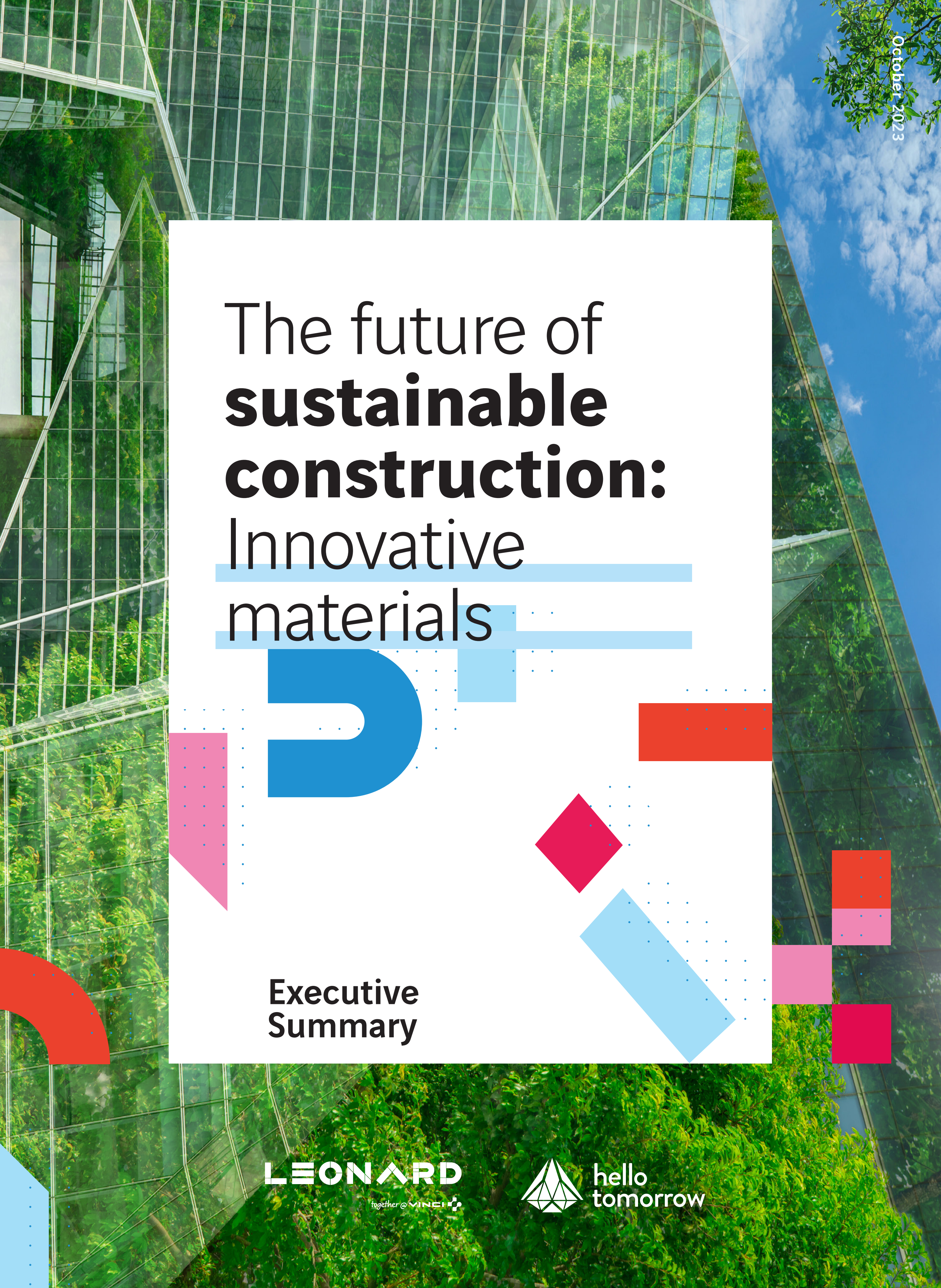

October 2023

The future of **sustainable construction:** Innovative materials

Executive Summary

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Forewords & Acknowledgements

In the light of the escalating climate crisis, the urgency for meticulous diligence, proactive approaches, and heightened awareness in our construction endeavours has never been more paramount. At Leonard's, the foresight and innovation platform of the VINCI group, our purpose is to foster this very awareness. Our mission is to navigate present, imminent, and rising transformations, ensuring that communities are ready to meet both contemporary and emerging challenges. Established in 2017, Leonard has continuously been at the forefront of the debate about the evolution of cities and infrastructure. Therefore, it seems only fitting that we delve deeper into one of the most foundational materials in human history – concrete. From the majestic edifices of ancient Rome to the towering skyscrapers defining our modern skyline, concrete has been a linchpin of architectural milestones. Yet, as we stand at a pivotal juncture where environmental responsibility is not just preferable but indispensable, our journey must be guided by both reflection and radical innovation.

It is imperative to remember that the guidelines governing concrete construction—encompassing material selection, execution, and design—were not established overnight. They have been set after decades of experience and some trial-and-error phases. Nowadays, society is asking for guaranteed safety in every domain and the introduction of new construction materials is not possible unless the reliability of corresponding structures is justified. Fortunately, we don't need any longer extended feedback over decades of use for providing such justification because concrete is more and more understood as far as durability and structural behaviour are concerned, and it can be assessed on these topics through relatively short-term laboratory testing. Anyhow, the newer construction materials incorporated into concrete are different from traditional material, the longer is the time needed for a correct and reliable assessment of possible applications, especially when structural applications are targeted. Due to the great complexity of the material, the evolution of concrete solutions towards decarbonisation is more likely to be gradual than driven by breakthrough solutions.

We would like to thank warmly CEMEX Ventures, NOVA by Saint-Gobain, Saint-Gobain and Zacua Ventures together with professionals from VINCI for their help. The advice and expertise provided by all the interviewed professionals have been of the utmost importance during the writing and assessment of the content of this report. We would also like to thank the members of the committee for the revision and valuable feedback for this project. Finally, this report would not have been possible without Hello Tomorrow. Thank you for supporting Leonard in proving that science and technology have the potential to build together a better future.

Julien Villalongue
Managing Director, Leonard

Introduction

As our society strives towards a sustainable future, the construction industry grapples with **a twofold imperative: the ever-increasing need for housing, coupled with the pressing need to dramatically reduce its ecological footprint.** As one of the planet's largest economic ecosystems, the construction sector shoulders a profound responsibility in the pursuit of global sustainability objectives. Indeed, in 2021, **building operations alone assumed** a substantial role in the global energy landscape, accounting for a share of **30% of the world's final energy consumption and 27% of the total releases emanating from the energy sector.**[1]

The journey towards decarbonisation spans the entire spectrum of activities of the construction industry, enveloping everything from the initial design, extraction and manufacturing of building materials to the construction process itself. Along the value chain, cement production emerges as a central driver propelling global emissions. **As the bedrock of modern construction, it accounts for 7 to 8% of worldwide CO_2 emissions, chiefly due to the energy-intensive characteristics of its manufacturing.**[2] In this context, achieving rapid decarbonisation within the concrete industry hinges on two fundamental approaches: reimagining the methods of production and exploring innovative materials that can provide sustainable alternatives. **These strategies encounter multifaceted challenges** that necessitate the critical involvement and support of deep technologies in redefining the construction landscape and offering new innovative methods and alternatives to concrete production.

In a concerted effort to foster awareness and deepen comprehension regarding the future landscape of cement and cutting-edge materials within the construction industry, Leonard & Hello Tomorrow shaped an analysis encompassing innovative strategies for future concrete and alternative materials usage and production.

Decarbonate the cement production: Deploying breakthrough technologies to meet 2050 climate targets

Concrete dominates as the go-to material in the building industry, accounting for 60% of usage on average[3], overshadowing any other construction materials. However, this material carries a heavy environmental burden, with a staggering **90 to 95% of its carbon footprint attributed to cement**[4]**, with clinker production being a primary culprit.** In response to this environmental challenge, three key levers are being explored today: **reducing the clinker-to-cement ratio, exploring alternative binders, and applying carbon sequestration techniques to concrete factories.**

The first two strategies share a common principle: they involve **adjusting current component proportions and altering the components of concrete** to incorporate greener alternatives, primarily targeting the energy-intensive and emission-heavy phases of production. The methods for producing low-carbon concrete have a long history, yet their application remains somewhat limited to specific use cases. In the short term, this approach not only seems to be the most financially pragmatic but also benefits from a certain level of industry-wide familiarity and acceptance. Nevertheless, it's unlikely to spur a full-scale revolution since prevailing **regulations still mandate a 50% clinker proportion**[5] in the material coupled with the inherent challenges surrounding the substitution of certain materials. While greener concrete solutions are emerging, the real revolution lies in on-site carbon sequestration and achieving a closed production cycle by recycling emitted carbon.

A significant 67% of cement production emissions can be attributed to the chemical reactions involved[6], rendering CO_2 capture a promising approach to curbing the environmental footprint of the concrete industry. Nevertheless, despite ambitious 2030 projections, **only a handful of factories have adopted carbon sequestration technologies**, frequently facing financial and thus scalability challenges. CO_2 recycling, for its part, driven by deep-tech innovations like waste fossilisation and carbonation curing, holds promise for transforming concrete utilisation practices.

For the industry to truly achieve transformative change, construction stakeholders must prioritise sustainable technologies more aggressively. Regulations also have a pivotal role in this transition. **Updated regulatory frameworks that incentivise or even mandate the adoption of these breakthrough technologies can not only fast-track the industry's journey towards sustainability but also provide a clear and level playing field for all stakeholders.** It is an imperative that both industry leaders and regulatory authorities recognise the gravity of the situation and work in tandem to overhaul outdated practices and standards. Because today, while some are currently far from achieving practical applications in construction, primarily due to extended duration required for compliance with safety regulations, numerous initiatives have garnered the attention and interest of industrial players.

Beyond concrete: Material science and biomimicry at the forefront of sustainable construction

Achieving emissions reductions within the sector demands a comprehensive approach harnessing a combination of levers to fully unlock the potential of deep technologies. Delving further into material science, the exploration of the unique properties of materials has unveiled new avenues for sustainable construction. **Two key approaches have emerged in the field: the first involves the modification of existing materials to imbue them with novel properties, while the second entails harnessing new sources for greener materials.**

The former, still in its infancy, relies on structure-changing and energy-exchanging materials. **These deep technologies can reduce environmental impacts by enabling self-sustainability in buildings, reducing maintenance costs, and optimising performance.** However, these technologies are still nascent, grappling with scalability and regulatory challenges. Meanwhile, the latter approach can be achieved by either exploring nature-sourced materials such as mycelium, bamboo, and timber or leveraging biomimicry, resulting in materials with new properties, such as self-healing concrete and self-cleaning surfaces. **Nature-sourced materials have short-term adoption potential due to historical usage and scalability feasibility, although the complete substitution of current materials is uncertain**. Biomimicry, for its part, holds the promise of reducing maintenance costs and offering environmental benefits. While still facing scalability and regulatory challenges, this process has promising prospects, even though widespread, mainstream adoption may not be immediate.

In summary, **the short-term adoption of existing alternative raw materials presents a straightforward and cost-effective path to sustainability. This trend is driven by increasingly stringent regulations promoting a greener industry.** Conversely, innovative techniques related to material enhancements for smart applications represent a more revolutionary yet evolving pathway. This approach must contend with a well-established industry and adhere to high-performance standards. **Although achieving full-scale implementation by 2030 may be challenging, it could become a viable goal for 2050**, particularly for technologies such as mycelium composites, corrosion-detecting coatings, self-healing concrete, and self-healing surfaces that have advanced beyond laboratory-scale experimentation and exhibited impressive performance records.

Our approach

The industry's transition towards net-zero CO_2 emissions constitutes what is arguably the most challenging transformation in its history. Thus, critical decarbonisation levers have been identified to help bring the industry towards net zero (Exhibit 1). **In the present report, we will focus on aspects directly related to construction processes and practices.** Although the significance of energy efficiency and alternative fuels in the broader decarbonisation discourse is undeniable, they are currently at a more advanced development stage, being pioneered by other industries. Furthermore, they will need to be used in combination with the described sustainable materials in order for the construction industry to reach its decarbonation goals.

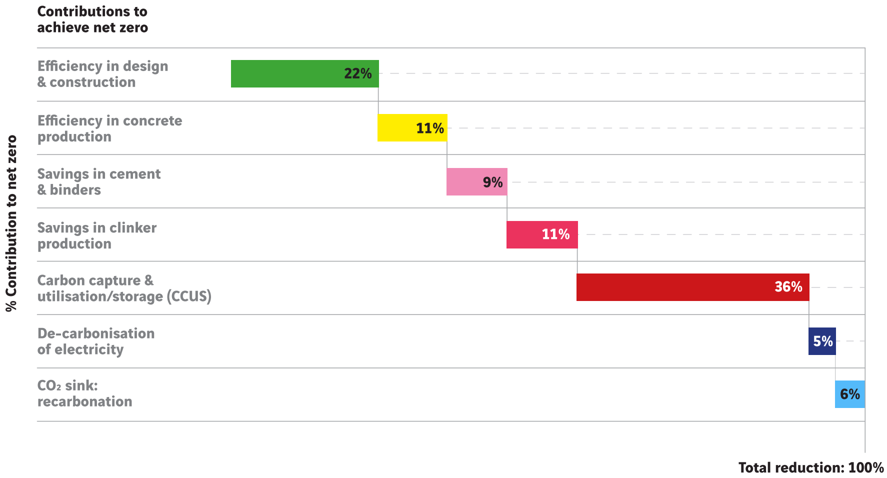


EXHIBIT 1: THE NET ZERO PATHWAY - GCCA

Guided by this framework, our aim has been to study how, through the utilisation of the most promising technologies, each step of the value chain (Exhibit 2) could be enhanced in terms of sustainability. **Certain stages of the value chain are more energy and emissions intensive** than others, and require greater efforts to implement sustainable strategies. For that reason, many solutions are specifically focused on these stages. This is the case of the **extraction of raw materials and manufacturing of products, which represent 65 to 85% of the global embodied carbon emissions** of the entire value chain. Notably, operational emissions at the use and maintenance phase are also of big impact, cumulating 8 to 15% of the global embodied CO_2.[7]

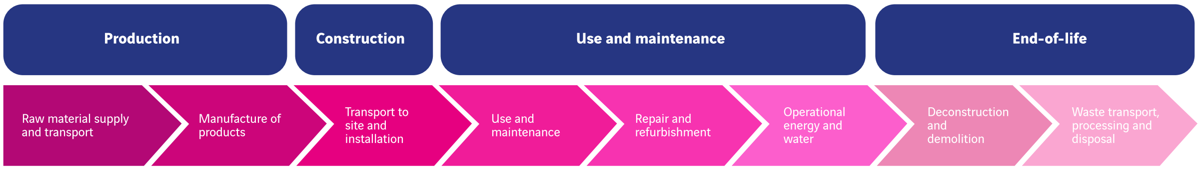


EXHIBIT 2: CONSTRUCTION VALUE CHAIN

This report encompasses an analysis of the construction value chain, considering every step from the production of its materials to the end-of-life of the buildings. **To do so, we have considered the value chain as a fixed framework of distinct stages – production, construction, use and maintenance, and end-of-life.** Each of these has its own set of internal stages, processes, and intricacies, all working in tandem to bring a project to fruition.

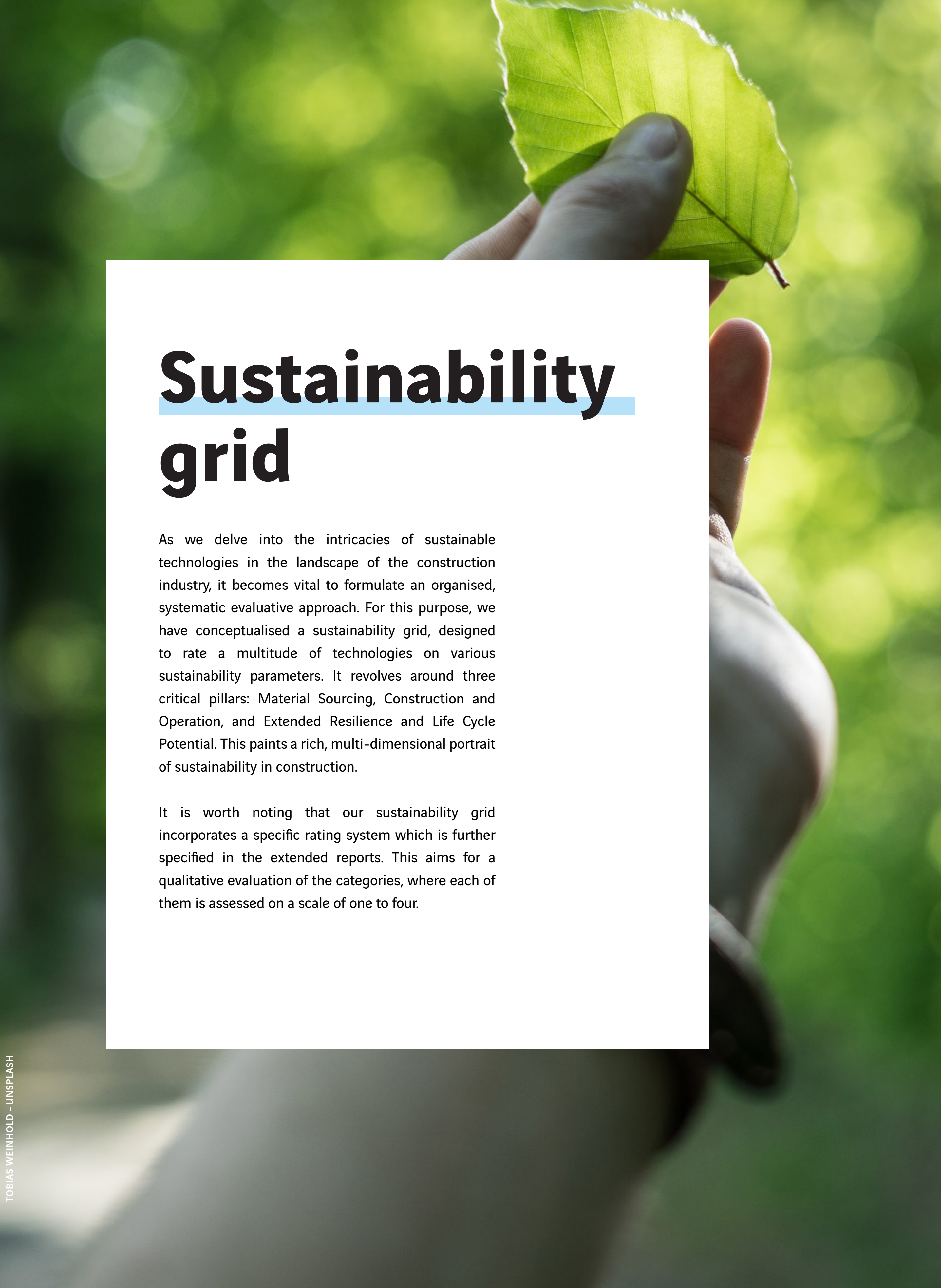
It must be noted that, even if compelling strategies in construction and end-of-life steps do exist, this analysis primarily revolves around advanced, material-centric, deep technologies. Consequently, construction, transportation, and deconstruction processes are acknowledged solely as part of the studied technologies, and not as independent operations.

In the first chapter of the report, the most promising technology trends tackle the production phase of the cement industry, which is acknowledged to be responsible for 0,6 tonnes of CO_2 per tonne of manufactured products.[8] In addition, in the second chapter, an array of novel materials are portrayed, most of which intend to increase the efficiency of the building over its life cycle, without forgetting about its production and appropriate disposal.

Sustainability grid

As we delve into the intricacies of sustainable technologies in the landscape of the construction industry, it becomes vital to formulate an organised, systematic evaluative approach. For this purpose, we have conceptualised a sustainability grid, designed to rate a multitude of technologies on various sustainability parameters. It revolves around three critical pillars: Material Sourcing, Construction and Operation, and Extended Resilience and Life Cycle Potential. This paints a rich, multi-dimensional portrait of sustainability in construction.

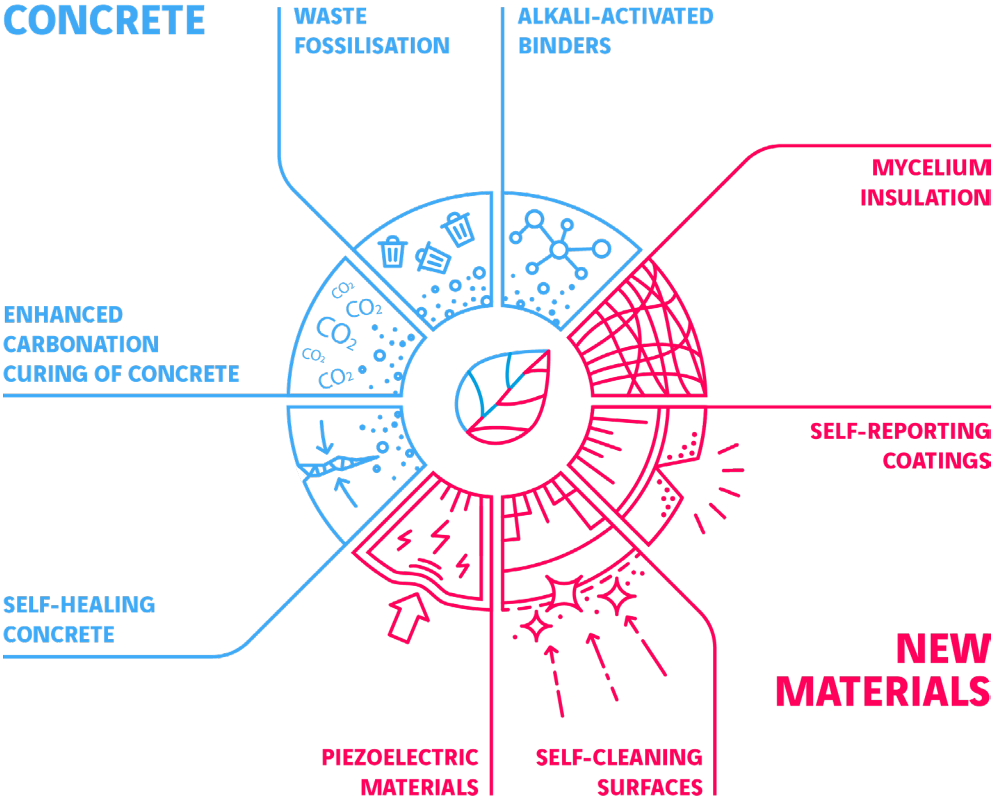
It is worth noting that our sustainability grid incorporates a specific rating system which is further specified in the extended reports. This aims for a qualitative evaluation of the categories, where each of them is assessed on a scale of one to four.



TOBIAS WEINHOLD – UNSPLASH

Technology investigation

Utilizing the framework provided by the sustainability grid, a selection of eight key technologies has been meticulously chosen for an in-depth investigation. These technologies, identified for their potential to significantly contribute to sustainable practices, will undergo a thorough analysis in the extended reports.



CONCRETE

WASTE FOSSILISATION

ALKALI-ACTIVATED BINDERS

ENHANCED CARBONATION CURING OF CONCRETE

SELF-HEALING CONCRETE

NEW MATERIALS

MYCELIUM INSULATION

SELF-REPORTING COATINGS

SELF-CLEANING SURFACES

PIEZOELECTRIC MATERIALS

Part 1: Pathways to sustainable concrete

Cement, a key building block of concrete

Concrete has become, in a matter of decades, the backbone of modern infrastructure, relying on one critical ingredient: cement. This binding agent has woven itself into the very fabric of civilisation, ranking as the world's second-most consumed resource after water.[9] Due to its exceptional availability and mechanical properties, concrete enables the construction of our entire built environment from homes to skyscrapers, roads to dams.

With an ever-increasing demand, global cement production surged to an astounding volume of approximately 4.1 billion tonnes in the year 2022. Given these data and following the upward industry trend in recent years, the International Energy Agency (IEA), in their Reference Technology Scenario (RTS), has forecasted a 12% boost in global cement production by 2050.[10]

This voracious appetite for cement poses a sustainability dilemma

The cement industry plays a substantial role in CO_2 emissions, responsible for approximately 8% of global human-made emissions, equivalent to a staggering 2.9 gigatonnes of CO_2 per year.[6] **Roughly 60% of these emissions result from mineral decomposition (from $CaCO_3$ to CaO), while the remaining portion arises from fuel combustion.[11]** As production continues to rise, a projected 4% increase in direct emissions is anticipated by 2050.[10]

As a result, to align with the sustainability goals set forth in the 2-degree Celsius (°C) Scenario (2DS), **the cement industry must achieve a significant 24% reduction in global direct CO_2 emissions from current levels by 2050.[10]** An urgent imperative compels us to re-evaluate and revolutionise the entire value chain to align with environmental considerations.[12] This transformation demands rapid progress in carbon dioxide reduction strategies, a corresponding regulatory framework, public-private collaboration, sustainable financing mechanisms, and societal acceptance.

The way forward is clear, with pathways under development

Over the recent decades, significant headway has been made in embracing novel technologies to tackle increasing environmental concerns and demand for sustainability. **Designing the future of construction isn't solely about diminishing emissions, but also involves developing materials and technologies capable of reversing the environmental damage already inflicted.**

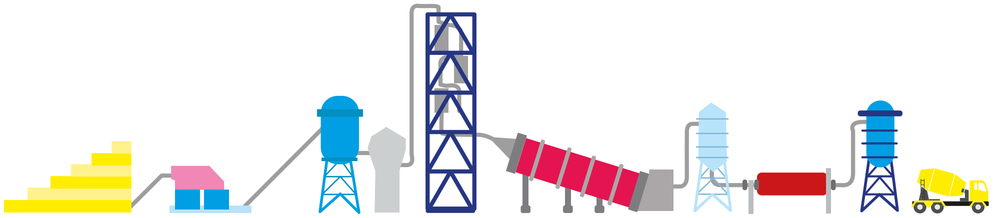
To catalyse pioneering advances in deep tech within the cement industry, two parallel approaches must be explored. The following approaches forge synergies among various facets to optimise the reduction of the environmental impact:

- **Altering the composition of cement and clinker to mitigate emissions, particularly during the most energy-intensive phase of concrete production.**
- **Altering the composition of concrete, by using supplementary cementitious materials and reducing cement content.**
- **Reducing the carbon footprint of the cement manufacturing process itself.**

REDUCING THE CLINKER-TO-CEMENT RATIO

Unveiling the ease of cement production

Raw materials, energy, and resources **Clinker and cement manufacturing**



	Quarry	Crusher	Transport	Raw mill	Kiln and preheater/ precalcinator	Cooler	Cement mill	Logistics	Total
Energy, mega-joule/ton	40	5	40	100	3,150	160	285	115	3,895
CO_2 kilogram/ton	3	1	7	17	479 Calcination process 319 Fossil fuels	28	49	22	925

EXHIBIT 3: MANUFACTURING PROCESS OF CEMENT - LAYING THE FOUNDATION FOR ZERO-CARBON CEMENT

Concrete is a ubiquitous construction material, with an astounding 6 billion cubic metres being utilised globally each year.[13] Its widespread adoption can be attributed to **its remarkable structural properties, combined with the fact that it can be produced using local resources, minimising the need for extensive supply chains.** The core constituents of concrete include aggregates, water, additives, and notably, cement. However, the production of cement, a mixture of limestone and clay, is a significant source of carbon emissions. Cement production involves heating the mixture to high temperatures (1,500°C) in kilns, primarily powered by fossil fuels, which releases CO_2 during the process, leading to the formation of clinker.

Portland cement is the most common type of cement the British engineer Joseph Aspdin first patented Portland cement in 1824. It was named after the natural stone from the Isle of Portland due to its colour and quality similarities and it typically consists of 95% clinker and 5% gypsum. This high proportion has been the standard for several decades, facilitating consistent structural strength and reliability for a multitude of constructions. **This high clinker content has significant environmental implications, as 85% of the emissions come from the production process.**[6]

Supplementary Cementitious Materials (SCMs): A crucial component in modern concrete

SCMs, as the term suggests, are materials used alongside or in lieu of traditional Portland cement (PC) in concrete mixtures. **Their origins can be traced to both natural sources and industrial by-products.** Common SCMs include fly ash (a by-product of coal combustion in power plants), slag (derived from the iron-making process), and natural pozzolans like volcanic ash. Each of these materials contributes uniquely to the properties of the resultant concrete, and their selection often hinges on the specific requirements of the construction project and availability of the materials.

Nonetheless, the replacement rate of SCMs for clinker was typically constrained to approximately 40%. This limitation was primarily due to the observed decline in the structural integrity of concrete as the usage of SCMs increases.[14] **Nowadays, High-Filler Cements with around 20% of clinker are proven.**[4] Having in mind that the global clinker-to-cement ratio is only projected to stand at 0.60 by 2050[10], the outcome would be a 30% decrease in the process CO_2 intensity of the cement process over that period, resulting in an average global value of 0.24 tonnes of process CO_2 per tonne of cement.[10] **This saving is nearly 35% of the current annual industrial direct CO_2** global emissions, demonstrating the significance of this approach in the pursuit of a more sustainable cement industry.

ALTERNATIVE BINDERS FOR CONCRETE

Rather than changing the recipe, it is also possible to replace PC

Although it constitutes only a small percentage of the mix (approximately 12-15% by volume)[4], cement is almost exclusively responsible for the resulting CO_2 emissions, as we saw in 1.1. Research is ongoing globally to optimise these alternative binders for widespread use in concrete. Key focus areas include improving early strength development, durability, and dimensional stability. Collaboration across industry, academia, and standards bodies is critical. With the right innovations in binder formulations and processing, coupled with performance testing and commercialisation efforts, alternative low-CO_2 binders have immense potential to transform the sustainability of concrete construction worldwide.

Some promising alternative binders

More innovative **alternative binders are now being explored, such as alkali-activated binders, geopolymers, calcium sulfoaluminate cements (CSA), and belite-calcium sulfoaluminate-ferrite cements (BCSAF).** These emerging binders use industrial by-products or natural minerals, and often require chemical activation. **Compared to Portland cement, they can lower CO_2 emissions by up to 90%.**[5] However, questions remain about their performance, production scale-up, and standardisation.

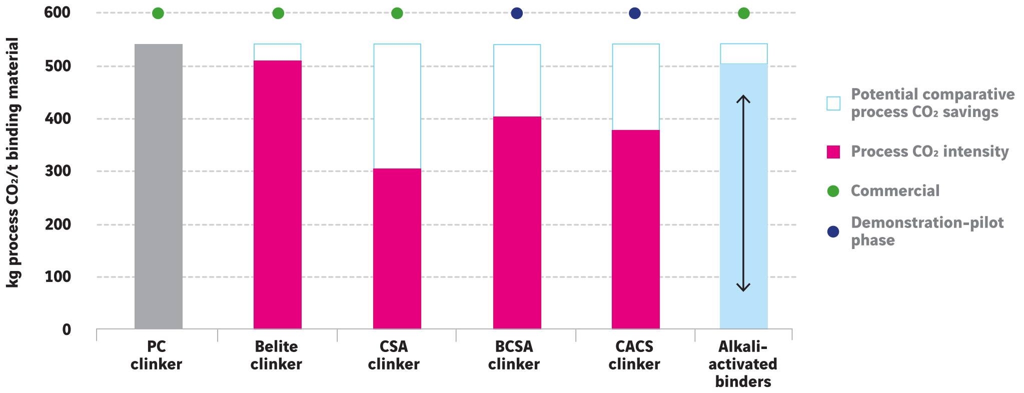


EXHIBIT 4: GENERATION OF CO_2 EMISSIONS FOR DIFFERENT CEMENT BINDING MATERIALS - IEA

Last in some instances, the challenge doesn't stem from the lack of clinker, but instead from the need to identify substitutes or partial replacements for traditional aggregates such as sand and gravel. This has sparked considerable interest in the exploration of innovative solutions that could be applied to various construction projects, further underscoring the industry's commitment to advancing sustainable practices. Two projects standing out in this field are MASUKO additive able to replace 100% sand/gravel with solid waste[15] and some researchers of the University of Kitakyushu that made the world's first house made with nappy-blended concrete.[16]

CARBON-SEQUESTRATION

One of the most promising technologies to achieve net zero

Natural sequestration alone is insufficient to balance the greenhouse gases that human activities produce. For instance, the natural weathering mechanism is able to sequester at least half a billion metric tonnes of CO_2 annually, but human activities are relentlessly emitting over 35 billion tonnes of CO_2 every year, far exceeding the planet's natural carbon recycling capacity.[17]

The knowledge on natural carbon-sequestration processes and the need for more intensive carbon removal from the atmosphere has led to the development of man-made sequestration techniques. These methods involve capturing CO_2 directly from large point sources like power plants, which are significant contributors to atmospheric CO_2.

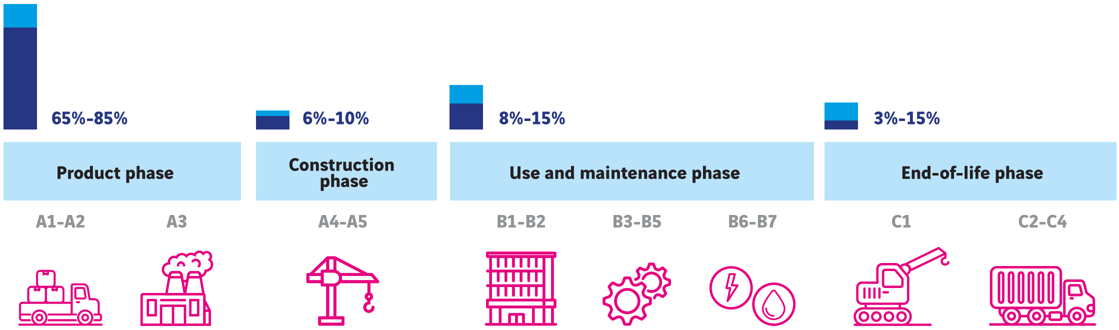


EXHIBIT 5: EMBODIED CARBON EMISSIONS DURING THE DIFFERENT PHASES OF LIFE CYCLE ASSESSMENT - RMI

While carbon capture, usage, and storage (CCUS) technologies can capture more than 90% of CO_2 emissions from power plants and industrial facilities[18], their penetration in the construction sector is limited. To meet future emission reduction targets, the industry must not only embrace these technologies but also address embodied and operational carbon emissions. **A significant fraction of a building's emissions arises during its production phase,** with materials like concrete being especially impactful. Innovations like carbonation in concrete and the use of bio-based materials such as hemp offer sustainable alternatives. However, effective CO_2 utilisation hinges on multiple variables including its source and its end use.

An emerging business arena

In the coming years, annual CO_2 capture capacity is expected to witness significant growth. **Project developers have set an ambitious target to have over 200 new capture facilities operational by 2030**, projected to result in the sequestration of more than 220 million tonnes of CO_2 annually. However, as of June 2022, only around 10 commercial capture projects under development had reached the final investment decision stage. This slower progress can be attributed to the fact that higher capture rates require larger equipment, more process steps, and increased energy consumption per tonne of CO_2 captured, leading to higher unit costs. Therefore, despite the progress made, the pace of CCUS deployment still falls significantly short of the benchmarks set in the Net Zero Scenario.[19]

Future challenges

The cement industry is facing increasing pressure to reduce its carbon dioxide emissions as part of global efforts to mitigate climate change. However, decreasing CO_2 emissions from cement production presents several key challenges that must be addressed. The first way to tackle concrete's ecological impact is by modifying the constituents used in its two energy-intensive steps. Allowing for cleaner alternatives or the capture of the CO_2 emitted during the process. **However, those alternatives, as explored in this chapter, pose challenges related to availability and appeal, particularly when considering SCMs or CCUS.**

The dwindling availability of supplementary cementitious materials

Considering the reality that cement requires abundant, readily accessible, and cost-effective raw materials, the availability of such materials consequently becomes a hugely important factor to consider. In that sense, the substitutes must be produced in considerable volumes to cater to the worldwide demand, a feat that is heavily dependent on the accessibility and quality of supplementary cementitious materials. In this context, the SCMs face two major issues. The first revolves around the availability of natural sources. The sheer volume required poses logistical hurdles for long-distance transportation, undermining their potential to effectively reduce CO_2 emissions due to this transportation burden. The second one is the predicted decline in the availability of traditional artificial SCMs, notably fly ash from coal-fired power stations and ground granulated blast furnace slag (GGBFS) from steel production, driven by the transition to cleaner energy sources. **Nevertheless, it is crucial to underline that SCMs alone are unlikely to achieve near-zero emissions production, considering that the current recognised minimum technical clinker requirement for most cement applications is roughly around 50%.**[5]

The attractiveness quandary

Despite the clear environmental benefits of using SCMs, there's a palpable lack of traction in their adoption. This can be attributed to several reasons. Regulatory frameworks, in many regions, do not incentivise the use of SCMs. The regulations surrounding clinker, a primary ingredient in cement, are not conducive to the substitution of base materials. Additionally, the limited availability of SCMs, as mentioned earlier, often leads to higher costs, making them unattractive for many producers. This scarcity and lack of demand create a self-perpetuating cycle, whereby SCMs remain expensive due to their rarity, and without substantial demand, competitive pricing remains elusive.

And a not yet attained profitability for capturing carbon

Whilst capturing carbon dioxide at the source of emissions holds great potential, its widespread use is hindered mostly by its costs. Increasingly, emitting polluting gases into the atmosphere is linked to certain economic penalties. For instance, the European Union Emissions Trading System (EU ETS) is a carbon pricing tool designed to lower greenhouse gas emissions by imposing a limit within specific sectors of the economy. However, the current CO_2 cost fluctuates around USD 80/t, and for CCUS facilities to be profitable, such fee should range from USD 80 to USD 130/t. In other words, **carbon capture, utilisation, and storage (CCUS) technologies will be unprofitable for as long as the CO_2 price is lower than the technology costs**.[20]

The industrial sector acknowledges that the current CO_2 quotation does not accurately anticipate the future, and there is a prevalent belief that prices will rise. But there's no consensus on the extent or timing of these increases. For example, different studies mention a too-wide range of CO_2 fee projections, spanning from USD 40 to USD 380/t by the year 2050. These economic uncertainties pose a significant barrier to carbon dioxide mitigation strategies, especially for low-profit sectors like cement. **Therefore, the industry's lack of guidelines or price ranges is slowing down the expansion of CCUS.**[20]

Emerging initiatives set to lead the way

Fortunately, several emerging CCUS applications are already being undertaken, even in the absence of an adequate CO_2 price. Their objective is to raise public awareness and lay the groundwork for future accessibility. CCUS projects in development are expanding geographically. Beyond North America and Europe, significant strides are being achieved in Asia Pacific and the Middle East. Among the diverse technologies known, chemical absorption and calcium looping are the closest to large-scale commercialisation (TRL 7). In 2014, Texas saw the launch of the first commercial chemical absorption facility with a 76,488-tonne annual CO_2 capacity, followed by a 50,000-tonne pilot plant in Wuhu, China, in 2018. Similarly, after successful pilot demonstrations of calcium looping technologies, a pre-commercial demonstration plant is set to begin operations in Italy, and a commercial-scale plant is anticipated in Chinese Taipei by 2025.[5]

Towards a sustainable future: Solutions for 2030 and 2050

In the short to medium term, the implementation of financial incentives and the establishment of consistent global regulations have the potential to significantly enhance market attractiveness and stimulate demand. **Indeed, regulations limiting clinker ratios would force cement producers to transition towards SCM blending. Carbon taxation could also encourage the use of greener cement through market forces.** Nonetheless, in the long run, research indicates alkali-activated binders could revolutionise cement and concrete manufacturing. These binders use an alkali activator-like sodium silicate to produce cementitious materials without Portland cement. If proven viable at scale, such binders could eliminate the need for traditional clinker entirely.

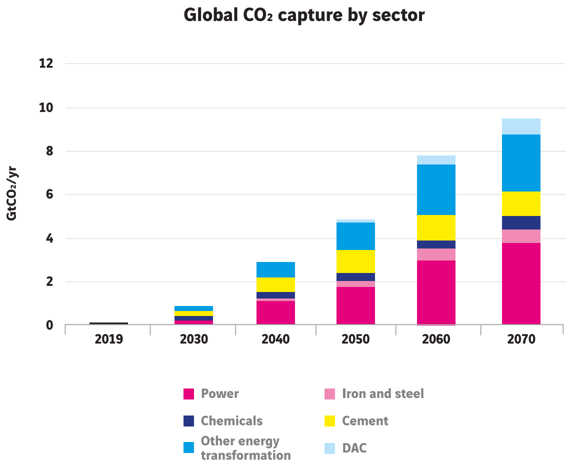


EXHIBIT 6: GROWTH IN GLOBAL CO_2 CAPTURE BY SECTOR, SCENARIO 2019-70 - IEA

In the meantime, prospective forecasts from the International Energy Agency plan that global net-zero emissions will not be achieved until 2070 by using only CCUS. Accordingly, the calculated CO_2 captured that year would be around 10 Gt (Exhibit 6), with a 10% contribution from the cement sector. These figures do not align with the carbon-neutrality target set for 2050 as outlined in the Paris Agreement. Therefore, to accomplish our endeavour towards sustainable concrete, different solutions must be used in conjunction. That is, alternative cement constituents, being already cost competitive at less than USD 100/t, will be deployed in the short-term, but will continue to be used further on, together with CCUS.[5]

Widespread availability and adoption of low-clinker or clinker-free binders appear essential to substantially reducing cement emissions, as there is significant risk CCUS might not be ready in time or cost-effective to be used. With the right incentives and investments today, price parity and availability of greener cement options could potentially be achieved by 2030 or 2050.

Part 2: Material science redefining construction

The growing global demand for buildings

With the world's population expanding rapidly, the UN estimates that 2.5 trillion square feet of new buildings will be constructed by 2060. **Building construction currently accounts for 39% of global CO_2 emissions and uses 40% of raw materials worldwide.**[21] The current global situation presents a dual challenge. On one hand, rapid urbanisation and population growth necessitate the construction of infrastructure at an unprecedented scale. On the other, the environmental crisis, marked by climate change and resource depletion, demands a drastic reduction in the carbon footprint and resource intensity of our construction activities.[21]

Exploring new pathways and materials

The first section of the report dissects the environmental impact of traditional construction methods and their mitigation strategies. As we move towards a future where environmental sustainability takes center stage, the construction sector is actively pursuing alternative solutions that deviate from conventional methods. **In this second section, we delve into these advances that are poised to alter the landscape of the construction industry.** It's worth noting that traditional practices and materials carry substantial adverse environmental effects such as deforestation, air and water pollution, and the emission of greenhouse gases. **Progress is being catalysed by materials science, as well as the sustainable sourcing of construction materials.** A significant part of this evolution concerns the development of materials with cutting-edge properties.

Rethinking construction: The promise of novel materials

The exploration of sustainable alternatives has led to a diverse array of new materials. **Bio-based materials (e.g. mycelium or bamboo) offer solutions that are both renewable and biodegradable.** On another front, **recycled and upcycled materials, ingeniously derived from urban waste or discarded products, present a golden opportunity to close the resource loop** and build with what we once considered waste. Additionally, there's a burgeoning interest in advanced composites and alloys, borne out of cutting-edge research, which promises enhanced durability and performance, all the while reducing environmental impact. The materials poised to shape our future cities are not merely intended to replicate their traditional counterparts; they are envisioned to surpass them in every conceivable way. Sustainability sits at the forefront; these materials are derived from renewable sources and ensure a low carbon footprint and minimal environmental degradation. Likewise, materials with improved insulation properties and thermal performance have the potential to reduce energy consumption and tackle a growing demand for energy-efficient buildings. **Durability is another hallmark; novel materials are crafted to resist wear and tear, ensuring that our cities stand the test of time with reduced maintenance.** Efficiency is also key; being lighter, stronger, and more adaptable, these materials have the potential to revolutionise construction methodologies. Lastly, circularity is a defining trait; future materials are meticulously designed for reuse and recycling, championing a circular economy, and drastically reducing waste and resource consumption.

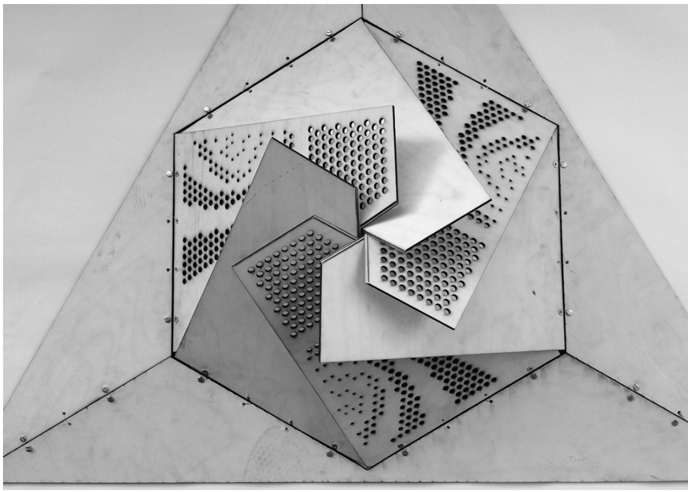
Deep technologies: The catalysts of change

At the heart of this material revolution lie deep technologies, acting as the catalysts driving change. **Nanotechnology, for instance, is enabling the development of materials with enhanced strength and insulation, and even the fascinating capability to self-heal.** Concurrently, by replicating natural structures and systems within built environments, biomimicry offers a unique blend of functionality, resilience, and sustainability. The industry is on the verge of a paradigm shift, and the incorporation of smart materials, alternative sources, and sustainable practices will redefine the way we build our world. The forthcoming pages will explore these pivotal aspects in more detail, aiming to provide comprehensive insight into the future of sustainable construction.

STRUCTURE-CHANGING MATERIALS

Envisioning buildings that adapt to our needs

Structure-changing materials can undergo a significant shift in one or more of their properties in direct response to a modification in their surrounding environment. These environmental conditions can range from ambient to human-generated direct energy inputs. Based on the input sensing and the output generated, **these smart materials have four classifications: colour-shifting, phase-changing, viscosity-changing, and adhesion-changing**.[22]



Considering their adaptive and responsive nature, the appeal of these materials in construction lies in the potential to create dynamic and resilient buildings. Nevertheless, this is still a nascent domain, with few technologies having reached the market. For instance, shape-memory-alloys, with the ability to transition between solid phases reversely, have been successfully used in medical, robotic, aerospace, and automobile applications since the 1960s. However, in terms of construction, they have been employed for structures repairs, but their use in adaptative buildings is still limited to demonstration scale.[23]

Harnessing smart materials to de-risk the built-in environment

Among the possible applications of structure-changing materials in adaptative construction, there is one trend emerging with strength: predictive maintenance and/or industrial safety. This aims to harness the responsive properties for risk indication and sensing, and colour-shifting materials are commonly employed.[24] For example, the US space agency uses a device with a chemo-chromic pigment sensible to hydrogen, as the gas has low explosion threshold and is a key concern for space shuttle processing.[25]

Nonetheless, the challenge remains on designing coatings with broader and more impactful applications within the construction sector. On this subject, the smart coatings market size is valued at USD5.15 billion, primarily dominated by anti-corrosion solutions. While a limited number of companies are actively commercialising, numerous actors, such as BASF and NASA, are engaged in research.[26,27]

ENERGY-EXCHANGING MATERIALS

Smart materials for energy-efficient constructions

Energy-exchanging or "first law" materials are able to produce an output energy from an input according to the first law of thermodynamics, meaning energy is converted from one type to another.[28,29] **This ability becomes especially relevant for reducing energy consumption in buildings and, therefore, improve efficiency.[30]** Overall, these materials can be used to conserve energy and reduce costs associated with heating, cooling, and lighting.

As an emerging field, most advancements are primarily concentrated within the realm of research. Nonetheless, some companies are making strides to commercialising products. For instance, Ubiquitous Energy is a next-generation technology company that develops and commercialises transparent solar technology for architectural glass. Their product, UE Power™, is a transparent solar coating that efficiently capturing energy from infrared and ultraviolet light, while allowing visible light to pass through. By harnessing energy from these invisible light spectrums, it becomes feasible to generate electricity without any visible impact or obstruction, enabling the seamless and inconspicuous integration of solar power generation.[31]

Recovering internal energy from buildings

Even if advances in the field of smart glasses seem to be the dominant field of development for energy-exchanging materials, other more ambitious attainments are being investigated. **Specifically, piezoelectricity is the ability to produce electric currents when subjected to mechanical stress and is gaining traction to harness the building’s natural vibrations** (i.e. human movements, vehicle passages, or winds) to obtain electric energy.

Several naturally occurring materials exhibit this property, and their earliest applications date back to the First World War. However, it has not been until recently that piezoelectric materials have been shown to be applicable in the design and construction of self-sustainable buildings, through smart sensing and energy harvesting. [32]

Currently commercialised piezoelectric materials for construction come in the form of sensors or actuators, meaning they are embedded in an electronic device as part of a broader composite. However, the most widely used material is lead zirconate titanate, which is poisonous to humans. Thus, the challenge remains on finding alternative polymers with piezoelectric properties to have compliant materials.[33] For that, the main stakeholders are research institutions such as ETH Zurich and Empa.

ALTERNATIVE RAW MATERIALS FOR SUSTAINABLE CONSTRUCTION

A tremendous consumption of feedstock

The construction industry exerts a substantial environmental footprint encompassing energy consumption, harmful emissions, and waste generation. Fossil fuels are frequently relied upon for equipment operation, and the fabrication and transportation of materials contribute significantly to global carbon emissions.[34] According to the Worldwatch Institute, **building construction alone consumes a staggering 40% of the global annual usage of raw stone, gravel, and sand, along with 25% of virgin wood.** Annually, buildings also represent 40% of energy consumption and 16% of water usage worldwide. The adverse effects of these practices are readily apparent.

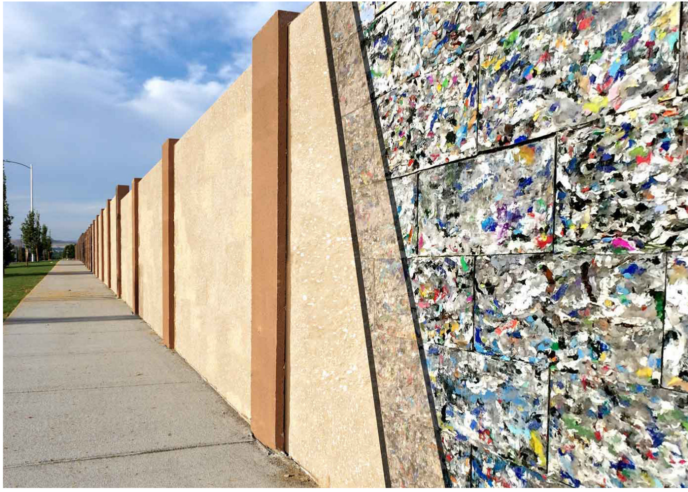
This hefty toll on the environment has a ripple effect. The procurement, transportation, and processing of raw materials often lead to resource exhaustion and a concerning loss in biodiversity, adversely affecting a wide range of animal and plant species. The industry's reliance on fossil fuels, beyond its direct environmental implications, releases emissions that play a part in escalating climate change and inducing acid rain. Construction waste further aggravates the situation. Instead of being responsibly managed, much of this waste finds its way into the air and water systems, creating formidable health hazards and compromising the safety of surrounding communities. As we move forward, reimagining and reshaping the construction sector's practices is not just an option but an urgent necessity for the well-being of our planet and its inhabitants.

A wide variety of materials are at our disposal

Unlike traditional building materials, alternatives like bamboo, straw bales, and rammed earth are inherently sustainable and are considered rapidly renewable resources. They require less energy for production and transportation, thereby reducing fossil fuel usage and resulting in a lower carbon footprint. This, in turn, allows for a more environmentally friendly construction process.[35]

Furthermore, these materials have the potential to boost the energy efficiency of buildings. For instance, straw bales have excellent insulation properties, doubling as a soundproof material, thus reducing the need for energy-consuming heating and cooling systems.[36]

From a financial perspective, alternative materials can also be more cost-effective. Using salvaged materials can bring down the overall construction cost and make construction projects more accessible to a wider range of people.[37] Embracing alternative materials can contribute to waste reduction. Bamboo, with its high self-generation rate, can be harvested without killing the plant, making it a continually sustainable and renewable source of building material.[35]



BIOMIMICRY FOR SUSTAINABLE CONSTRUCTION

The impact of biomimicry on sustainable architecture

In 2021, the building sector contributed to approximately 37% of global CO_2 emissions related to energy and processes, as well as representing over 34% of global energy consumption.[38] In this context, biomimicry holds a bright future, as it has shown to be able to reduce energy costs by 30%, and artificial lighting by 55% when applied to architecture.[39] Drawing inspiration from nature's intricate structures, this field is gaining wider recognition as a viable construction strategy thanks to progress in materials, techniques, and technologies that align with biodiversity.[40] Biomimicry stands out from other bio-inspired design approaches due to its focus on studying and replicating the solutions found in living systems to address specific, functional challenges. This emphasis on learning from nature's ability to heal, renew, and adapt sets biomimicry apart, as it seeks to harness these biological principles to create innovative and sustainable solutions.[41]

Inspired by nature's ingenuity, to bridge efficiency and construction

Biological materials are practical in terms of engineering. They have evolved to provide strength and other special properties while remaining biodegradable. Therefore, using natural materials does not compromise performance and, on the contrary, can bring significant value to construction projects.[42] On the other hand, **biomimetic materials replicate the functions and attributes of those that have been produced by living organisms, with which they share similar characteristics and therefore are also valuable for construction.**[43] By drawing from nature's wisdom, construction stakeholders have tapped into an extensive repertoire of strategies and principles with the potential to contribute to the development of more efficient and sustainable building materials.[42]

Nature-based design principles in building materials

In the natural world, trees have evolved mechanisms to withstand the forces of high winds and storms by adopting optimal forms, density, and fibre orientations. This is why natural wood can exhibit a strength surpassing that of steel. For example, by combining material science with the latest digital optimisation tools, the startup Strong by Form has developed their product, Woodflow. It consists of a fabrication technology that mimics the natural form functions of trees. They possess a proprietary additive manufacturing process that can create high-performance, ultralight, timber-based structural composites for the construction and mobility industries at a fraction of their conventional environmental impact.

The leaves of the lotus plant have a very high-water repellency (hydrophobicity) which causes water to bead up and roll off the surface. As the water rolls off, it picks up dirt and other contaminants, effectively cleaning the surface. This phenomenon is named after the lotus plant because it was one of the first places where this effect was observed. In the construction industry, the concept of the Lotus effect has been used to develop self-cleaning surfaces. These are surfaces that are designed to be hydrophobic, so that water will roll off them, carrying away dirt and debris. This reduces the amount of maintenance required to keep a building looking clean, and it helps to prevent the growth of mould and mildew.

Future challenges

Material science to face the industry's evolution

To meet the global demands of a growing population and address infrastructure gaps, the construction industry will require an investment of USD 94 trillion in the next twenty years.[44] This, combined with the necessary drive towards sustainable construction, has fostered a growing interest in material science to promote alternatives to conventional practices.

Given the promise of **structure-changing smart materials as non-invasive, easy-to-deploy techniques for resilient constructions,** research is being promoted for their optimisation and discovery, as well as efforts are being made to align their applications, and ultimately achieve commercial availability.[45] Likewise, **energy-exchanging materials,** with their unique capacity **to recover internal energy in a more usable form,** are gaining momentum to boost efficiency in urban environments.[46,47]

Alongside innovative solutions, more **conservative techniques also offer promising opportunities.** Alternative raw materials, being **inherently sustainable and easily accessible,** are most likely to be deployed in the short term. For instance, mycelium composites are already being commercialised for non-structural applications, and research is focused on improving their strength and resistance so that they can be employed in self-supporting structures. Furthermore, with nature as the foundation, biomimicry offers a new, yet already existent, **repertoire of techniques that can be seamlessly integrated into current construction.** Ultimately, the development of an eco-responsible business will depend on a combination of exploring the existing and the yet-to-be.

The underlying potential of the portrayed technologies

After a careful analysis of a range of technologies, we highlight that their tangible value becomes evident when applied within the context of the value chain. Taking **the structure-changing and energy-exchanging material** examples, both are **expected to provide benefits during the use life of the building.** On the one hand, self-reporting coatings, with their unique ability to sense and alert of corrosion, are capable of anticipating repairs, ultimately helping to preserve infrastructure. On the other hand, the use of piezoelectric materials will help improve the energy efficiency of buildings while using renewable sources.

Even if nature-wise solutions are closer to market or already commercialised, they are not yet fully implemented as the go-to materials. They must therefore establish themselves as advantageous and viable choices as well. From the technological deep dives of the report, **mycelium composites stand out as the ones able to tackle the most steps of the value chain,** those being production and end-of-life of the building. For the production process, as the product comes from waste streams, raw material supply becomes greener. Moreover, the manufacturing process utilises 40% less energy, and emits 60% less CO_2 than its conventional counterpart (polystyrene). For the end-of-life process, proper waste management and recycling are ensured as the materials are renewable and thus appropriate for circularity. As for biomimetic techniques, **self-healing concrete achieves self-sustained maintenance** through the bacteria, whilst **self-cleaning surfaces increase environmental quality** by reducing the need for chemical agents.

Applicability challenges interfere with adoption

The current limited adoption of smart materials in buildings can be attributed to applicability considerations such **as technical risks, lack of awareness among construction stakeholders,** and **higher costs compared to traditional construction methods.**[48] Due to these barriers, these technologies have yet to evolve to more advanced phases of the development process. Moreover, it is essential to familiarise construction professionals with both structure-changing and energy-exchanging materials in order to foster understanding and promote their benefits. This can be achieved through financing projects, such as the initiatives undertaken by entities like the European Commission to boost the development of eco-friendly, multifunctional, smart coatings.[49] Also, materials such as phase-changing or piezoelectric could be deployed in public locations, visible to consumers, serving to foster a broader interest.[50]

For alternative feedstocks, their **procurement and reliable availability is what prevents them from establishing themselves as conventional methods.** Supply chain disruptions can cause material shortages, leading to project delays and escalated costs.[51] For instance, when using timber, it's vital to ensure sustainable production to avoid potential deforestation caused by excessive demand.[52] Also, the disparity of geographic availability of materials such as bamboo, not only poses logistical challenges but also drives up transportation costs when supplying construction hubs.

Furthermore, once a natural source has been identified and a biomimetic approach wants to be followed, **the inspiration will have to be translated into concrete technology**, requiring a deep understanding of both natural sciences and construction techniques. Acknowledging this challenge, numerous research groups globally have taken the mantle with the vision of championing the integration of natural systems into the fabric of our built environment.[53]

The road ahead: Market scalability and real-world acceptance

Insufficient government backing, ineffective sustainable development strategies, and the overall 25% higher price tag attached to sustainable methodologies are still hurdles to overcome.[54] In this context, governments should consider **implementing initiatives and promotional strategies that will contribute to cost reduction** in the long term.[54,55] Beyond that, approaches such as **subsidies for the adoption of sustainable technologies, or grants for research** into new materials, will create an environment whereby sustainable practices are not just encouraged but are also economically viable.

Upon achieving widespread knowledge and acceptance, a surge in demand for their utilisation will ensue, **facilitating economies of scale and mass production.**[48] As a matter of fact, a transition of this kind has already been seen in the smart materials market for electrochromic glass, which anticipates that the deep technologies outlined in this report will eventually gain a foothold as well.

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