or shortcomings) needs to continue in conjunction with continued testing to prove their viability. For those that are already high performing, continuation of pilot projects, reporting, and awareness building surrounding these products should spread. Successful pilots, specifically those that have been around longer, and availability of reliable testing data were cited to decrease risk aversion. However, geopolymers have been fairly widely demonstrated through numerous pilot projects yet have not been widely commercialized. This suggests proven performance may not be as dominant a barrier as perceived, or that other underlying barriers or lack of motivation to change are more persistent.

5.4.2 Standards

Lack of inclusion of standards and specifications were portrayed to be one of the greatest restrictions to novel cement consideration. Transition towards more performance-based standards was described to likely create a more conducive environment for these products. However, along with this transition comes necessitated improved lab and in-situ testing methods, for instance, requiring additional research and resources to implement and thus highlighting the interrelatedness of several barriers.

As standard change processes can be extremely slow, acceleration through increased resource allocation or other means could be highly impactful. On the other hand, to get around standards entirely, organizations could increasingly adjust their internal specifications to become more inclusive of green cements without alignment to standards in many cases. Trade associations and other industry groups may be able to offer assistance to companies in these rewritings.

More broadly, standards and specifications have historically been written surrounding OPC products. As more cements enter the market, the structure of standards and specifications should transition away from focus around a singular product in order to increase applicability to and efficiency in this new landscape.

5.4.3 Implementation & Logistical Factors

Building new facilities can be extremely costly. Further, as cement plants have long lifetimes and many are not looking to retire or convert plants, stranded assets may likely result from a company shifting significant focus towards novel cements. While the use or conversion of existing plants is more ideal, this transition would still present significant costs and logistical challenges (e.g. where to put material silos on a small site).

Certain properties of novel cements can also create logistical issues (e.g. long setting times delaying construction schedules and affecting construction loans). Different surface qualities, for example, may also necessitate the use of rollers adding to costs and logistical challenges in execution. Challenges relating to properties may only arise in practice (under field conditions) that were not raised during testing procedures. Accordingly, site workers need to be equipped to work with these projects in different conditions (e.g. weather) as screw-ups with novel cements could decelerate further uptake of these products.

Lack of personnel experience is a major barrier to execute novel cement implementation. Experience and training for contractors and on-site workers to use these products may help minimize logistical issues. These efforts would not only boost confidence in technologies if properly executed but also boost confidence in implementation abilities.

Finally, adopting novel cements can in itself create logistical issues. In some ways, OPC is a silver-bullet technology. Switching to procuring several novel cements to compete with the 'ultimate tried and true' cement will generally involve additional transaction costs (e.g. procurement hassle, training requirements). Even if some wish to procure novel cements, enthusiasm to deal with additional logistical considerations may not be strong enough for execution. Accordingly, due to the early development stages of most novel cements, initial adopters may need to be willing to undergo some logistical hurdles.

5.4.4 Cost / Financing

While some customers are willing to accept small price increases for sustainability or specialty features, most are too highly price-sensitive to do so. As cement producers already have small profit margins, accepting significant capital or marginal cost increases will likely be too prohibitive to adopt new technologies. Accordingly, optimizing supply-side production costs may be the only economically feasible way to sell these products without significantly raising prices. Within marginal costs, raw material costs become very influential, however, it is difficult to compete with the already inexpensive limestone. On the other hand, financing is needed for the development and expansion of novel cement SMEs, while funding is needed by demand-actors to test and pilot these technologies.

As the price of cement has a small impact on end-customers' project costs, they may be much less price-sensitive and more willing to adopt price increases associated with novel or green cement implementation. Coordinating the passing-down of these costs to the end-users through the demand-chain structure, however, could be very logistically challenging and infeasible.

5.4.5 Material Resource Availability

Due to differences in regional availability and material pricing, novel cement technologies using more limited resources may only be feasible in current locations during the short term. These limitations may decrease incentives and viability in developing these technologies. Future resource limitations also pose the question if novel cement technologies prioritized for development should be those most feasible in the short term (e.g. slags and fly ash) or those with greater resource availability from a long-term perspective. Many materials like calcined clays, volcanic ash, and limestone fines are all the focus of current research and could play significant roles in the development of both novel and blended cements.

5.4.6 Competing with Other Green Cements/Concretes

Novel cements can be seen as competing with both established, widely available blended cements and smaller green technologies (e.g. CarbonCure, Blue Planet). The focus of many interviews and resources fixated more around blended cements or other green technologies than novel cements raising two potential questions: 1) are novel cements a viable or good technology choice and 2) how do they line up in comparison with other technologies? Some suggested that novel cements will not achieve wide success due to performance compromises and typically higher prices while other technologies offer cheaper decarbonization potential. While this sentiment was not shared by all interviewees or literature, blended cements are more developed and proven than novel cements and may accordingly seize some demand from those that may otherwise be potentially interested in novel cements. Other niche, innovative technologies like CCU, green aggregates, and admixtures also have similar decarbonizing attributes to novel cements. While decarbonizing technologies can in some ways compete with one another, they can also be supportive in raising awareness surrounding the existence of green cements and other mitigation mechanisms. Ultimately, decreasing carbon emissions is the main goal of technology development so success of other technologies is valuable. Yet as no single technology can achieve long-term reduction goals alone the development of multiple technologies, like novel cements, is essential. Preparing 'higher hanging fruit' to be deployed if/once the sector begins to maximize reductions from blended cements will help achieve and accelerate further decarbonization. On this note, multiple technologies can be used within the same projects to achieve greater emissions reductions.

5.5 Paths Forward

Various business strategies, policy options, and collaboration opportunities were proposed to help diminish barriers and leverage demand-drivers to propel the commercialization of novel cements.

5.5.1 Business Strategies

Providing a more **service-based approach** was agreed upon to likely reduce risk aversion and other barriers for customers, especially when paired with **legal and fiscal risk adoption**. Increased levels of vertical integration may help to enhance the feasibility of this. However, as many novel cement companies already deal directly with customers, they may already be sufficiently situated to do so. A hybrid version of this risk adoption could take the form of **longer warrantees and performance guarantees**. Few concrete producers and construction services in general offer long term guarantees (generally one-year builders' guarantee). Longer-backed guarantees could decrease financial risk aversion. However, as most are attracted to concrete products with longevity over 30 years, having drastically long-term warrantees may become less feasible. Notably, concerns were raised surrounding financial backing of SMEs in both implementing this strategy and in wider demand considerations (i.e. if SMEs in particular do not have or are not perceived to have sufficient financial backing, customers may be more averse in working with them).

For end-customers, cement and concrete products typically constitute a small proportion of total project costs. Further, end-customers are likely more willing than other demand-chain actors to accept price increases, even if doubled (however, concerns and sensitivity to housing prices could make housing markets more sensitive). Service-based approaches could help pass costs down the demand-chain adding value through personalized service and enhanced communication with consumers while mitigating barriers surrounding novel cements being more costly. Moreover, without enhanced communication other demand-chain actors may not be aware that customers are willing to pay a premium for these products.

Cement is often regarded as a commodity, but in reality, numerous specialty cements make this sector more differentiated than that of a pure commodity market. Given this, results pointed to **enhanced marketing** as a potential means to increase awareness surrounding novel cement products and in creating more lasting relationships with customers.

Some companies have also **integrated sustainability as a key part of their overall business strategy**. Being a market leader in terms of sustainability can help both meet demand for green attributes and bolster awareness of green technologies. It can also potentially increase companies' overall demand and provide potential first-mover advantages from sustainability in the event that demand for green cements increases drastically in the future.

Some novel cement companies, rather than selling their own products, **sell green cement technologies** or concepts to existing cement/concrete companies. This is reliant on other companies having resources to be able to implement these technologies but could potentially increase speed of dispersion, as multiple companies could be able to adopt the same technologies simultaneously. Further, this approach could capitalize on resources (e.g. finances, existing customer bases, reputation) of more established companies that SMEs may lack.

Focusing on niche applications, optimizing novel cements for these specific contexts, and marketing them to corresponding customer groups is another strategy already employed by many. Upon wider implementation of novel cements in these niche applications, increased abundant, demonstrated success may help lower risk aversion for new customers, both in these niches and beyond. While this strategy was supported by all interviewee subjects, consensus surrounding whether novel cements can ever have a place in larger markets outside of niche applications was not unanimous. As discussed in the previous sections, there are multiple classifications of niches (e.g. manufacturing method, application, customer base). Preferably, each of these could be optimized, however, this 'perfect storm' of conditions may not exist in reality.

5.5.2 Policy Strategies

While not an initial focus of this research, policy options arose in both the literature review and interviews as playing key roles in product and demand propulsion. Policy paths potentially helping to promote uptake of novel cements include:

The introduction of **emissions pricing mechanisms** (e.g. cap-and-trade programs or carbon taxes) or significant price increases in existing trading schemes or taxes would provide strong incentives to manufacturers. They will likely only be effective in spurring significant development in green cement technologies if prices are far higher than present levels. While carbon pricing mechanisms are predominately supply-side drivers, supply pressures can encourage manufacturers to push green products helping to induce demand from the top-down. They may also further incentivize the development of greener technologies like novel cements and allow for tackling some 'higher hanging fruit'. **Tax incentives** can also be an economic tool to encourage novel cement adoption.

Regulatory approaches also arose like 'Buy Clean' laws, mandatory technology adoption, and restrictions surrounding clinker ratios. Similarly, **public procurement standards or incentives** can help stimulate demand. Public sector actors consume large amounts of cement and typically have substantial influence on other public organizations having potential to create sorts of 'domino effects' in adoption. Several public sector groups are already pursuing novel cements, and some discussed willingness to accept minor price increases. Conversely, however, this sector is notorious for being slow to change.

Novel cement or low-clinker inclusion in **sustainability certifications programs** (e.g. Green Star, Infrastructure Sustainability, LEED, BREEM, etc.) provides positive incentives to incorporate green products while potentially helping boost awareness of these cement/concretes. Some policies require project certifications in some cases encouraging these impacts. **Informational tools**, like **EPDs,** can help increase awareness surrounding relative emissions of products and can be used in substantiating other regulatory policies. From the supply-side, policies can also help increase the **accessibility of waste materials** to be used as SCMs in both novel and blended cements.

In some cases, **government leadership** can also serve a role in encouraging novel cement consideration. **National and regional targeting setting** can help to garner leadership and raise sustainability-related awareness. Finally, **pilot projects** pursued by the public sector (or the private sector) can help to demonstrate viability addressing lack of demonstrated performance, one of the main complaints concerning novel cements. Finally, **public funding of novel cement R&D, testing, vetting, and financing of infrastructure** would help to address additional supply-side barriers.

Policy changes require motivated actors to drive and support them. To attain industry buy-in and additional support for some of these policies, anti-competitive concerns may need to be addressed. Essentially, restrictions placed on cements were recommended by some to apply to all cement and building products within a given market so that none are faced with greatly heightened competition from cheaper, non-green products if these policies raise cement prices. This implies that restrictions should apply to all building materials as opposed to being sector specific. Further, despite most cement markets being highly localized, some argue that restrictions should apply to imports as well. Another consideration posed by industry groups was the potentially misguiding nature of policies setting targets or restrictions based on clinker content thresholds. As types of cements/concretes required in projects can be so highly variable given the need for certain performance characteristics in different applications, comparison of sustainability indictors for different products can be misleading (i.e. clinker restrictions may be too strict for certain products while too lenient for others). Alternatively, products should be assessed relative to others with similar characteristics and targets set at project levels. Certain software can help achieve this.

5.5.3 Collaboration

While there may be some degrees of conflicting interests between competing large cement/concrete manufacturers and smaller, start-up-like companies, other actors like industry groups, non-vertically integrated concrete companies, and policy actors may have a vested interest in propelling novel cements forward. Seemingly, degrees of collaboration within the sector are already beginning to increase concerning decarbonizing cement technologies (e.g. one organization's webinar hits relating to these topics reaching all-time highs).

Major demand and supply barriers relate to lack of awareness, knowledge, and experience with how specifically to deal with novel cements. Given the many types of novel cements and rapidly expanding realm, **consistent learning opportunities** can help actors stay informed and grasp opportunities within the field. Various forms of collaboration can enhance sharing of existing knowledge to better equip actors in decision-making concerning novel cements and successful execution of projects. For instance, trainings, webinars, and workshops tailored to specific actor groups can help increase familiarity with these technologies and how to implement them. Both industry groups and cement companies put on these sorts of events. Actors across demand and supply chains need to be able to understand these products and how to use them, particularly those installing them like contractors and site workers.

Close connections between manufacturers and demand-side actors and customers can also be extremely beneficial in convincing demand-side decision makers to try green or novel cements. Manufacturers can be well equipped to answer ranges of questions from technical features to performance examples to logistical considerations on construction-sites. Further, manufacturers can help bridge gaps between different actors within the demand-side. For instance, architects, who often promote these technologies, may not be able to respond to concerns posed by structural engineers. Manufacturers can help address these concerns while helping translate sustainability drivers back to the engineers.

While R&D budgets for various actors can be quite limited, combining forces in terms of **research funding or other resources** may help accelerate development of new novel cements, improve performance characteristics and reliability, and demonstrate proven testing of existing novel cements. Research consortiums and other **mechanisms to share research** can also be important, especially in building cases for these products through existing success stories.

Industry groups and trade associations can provide valuable services like information provision surrounding statuses of novel cements (e.g. trainings, established EPD industry baselines), pursuing policy changes, and providing sorts of consulting services to members to increase sustainability. Given the lack of personnel dedicated to decarbonization technologies within the industry, these groups can help compensate for this through executing research, promoting best practices in green cement development, and providing services to help companies sell and acquire these products.

In pushing for major industry changes – whether implementing policies, advocating for standards changes, pursuing novel cement start-ups, or taking a perceived risk in product adoption – driven individuals and human capital are needed to drive major change, especially in an industry with limited lobbying power and marketing potential. Further, personnel experience in working with novel cements and other green technologies is critical in the success and pursuit of these products. Education can help prepare professionals to take on novel cement projects, and awareness building can help spur interest in these issues and widen awareness amongst those willing to consider helping implement these changes.

5.6 Wider Implications

Regional differences play a major role in differentiating various existing landscapes. These include divergence in policies, material availability, standards, sustainability interest, numbers of existing pilot projects, and more, all affecting barriers and drivers. Ideally, novel cement ventures will arise first in locations with optimal features to foster rapid uptake (e.g. access to cheap materials, conducive standards and policies, and pre-established novel cement markets).

Despite collective discussion of novel cements in this thesis, individual novel cement technologies vary significantly. Accordingly, selection of novel cement technologies to pursue in a given landscape needs to be optimized to the market conditions (e.g. material availability, ability to retrofit existing plants, existing infrastructure, etc.). However, in reality, technology options are largely at the mercy of available chemistries and surrounding comprehension.

In some ways, OPC can be seen as silver bullet technology in most aspects except sustainability (e.g. inexpensive, widely applicable, optimized manufacturing, widespread familiarity with use and execution). Transitioning from a seeming silver bullet technology to the use of several products can inherently generate logistical and burdensome challenges requiring significant drive and exertion from organizations and individuals to overcome.

For the most part, consensus was reached that there is no green 'silver bullet' technology. Accordingly a mix of green technologies is required and advantageous to pursue from a global perspective. In order to achieve effective technology mixes, strategy and policy mixes are likely necessitated as well. While novel cements may currently be perceived as 'higher hanging fruit', they may receive more attention if/once impacts of other technologies begin to saturate. Dedicating attention to 'higher hanging fruits' in the meantime, however, can help attain head starts in their development helping to accelerate longer-term deep decarbonization.

While the scope of this research perhaps generates less conclusive findings than if it had been narrower, the importance of global engagement in decarbonizing this sector is imperative to achieve deep emission reductions. Deep decarbonization in a singular region or plant, will be incredibly challenging in this sector, especially given demand barriers. Yet smaller cuts in emissions intensity achieved globally can be cumulatively extremely significant. This further undermines benefits of successful technologies being globally applicable.

Major industry shifts could rapidly change the cement sector landscape and implications for novel cement drivers and barriers. For instance, discovery of a new, well-operating novel cement technology or the launch of a new carbon tax could drastically and quickly change circumstances. In event of these radical changes, parts of the findings of this research could become outdated.

6 Conclusion

Concrete has unique value as a construction material whose demand cannot be met by any other building material in the near future. Accordingly, significantly improving climate impacts of this sector and of the wider construction sector, requires addressing process emissions. With limits to blended cement penetration, and challenges and price concerns relating to CCS, novel cements are likely necessitated to achieve deep emission cuts. Demand for novel cements both necessitates and supports the commercialization of these products; the economic and business viability of these products will enable their market presence by allowing this demand to exist. Accordingly, propelling development and accelerating commercialization of these products is essential in their contribution to innovative emissions reductions.

The exploratory and at times anecdotal nature of this thesis helped to generate findings surrounding novel cements' market trajectory and landscape as a whole. However, conclusions are likely less applicable in specific market contexts as various conditions within particular settings necessitate tailored solutions which are not prescribed in this thesis (i.e. not all paths forward can be implemented successfully in all contexts). Differing context-specific nuances and implications should be seen not only through a geographic lens, but also through a technology-specific one. While novel cements were for the most part discussed collectively in this research, differences in chemistries, decarbonization potential, manufacturing techniques, material constituents, performance characteristics, costs, and much more shape various circumstances and conditions in which each of these technologies can thrive. Accordingly, novel cements need to be individually understood, recognized, and separated for them to be propelled.

More conclusions formulated broadly by RQ topic can be found in the following sections:

6.1 Niche Management & Optimization

Consensus amongst interviewees and consulted literature endorsed targeting of niche market segments to incubate, develop, and commercialize novel cement products (these niches referring to various classification categories). Offering superior performance characteristics to OPC can help niche products not only generate demand but also address price acceptance concerns as customers are often willing to pay premiums for specialty cements. Applications for which novel cements are not only sufficient but offer superior attributes, like specialty cements, may serve as ideal niches to devote initial commercialization attention towards due to their superior value proposition. Upon successful development within various niches, proof of concept and performance confidence will likely grow. Accordingly, novel cements could follow a similar trajectory to the demand of blended cements which were faced with initial risk aversion and were not sustainability-driven but are now largely met with confidence and green-driven demand.

In addition to advantages posed by certain manufacturing methods (e.g. pre-cast) and certain types of applications (e.g. non-structural slabs), unique customer groups can also be targeted to optimize initial uptake of novel cements. In addition to ownership characteristics, those with vested sustainability interests or pressure (e.g. municipalities with embodied carbon footprint goals, companies looking to increase sustainability with limited remaining options), may be incentivized to not just take perceived risks on new products, but also exert efforts and transaction costs in changing procurement and practices that may be too burdensome for others. Customers who require specialty attributes (e.g. high acidity withstanding in wastewater infrastructure) may also be ideal to target. Even better would be the intersection of the two driven groups, perhaps certain public sector organizations.

Differing conditions due to regional dissimilarities also shape the preferentiality of certain niche applications or products. On this note, finding or optimizing a 'perfect storm' of various niches may help amplify benefits of niche-targeting (e.g. selling pre-cast slabs for non-structural purposes to sustainability-driven actors tailored to other regional characteristics). However, this may be difficult or infeasible in practice. Once novel cements have proven viability within niches and have been further visibly demonstrated (building awareness of both novel cement existence and success), potential risk aversion levels may decrease within these niche applications and beyond. And so, niches can possibly serve as a foothold for products to develop further, become commercialized, and more widely implemented. There was not, however, unanimous consensus amongst interviewees that novel cements can achieve wide-spread, successful commercialization beyond these niches.

6.2 Demand-Side Landscape

The general cement industry is structured like that of a commodity. With very slim margins, this sector is a difficult one to make money in. Larger incumbent players currently do not have enough incentive to widely pursue novel cement products. While wide-spread implementation may be widely reliant on incumbent adoption, SMEs are left to incubate, develop, and commercialize these innovative products in the present. Once these technologies achieve degrees of success within niche markets and limited customer bases, larger incumbents might be more incentivized to participate and focus on these markets.

While greening demand is currently not strong enough to drastically move these novel cements, this may grow in the future with the potential to increase general demand for green cement and concrete products substantially. Further, other major landscape shifts or rapid market transformations (e.g. drastic increases in carbon-pricing mechanisms) could provide sufficient drive and pressure to spur major change by larger incumbents.

Various types of actor collaboration can help boost awareness and address questions or uncertainties within demand chains. This can be especially vital within the construction sector due to its make-up of numerous actors and convoluted decision-making chains. Actors outside of the industry purview, like policy makers, can also have significant roles to play in shaping the demand landscape for novel cements. General engagement of a broad range of actor groups may help in diminishing wider breadths of barriers.

6.3 Barriers

Results underlined the interconnection and reinforcement between demand- and supply-side barriers. Several key demand-side barriers and additionally relevant supply-side barriers inhibiting the widespread adoption of novel cements were identified and include:

Table 6-1. Novel Cement Barriers Summary Table.

Novel Cement Barriers	
Risk aversion due to 1) safety and liability concerns and 2) long-term durability	Demand-side
Substantiated and unsubstantiated concerns regarding material characteristics or performance, even benign differences	
Potentially higher price points	
Lack of inclusion in standards, codes, and specifications	

Lack of awareness of product or technology existence or how to pursue	
Implementation/logistical challenges	
Lack of existence or awareness of demonstration/pilot projects	
Insufficient research and product-vetting resources of demand-actors	
Competition with other green cement/concrete products	
General lack of incentive to move away from a proven, familiar, inexpensive product when lacking desirability of unique qualities or sustainability	
Financing, implementation costs, and operating costs	Supply-side
Implementation/logistical challenges	
Material availability and pricing	
Stranded asset potential	
Lack of incentive to change, specifically for larger companies with existing business models; potential undermining of these proven models	

Barriers classified as being most prominent diverged significantly depending on the context in question (e.g. transportation vs. building sector, country of implementation, etc.). However, risk aversion, concern with performance characteristics, and standards/specifications were likely the most universal. Differences in experienced barriers perhaps encourage actors to prioritize efforts surrounding those most pertinent in their specific context. Finally, consensus underlined that diminishing barriers will not necessarily generate demand. Further, demand may not even facilitate novel cement dispersion as supply-sides need to be able to profit in producing these products, pulling aspects of the wider landscape into play. Accordingly, some of these wider considerations will need to be accounted for in successfully mass deploying novel cements.

6.4 Paths Forward

Results brought to light various strategies or changes to potentially both accelerate development and commercialization and diminish aforementioned demand barriers. These key actions were identified and include:

Table 6-2. Paths Forward Summary Table.

Path Forwards	
Service-based business model, with possible risk adoption	Business strategies (manufacturer perspective)
Targeting niche applications	
Heightened marketing and customer engagement	
Mandated EPDs for all cement, concrete, and/or building material products	Policy options

Procurement requirements and/or incentives (e.g. focusing on decreased clinker content, use of green cements)	
Implementation or raising of carbon-pricing schemes	
Increased resources for research and testing surrounding novel cements in public sector	
Awareness boosting (e.g. trainings, conferences, webinars, symposiums)	Actor Collaboration
Industry groups' services (e.g. trainings, awareness building, resource/information sharing, specification modification services, policy lobbying, provision of industry baselines, promotion of and EPD services)	
Information and research sharing	
Pooling of research resources and efforts through research symposiums	
Various actors lobbying together for standardization change or creation including or permitting novel cements	
Demand-side actors modifying project specifications to include or permit novel cements	Other
Inclusion or magnification of green cement criteria in sustainability certifications	
Goal setting surrounding normalized embodied carbon levels or clinker content	

While the initial focus on paths forward exclusively surrounded business strategies, other pathways like policy adoption and collaborative opportunities continuously arose organically throughout the research process. This may imply both needs for and willingness to drive change from multiple directions within the larger industry landscape. Though this research focused on ways to propel novel cements, penalizing the use of OPC is another mechanism unexplored in this research that could also indirectly increase demand for novel cements.

6.5 Implications for a greener cement industry

One major theme found in this research was potential competition between novel and blended cements. With wide acceptance and demonstrated success of blended cements and similar emissions reduction potentials to currently developed novel cements, from risk aversion and sustainability-driven demand standpoints, there is not much incentive to choose novel cements over other products. While one could view these product categories in direct competition for sustainability-driven demand and for shared material constituents, unique characteristics of certain novel cements could help differentiate their own demand. Further one could view the success of either product segment as helping to increase awareness of green cements in general and as strengthening supply chains and know-how concerning raw material use. From a broader sustainability perspective, competition is not necessarily bad as adoption of any low-carbon product will contribute to emission reduction targets. Nonetheless, from a longer-term perspective, the current and continuous development and propulsion of novel cements may help hasten continuing reductions once those from blended cements or other technologies have saturated, as novel cements will then be more prepared for deployment. This feeds into the notion of a sentiment shared in both interviews and literature: there **needs to be a technology mix** as the development of a silver bullet technology within the green cement and concrete sectors is highly unlikely, and no single technology is able to decarbonize the sector alone.

Another major theme, relating to numerous geographic differences, is that contrary to how some SME novel cement companies may market their products, there is likely **no novel cement silver bullet technology.** Material availability and costs, standard variations, and policy differences all incentivize different sorts of cement chemistries. This on one hand suggests that novel cements should be developed and optimized to fit their local markets. On the other hand, however, from a global perspective, focusing on technologies that could be more widely applicable could increase global emissions reductions further. Much novel cement innovation comes from the U.S., Australia, and Europe, but these countries make up relatively little market share. While China, India, and other developing countries comprise well over half of future demand, ideally solutions developed elsewhere will be transferable to these regions if not developed there themselves. This presents a contrast in optimizing technologies to thrive in niches vs. creating broadly applicable products.

If novel cements are successfully commercialized, several may be applicable in different applications within the same project. **Widening product availability** will likely complicate procurement and other implementation considerations. Accordingly, buy-in and enthusiasm from actors along demand-chains can help overcome additional transaction costs associated with these shifts. Further, in order to achieve significant changes in industry landscape, committed actors or groups of actors will be necessary to push things like policy and standard changes, pilot projects, and experimentation with new business strategies. Accordingly, the importance of **committed human capital** in actors throughout the industry should not be underestimated.

Many points and topics that arose during interviews were not found in literature and vice-versa. This could perhaps exemplify lacking formalized discourse surrounding market landscape and/or imply lacking collaboration and centralized focus in addressing decarbonization concerns. Due to limited power of novel cement SMEs, wider industry and stakeholder collaboration is likely needed to accelerate the progression of novel cements. However, release of market-based research and interviews citing increased focus and collaboration together suggest that the pursuit of these needs may have already begun. As novel cement development progresses, closer examination of specific novel cement technologies, specific markets, and the intersection of the two may help provide industry actors with more prescriptive pathways in progressing these technologies further.

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Appendix

Appendix A: Green Cement/Concrete SME Technology List

Company/Product	Category	Technology	Country of Origin
Aether	Novel cement	BYF clinker	EU
LC3		Calcined clays	HQ in Switzerland, piloted in Cuba and India
Celitement		Calcium silicate hydrates	Germany
Schwenk Goup		Calcium silicate hydrates	Germany
Calera Cement		Calcium-carbonate based	US
Zeobond		Geopolymers	Australia
BanahUK		Geopolymers	UK
Cemex's Vertua/Vertua Ultra Zero		Geopolymers	Mexico HQ, products offered in UK
Wagner's Earth Friendly Concrete		Geopolymers	Australia
CeraTech's Ekkomaxx		Hydraulic binders (95% fly ash, 5% liquid additives)	US
US Gypsum's Grancrete		Magnesium-based	US
Ceramicrete' (Argonne National Laboratories)		Magnesium-based	US
Novacem		Magnesium-based	UK/Australia
TecEco - Eco Cement		Magnesium-based	Australia
Rocla		Geopolymers	South Africa
NuRock		Geopolymers	Australia
Murray and Roberts		Geopolymers	South Africa
Solida		OPC constituents; lower firing temperature; carbonation-hardening based on calcium silicates	US
BioMason	Miscellaneous	Microorganism- and sand- based brick making	US
EcoCem		Low-clinker (GGBS)	Ireland
EMC		Low-clinker (natural pozzolans)	Sweden
Calix Limited / LEILAC	CCS	Superheated steam & direct separation of CO2	Australia
BluePlanet	Carbon Curing	CO2 capture and CO2 sequestered aggregates	US
Carbon8		Accelerated-carbonation	UK
CarbonCure Technologies		Mineral carbonation	Canada
Carbon Upcycling Technologies		Mineral carbonation	Canada

Appendix B: Sample Interview Questions

The questions below exemplify some posed to interviewee subjects. As interviews were flexible, this list in not exhaustive, and many of these questions were tailored more specifically towards the background and experiences of the subject:

Demand:

- Demand side barriers and risk aversion rest on there even being demand in the first place, so is there demand?
- Do you see a lack of demand due to barriers (e.g. risk aversion) or just due to a lack of demand drivers?
- Do you see demand stemming more from the decarbonizing benefits or unique/differentiating physical properties?
- How can demand/uptake for novel cements be differentiated from blended cements/other green cements/SCMs?
- Which actors along the demand-chain are driving demand for novel cements (or SCMs if novel cements not considered?)

Barriers and risk aversion:

- How large of a barrier do you see demand-side risk aversion as in relation to other barriers?
- What are the main categories of risk considered with novel cement use (e.g. safety, legal, uncertain properties like decreased longevity, construction challenges) from your company's perspective?
- Which actors in your organization are involved in the decision-making process when it comes to construction material risk? Who has the final say?
- If novel cements or SCMs are currently used, do you have any insights on what that technology adoption process looked like from your company's perspective? (mostly for end-of-chain actors)
- Which actors along the demand-chain are most concerned with the main risks perceived?
- How does risk perception, risk aversion, or risk management strategies differ by customer type?

Testing and standardization:

- If lab tests successfully demonstrate viability (e.g. pourability, set time, strength development), would this be enough to consider piloting/utilizing?
- Is it about using cement that has gone through certain types of testing or those that are included in certain sets of standards? (if so which sets of standards?)
- What are your interactions or potential interactions with institutions like standards committees and other institutions that set guidelines and how can these be optimized?
- Will opening standards help to drive demand and/or lower risk aversion towards adoption?
- How would you describe the process in changing standards? Could it be accelerated at all?
- Do additional funding and resources play potential roles? Who would this come from?

For cement SMEs:

- Which stakeholder groups within the demand-chain do you work most closely with? Does it ever get down to end-client building/infrastructure level?
- How do you see novel cement producers' roles in shaping the demand for these products if at all?
- Do you see competing/various alternative cement technologies as mutually exclusive, competitive, or how can they work together to help build demand?

For demand-side actors:

- General interest in novel cements – as its own question? – have you ever considered the use of novel cements and/or is this of any interest to your company?
- Would you be willing to pay a premium for carbon-sequestering/mitigating services?
- Would you be willing to consider additional risk for carbon-sequestering/mitigating services?

For industry groups:

- Which stakeholders do cement groups work most closely with?
- What are industry groups' roles in standardizations, testing, and communicating risk (or lack thereof) to potential consumers?

For downstream actors:

- How would you describe the interactions between the architects, structural engineers, client, and contractors in selecting building materials/cement/concrete types?

Effects of demand issues on business models:

- Will increased demand actually help your company propel forward (in the short- and long-term)? Or are demand-side issues not a major barrier you're dealing with right now.
- Where do you see your clients coming from in the short-term (e.g. buildings vs. infrastructure, public vs. private sector)? And how/do you see this shifting in the future?
- More service-oriented business models seem to come up a lot in literature and discussions in this field. Do you see a more service-oriented approach as a viable approach to increase demand? Do you see a more service-oriented approach as a viable approach to deal with risk aversion of potential clients?
- Does risk aversion tie into the focus on pre-cast application? I.e. do pre-cast applications somehow have less risk

Miscellaneous:

- Do you think there will be a silver bullet novel cement or how do you see the field playing out?
- Do you see alternative cements becoming mainstream in the near future as opposed to remaining in niche markets?
- Which markets (geographically) do you see novel cements taking off first?
- Are there certain niche products that you see novel cements being best for and/or taking off first?
- How big of a factor are the building/ construction aspects (e.g. set time, easy to pour, etc.) in various stakeholders decision-making processes?

- Have you used building information modeling at all (BIM)? Do you see this as a useful tool in making more collaborative decisions with other actors on building materials? (for downstream actors)

Appendix C: Select Novel Cement Categorization Descriptions

Note: these categorizations and summaries developed as part of a pre-study for this thesis are limited to major broad categorizations found in literature and should not be considered to be an exhaustive list of all types of novel cements.

Calcium sulfoaluminate (CSA) cements: CSA cements are the only novel cement in widespread use on an industrial scale having been utilized in China since the late 1970's. CSAs are classified as containing limestone-based clinker containing belite and ye'elimite. Its qualities and strength characteristics are similar to OPC's and can in principle be produced in OPC plants (Imbabi et al., 2012). CSA produces lower GHG emissions than OPC due to decreased calcination emissions and lower processing temperatures (1250 to 1350°C) (Imbabi et al., 2012), achieving up to 25% energy savings (*What is CSA Cement?*, n.d.). Estimates of GHG emissions reductions range from 20% (Imbabi et al., 2012) to 62% (*What is CSA Cement?*, n.d.). Costs of materials are currently greater than those of OPC (Lehne & Preston, 2018).

Belite–ye'elimite–ferrite (BYF) cements: The components of BYF cements are similar to those of CSA cements (Gota et al., 2016), but are uniquely classified by the quantity of belite > ye'elimite > ferrite. This classification of cement is well recognized and covered under many existing concrete and cement and standards, yet is not widely used due in part to low early-age strength and perception as being of equal or lower quality than traditional CSA cements (Ellis Gartner & Hirao, 2015). BYF production have relatively low GHG emissions reductions stated as low as around 10% (Ellis Gartner & Hirao, 2015; Lehne & Preston, 2018). Intermediate CSA cements, a mixture of traditional CSA cements and belite-rich cements, have been the focus of recent research. These technologies are still in development stages with relatively little information of its performance in academic literature and no inclusion in industry standards. The EU-funded "Aether" project developed by LafarageHolcim has developed a BYF clinker and conducted initial quality testing with reported CO2 emissions reductions of at least 20% through decreased limestone usage and lower processing temperatures (Lehne & Preston, 2018). Aether's BYF cements, however, have been found to face similar durability issues to OPC clinker with high SCM levels (Ellis Gartner & Hirao, 2015). Vicat and HeidelbergCement are other European cement manufacturers that have also been working to develop BYF clinkers, however, BYF cements are not currently cost-competitive with OPC due to raw material costs (Lehne & Preston, 2018).

Calcium aluminate and calcium alumina-silicate cements: These are also limestone-based cements, but instead of using typical calcium silicates found in clays, they utilizes bauxite (an aluminum ore). The rest of the manufacturing process is the same as OPC's. Its differing properties from OPC include high early-stage strength and its high heat and chemical resistance. The production of this cement has a lower CO2 footprint. It is also more expensive to make than OPC. (Imbabi et al., 2012)

Super sulfated cements: These cements are limestone-based and consist of 80–85% selected GGBS, 10–15% calcium sulfate, and 5% OPC clinker. They are typically used when exposure to high sulfates, acids, or organic oils are expected. The costs to produce these cements is significantly higher than those of OPC due to material availability limitations (Imbabi et al., 2012).

Magnesium-based cements (magnesium oxide/magnesium silicates/magnesium carbonate based): Water-activated-magnesium-oxide based cements have been used since ancient times. Their production uses approximately 30% less energy than OPC (Ellis Gartner & Hirao, 2015). In comparison to OPC, these cements are more permeable, i.e., better to regulate heat, breathable, and stronger. Currently, this cement is used to make 'Grancrete' – a spray-on structural cement, for housing in developing countries, and in wallboard manufacturing in China (Imbabi et al., 2012). Magnesium oxide-based 'Ceramicrete' cements have been tested by Argonne National Laboratories in aims to develop them into commercial products. A small Australian research and development company, TecEco has been one of the first to work with magnesium oxide-based cements and receive patents to utilize this product as a substitute for OPC. They have developed various cement products including Tec-Cements, Eco-Cements and Enviro-Cements using this method (Imbabi et al., 2012).

The production of a carbon-negative magnesium silicate-based cement has been pursued by the company Novacem in partnership with Lafarge and Laing O'Rourke. Their product is said to sequester a net of 100kg of CO2 for every tonne produced. This is due in part to lower temperature requirements in production, these lower temperatures' enabling of biofuel use, and the recycling of CO2 in the production process. Limitations of this technology include that magnesium oxide is not as readily available as limestone with high capital costs necessary to obtain magnesium oxides, costs to integrate with existing cement plants, and uncertainties about long-term strength and durability (Schneider et al., 2011). Trials have demonstrated similar strength to OPC. Since these trials, Novacem was liquidated and its tech and intellectual property was sold to Calix Limited due to financial issues (Imbabi et al., 2012).

Calera cement: In Calera cement production CO2 rich gases are injected and mineralized in sea water through an aqueous precipitation process (Maddalena et al., 2018). The calcium and magnesium in the sea water react with the gaseous CO2 to produce a cement product. This output is stronger than OPC, air permeable, and a "high quality cement". This process imitates the coral structure making process (carbonates) or "marine cement" which utilizes carbon, magnesium, and calcium in sea water to make the coral structure (Imbabi et al., 2012). The Calera Company seems to have reached the most advanced stages of development of this technology having launched a pilot plant, however other labs and research institutes are/have also investigated this concept. Calera has piloted the sale of concretes made from are a blend of Calera cement and OPC, however, they more recently halted their production of these products to shift their focus to other green products (Imbabi et al., 2012; Lehne & Preston, 2018). Potential buyers/clients that have expressed interest in purchasing Calera cement products include the California Department of Transport and a power plant (Imbabi et al., 2012). Calera products are estimated to be able to achieve a capture efficiency of 70-90% of GHG emissions while its inventors assert these products can be carbon-negative (Maddalena et al., 2018).

Carbonation-hardening systems based on calcium silicates: These systems produce a binder cased on calcium silicates that then allow for CO2 to be cured in the concrete making process. Carbonation-assisted curing of concrete made from OPC (often utilizing flue gases) is recognized and practiced in limited precast concrete production, however it is not yet widely commercially viable. (Ellis Gartner & Hirao, 2015). One company, Solida, a US- based start-up has piloted these technologies in which they create a non-hydraulic binder based primarily on wollastonite or pseudo-wollastonite (CaSiO3). The production process uses less energy than OPC manufacturing as the raw materials are easier to grind in the clinker making process and kilns only need to be heated to temperatures as low as 1200 °C decreasing necessitated energy use and enabling the proportion of alternative fuels able to be used. Accordingly manufacturing emissions can be reduced by up to 30% (Schneider et al., 2011). During the concrete production process, CO2 is cured into the cement through a counter-diffusion process in which CO2 gas replaces water inside the concrete pores in a sealed chamber. For every ton of concrete that Solidia cement is used in, approximately 300 kg of CO2 is sequestered. Mechanical properties of Solida-derived concretes are supposedly comparable to OPC, yet chemical properties differ (Ellis Gartner & Hirao, 2015).

Calcium silicate hydrates: These cements are also limestone-based, but differ from OPC in that their carbonates are calcined before processing reducing CO_2 emissions (Lehne & Preston, 2018). Celitement and the Schwenk Group are actively developing these cements with an active pilot plant (U. Dewald et al., 2015; Naranjo et al., 2011). Emissions reductions have been reported to be >50% (Lehne & Preston, 2018). These cements are also said to be capable of being produced at exiting OPC plants with limited retrofits. While said to have a wide-range of potential applications, comparable to those of OPC, they are not currently covered by standardizations (U. Dewald et al., 2015; Lehne & Preston, 2018). Complex manufacturing process demonstration and pilot phase; the development of the first industrial-scale pilot plant was scheduled to deploy 2018 (International Energy Agency, 2018b).