November 2023

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

Part 2
Material science redifining construction

LEONARD
together@VINCI

hello tomorrow

Forewords & Acknowledgements

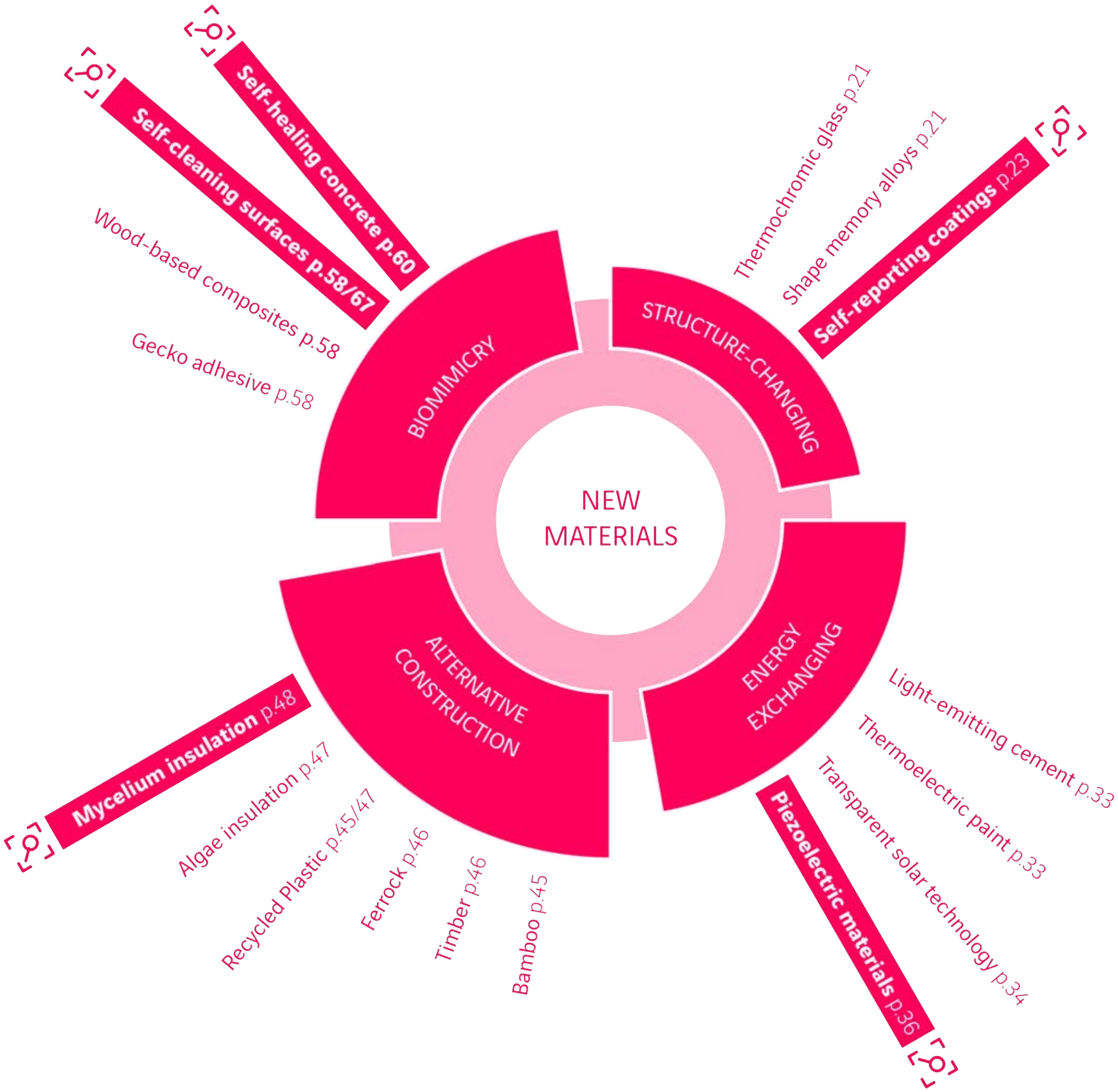
In the light of the escalating climate crisis, the urgency for meticulous diligence, proactive approaches, and heightened awareness in our construction endeavours has never been more paramount. At Leonard's, the foresight and innovation platform of the VINCI group, our purpose is to foster this very 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

Table of contents



NEW MATERIALS
BIOMIMICRY
STRUCTURE-CHANGING
ENERGY EXCHANGING
ALTERNATIVE CONSTRUCTION
Self-healing concrete p.60
Self-cleaning surfaces p.58/67
Wood-based composites p.58
Gecko adhesive p.58
Thermochromic glass p.21
Shape memory alloys p.21
Self-reporting coatings p.23
Light-emitting cement p.33
Thermoelectric paint p.33
Transparent solar technology p.34
Piezoelectric materials p.36
Mycelium insulation p.48
Algae insulation p.47
Recycled Plastic p.45/47
Ferrock p.46
Timber p.46
Bamboo p.45

Executive summary

The call for sustainability in the construction sector involves exploring solutions beyond conventionalism. Indeed, in the first chapter of this report (see Part 1: Pathways to sustainable concrete) we assessed the ecological impact of the cement industry, widely recognized as the central driver propelling global emissions. After a thorough analysis of potential enhancements, the findings suggest that the green transition requires collaborative efforts involving other materials as well, not limited to cement.

Expanding the scope for decarbonization avenues

Diversifying the array of decarbonisation pathways holds the potential to facilitate the industry's alignment with increasingly stringent environmental regulations. Such policies, aim to reduce the carbon footprint of new buildings over their lifetime, from initial construction, use, to final demolition. Thus, a comprehensive approach is demanded to harness a combination of levers to fully unlock the potential of deep technologies in achieving an eco-conscious construction future.

As part of a collaborative endeavour to enhance awareness and deepen understanding concerning cutting-edge developments in the industry, Leonard & Hello Tomorrow conducted an analysis to shape the way of our forthcoming built environment.

Material science at the forefront of sustainable construction

Delving further into material science, the exploration of 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 optimizing performance. However, they are still nascent, grappling with scalability and regulatory challenges.

Exploring natural pathways

On the other hand, finding greener sources can be achieved by either exploring nature-sourced materials such as mycelium, bamboo, and timber, or leveraging biomimicry, resulting in materials with new properties like self-healing concrete and self-cleaning surfaces. Nature-sourced materials have short-term adoption potential due to historical usage and scalability feasibility, although complete substitution of current materials is uncertain. Biomimicry, on its part, holds the promise of reducing maintenance costs and offering environmental benefits. While still facing scalability and regulatory challenges as well, the future holds promising prospects, even though widespread mainstream adoption may not be immediate.

Up-and-coming adoption and revolutionary innovations in green materials

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.

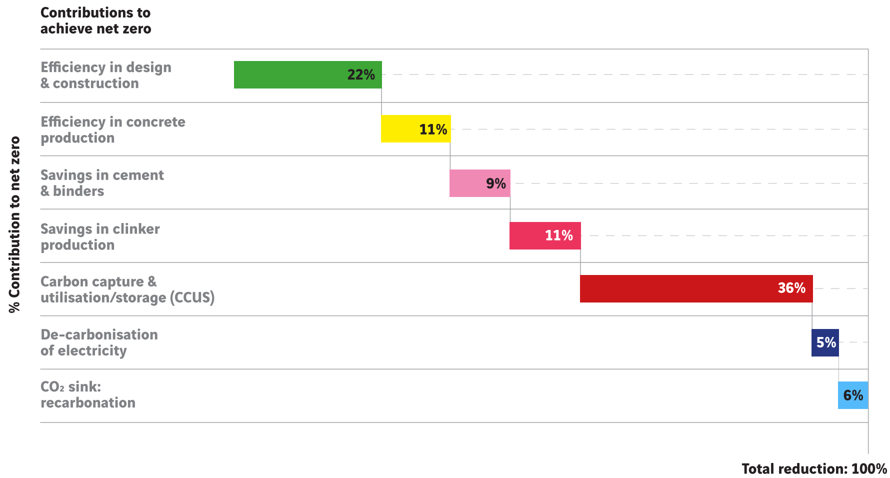


EXHIBIT 1: THE NET ZERO PATHWAY - GCCA

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.[1]

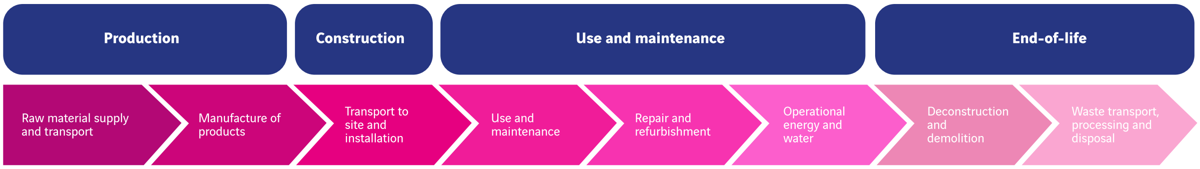
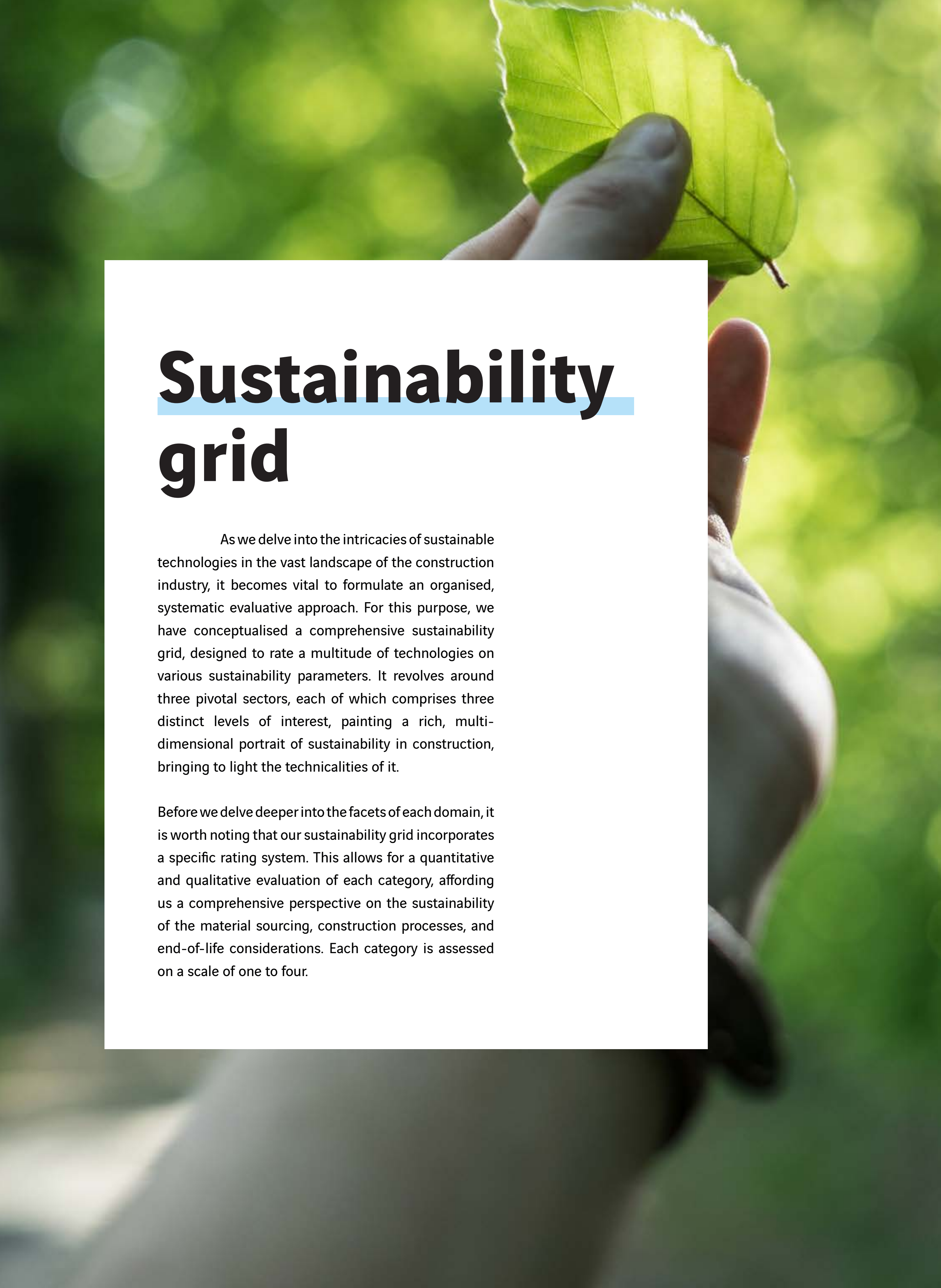


EXHIBIT 2: CONSTRUCTION VALUE CHAIN

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 this report, the most promising technology trends tackled the production phase of the cement industry. Here, we provide an array of novel materials, most of which are intended to increase the efficiency of the building over its use-life, without forgetting its production and appropriate disposal.



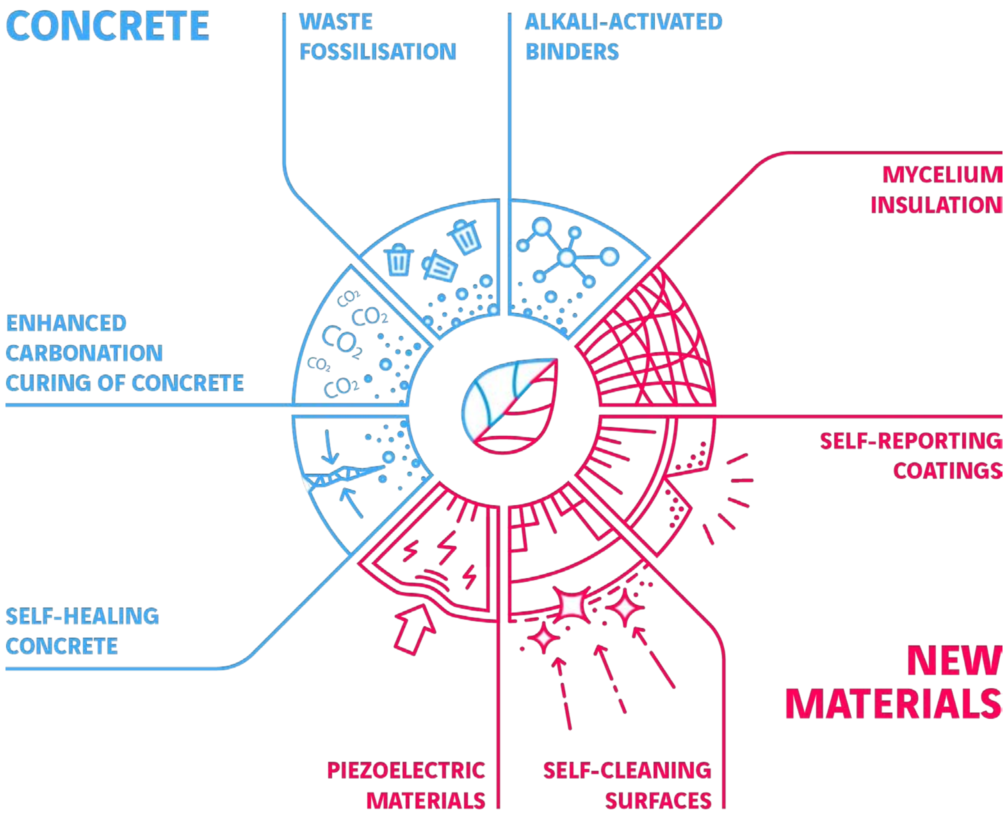
Sustainability grid

As we delve into the intricacies of sustainable technologies in the vast landscape of the construction industry, it becomes vital to formulate an organised, systematic evaluative approach. For this purpose, we have conceptualised a comprehensive sustainability grid, designed to rate a multitude of technologies on various sustainability parameters. It revolves around three pivotal sectors, each of which comprises three distinct levels of interest, painting a rich, multi-dimensional portrait of sustainability in construction, bringing to light the technicalities of it.

Before we delve deeper into the facets of each domain, it is worth noting that our sustainability grid incorporates a specific rating system. This allows for a quantitative and qualitative evaluation of each category, affording us a comprehensive perspective on the sustainability of the material sourcing, construction processes, and end-of-life considerations. Each category is assessed on a scale of one to four.

Technology investigation

Utilising 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.



●○○○

Materials are primarily imported or rare, non-renewable, and non-recyclable. No consideration is given to reuse or upcycling of existing materials.

●●○○

Some common/local and renewable materials are used, but reliance on imported or rare materials is still significant. Minimal reuse and upcycling of existing materials.

●●●○

Most materials are locally sourced and/or renewable, with a strong focus on reusing and upcycling existing materials when possible.

●●●●

All materials are locally sourced, renewable, and/or recyclable, with a comprehensive approach to reusing and upcycling materials throughout the project.

#1 Material sourcing

Material sourcing and transport

Minimising the rarity and transportation of materials required.
By balancing the need for imported, heavy or rare compounds within the material, construction projects can significantly reduce their environmental footprint and contribute to more sustainable practices.

Reuse of existing materials

Reusing materials from demolished or deconstructed buildings, as well as repurposing items that would otherwise be discarded.
With the reuse of material, construction projects can significantly reduce waste, minimise the need for new materials, and lower their overall environmental impact.

Upcycling

Reducing waste and promoting a circular economy.
Upcycling strategies reduce the ecological footprint of construction projects while fostering inventive and sustainable solutions.

#2 Construction and operation

Energy efficiency for production

Optimising design, using energy-efficient materials, and employing technologies to minimise energy consumption and non-renewable sources.
To further improve energy efficiency, techniques should be successful in reducing energy usage during the construction process.

Water efficiency for production

Using water-efficient fixtures and appliances, collecting rainwater for reuse, and implementing water-saving landscaping techniques.

●○○○

No energy or water efficiency measures are implemented, and environmental impact is not considered during construction.

●●○○

Some energy and water efficiency measures are used, but overall consumption is still high and not relying on renewable energies. Environmental impact is minimally considered.

●●●○

Energy and water efficiency are prioritised through uilding design, technology, and material choices, but the sources are not renewable yet. Some measures are taken to minimise the environmental impact.

Efficient water use helps preserve this valuable resource and reduces the overall environmental impact of the project.

Environmental risk management

Minimising site disturbance, protecting natural habitats and ecosystems, and implementing erosion control measures.
Selecting eco-friendly materials and incorporating green building techniques can improve the environmental quality of the construction process to avoid the spread of volatile compounds.

●●●●

Fully optimized for energy and water efficiency, using innovative designs and renewable sources. Environmental impact is minimized through eco-friendly materials and responsible construction practices.

●○○○

The building design does not consider extended lifespan or resilience to changing conditions. No efforts are made to facilitate material recovery at the end of life.

●●○○

Includes some elements of resilience and extended lifespan but lacks comprehensive strategies. Some efforts are made to enable material recovery at the end of life.

●●●○

Prioritises resilience and extends lifespan through careful material choice and flexible design. The end-of-life plan facilitates significant material recovery.

●●●●

Designed for maximum resilience and lifespan, with adaptable spaces and durable materials. At the end of life, the building is completely de-constructible for material recovery and recycling.

#3
Extended resilience and life cycle potential

Extended life cycle

Entails designing and constructing buildings to have a longer-than-usual lifespan, reducing the frequency of demolition and new construction.
By using durable materials, flexible design principles that can adapt to changing needs over time, and regular maintenance to keep the building in good condition.

Recycling potential

The ability to recycle materials at the end of a building's life and design for easy disassembly.
By maximising the recycling potential of a structure, waste can be reduced and resources conserved. An example of this would be recycling concrete debris into aggregate for new concrete mix or melting down metal components for reformation.

Part 2:
Material science redifining construction

Material science redifining 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.[2] 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. Alternative materials often grapple with their unique set of challenges, consider timber, a material occasionally proposed as a substitute for concrete. **To replace just a quarter of cement used in construction with timber, an area of forest 1.5 times the size of India would need to be felled annually**.[3]

Exploring new pathways and materials

The previous section of the report dissected the environmental impact of traditional construction methods and their mitigation through improvements in production processes. 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. 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. The progress is being catalysed by advances in materials science as well as the sustainable sourcing of construction materials. In this second part, we delve into these exciting advances that are poised to fundamentally alter the landscape of the construction industry. 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 materials. Bio-based materials, such as mycelium, which is the root system of fungi, and bamboo, a rapidly renewable grass, 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, ensuring 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. Amsterdam, for instance, has set a goal to become 100% circular by 2050, with construction materials playing a pivotal role in this ambition.[4]

Deep technologies: The catalysts of change

At the heart of this material revolution lie deep technologies, acting as the catalysts driving change. Structure-changing materials have the potential to redefine construction methodologies by altering their physical properties (such as shape, size, or colour) in response to external stimuli like heat, light, pressure, or electric current. Nanotechnology, for instance, is enabling the development of materials with enhanced strength and insulation, and even the fascinating capability to self-heal. Concurrently, Biomimicry is another innovation in this space. It involves replicating natural structures and systems within built environments, offering a unique blend of functionality, resilience, and sustainability. From designing structures inspired by termite mounds for passive cooling to using mycelium to develop organic building materials, biomimicry presents many possibilities for a more sustainable future.

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 into these pivotal aspects in more detail, aiming to provide a comprehensive insight into the future of a sustainable construction.

2.1 STRUCTURE-CHANGING MATERIALS

"Smart materials technologies are the key to 21st-century competitive advantage."

Abeer Samy Yousef Mohamed
Smart Materials Innovative Technologies in architecture

The essentials of structure-changing materials

Structure-changing materials can significantly alter **their chemical, thermal, mechanical, magnetic, optical, or electrical properties in response to changes in their environment**, which may include ambient conditions or direct energy input. The conversion in the properties of structure-changing materials is made by **changes in its microstructure**, which are triggered by a variety of ambient or energy inputs. According to the type of input they are able to sense, and the class of output they release, structure-changing smart materials can be classified into four types:[5]

	Type	Input	Output
Colour-shifting	Thermochromic	Temperature difference	Colour shift
	Mechanochromic	Deformation	Colour shift
	Chemochromic	Chemical reaction	Colour shift
	Electrochromic	Voltage	Colour shift
	Photochromic	Light	Colour shift
Phase-changing	Thermotropic	Temperature difference	Phase change
	Electrotropic	Voltage	Phase change
	Phototropic	Light	Phase change
	Shape memory	Temperature difference	Crystalline phase change
Viscosity-changing	Magnetorheological	Magnetic field	Viscosity change
	Electrorheological	Electric field	Viscosity change
Adhesion-changing	Photosensitive	Light	Adhesion change
	Electrosensitive	Electric field	Adhesion change

EXHIBIT 3: TYPES OF STRUCTURE-CHANGING MATERIALS

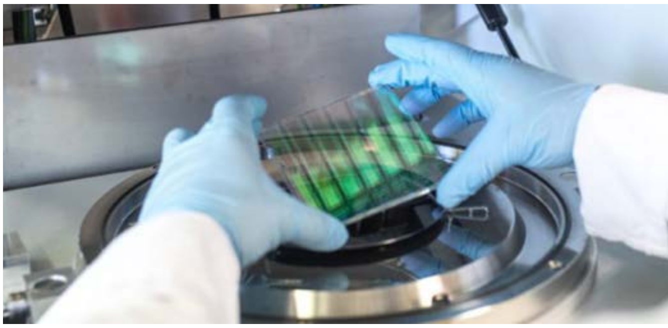
Depending on the type of product used, the **property changes observed in the output can be reversible or not**. For example, **a leuco dye system is a type of thermochromic material that switches reversibly between two chemical forms**, from colour to colourless on temperature change. They come in a variety of forms, including ink, powder, or plastic pellets, and are commonly used in designed textiles. Thermochromic plastic products can also be created through the pellets, opening up the possibilities to apply them in more interesting or experimental ways to a broader range of materials. In contrast, **irreversible thermochromic paints operate through unidirectional chemical changes** occurring within the solid components of the coating, and are usually used as safety indicators.[6,7]

It should be mentioned that within the phase-changing materials, **shape memory materials have distinctive characteristics from the other three of the group** (thermotropic, electrotropic, and phototropic). Traditional phase-changing materials are substances that undergo phase transitions between solid and liquid states, or between different solid phases, absorbing or releasing latent heat.[8] Instead, shape-memory materials exhibit the unique property of shape-memory effect, recovering their original shape upon deformation. This is achieved through a solid-state phase transformation between two different crystal structures, typically called martensite and austenite.[9] Therefore, **while both types of materials involve reversible phase transitions, the underlying mechanisms differ**.

Examples of structure-changing materials in construction

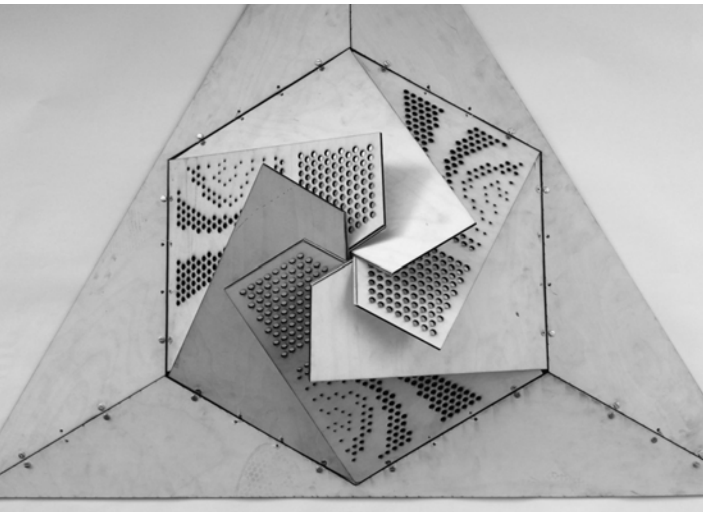
Thermochromic glass[10]

Researchers at the Brightlands Materials Center are developing smart thermochromic coatings for windows. Such coatings have the ability to switch from blocking heat to allowing it to pass, responding to the outdoor temperature. To produce the coating, a liquid layer is applied and left to dry. Subsequently, a heat treatment of 400-500°C is applied, and the material develops a crystal structure that is able to respond to thermal energy change. Text BoxWhen exposed to high temperatures, the crystal structure acts as a barrier, effectively blocking the heat from the sun. However, once the temperature of the glass drops below a certain tailored threshold, a transformation occurs in the crystal structure, causing the coating to switch and allow the transmission of heat. Within the switching process, the group has achieved the innovation of keeping neutral colours so that it is not visible to naked eye.



BRIGHTLANDS MATERIALS CENTER'S THERMOCHROMIC GLASS - TNO INNOVATION FOR LIFE

This characteristic makes thermochromic glass highly suitable for use in residential buildings, as it provides both heat control and visual comfort. The goal of the research is to reduce the energy costs of heating and cooling systems. They have calculated that by combining their coating with double-glazing windows with a heat-transfer reducing layer in detached houses in the Netherlands, it could save up to 638€ per year on energy bills. Based on that, approximately 20% of the savings could be attributed to their thermochromic coating. As of today, they are currently working on verifying the performance of their technology in test buildings, scaling up the area of application on windows measuring 1x1.5 meters.



MATERIAL PROTOTYPE USING SHAPE MEMORY ALLOYS - TACTILE ARCHITECTURE

Shape memory alloys

Shape-memory alloys were first developed in the 1960s. Since then, they have been successfully used for medical, robotic, aerospace, and automobile applications.[11]

Their initial use in the construction industry was to reinforce the concrete structure of a highway bridge in Michigan. The bridge presented cracks on the girder due to insufficient shier resistance, and iron-manganese-silicon-chromium shape-memory alloy rods were used to mitigate further structural issues.[11]

Following this, the material was used to repair and strengthen architectural heritage structures. The bell tower of San Giorgio church in Trignano, Italy was restored by using a shape-memory alloy device. This device was developed by the EU-funded Istech project[12], which included nickel-titanium shape-memory alloy wires pre-tensioned within it. The smart, phase-changing material was therefore not used by itself, but within mechanical equipment. Consequentially, by 2008, at least 19 buildings were strengthened following this technique. Moreover, these types of devices have also been developed to protect buildings from earthquakes.[11]

Several research projects have been developed to embed shape-memory alloys into structures for a preventive approach, more than simply repairing. For concrete, the use of the material in a shear wall has proven to reduce the residual displacement of a building during an earthquake. Nonetheless, the structure would still be damaged during the devastation, for which further research is still needed to achieve applicability.[11]

Shape-memory alloys can also play a significant role in the emerging field of adaptive buildings, facilitating their response to fluctuations in the ambient environment. For example, in 2016, Tactile Architecture developed a prototype using shape-memory alloy springs to be used as a shading device.[13] However, the use of these materials in building design is still in the early stages and largely limited to demonstration-scale projects.[11]

Why zoom in on self-reporting coatings?

Structure-changing smart materials with chemochromic properties have the potential to sense a chemical reaction and change their colour reversibly or irreversibly.[5] This approach can be harnessed for applications in **predictive maintenance and/or industrial safety**, as the colour indicators have the advantage of being universally understood.[14]

Colour-change materials are commonly chosen in industrial sectors for the purpose of gas detection.[14] For example, at NASA, hydrogen safety is a key concern for space shuttle processing, as the gas has low explosion threshold but is also odourless and colourless. The US space agency therefore uses a device with a chemo-chromic pigment whose sensitivity can be tailored to its application.[15]

Nowadays, the challenge is to **design coatings with chemochromic abilities**, and a potential field of application is to detect corrosion in infrastructure. Corrosion costs in 2020 were estimated at **USD 3 trillion per year**.[16] Unfortunately, common corrosion protection strategies consist of protective coatings that tend to deteriorate over time, posing a need to detect these damages at early stages. Subsequently, evaluation strategies such as electrochemical measurement, thermal imaging, ultrasonic inspection, acoustic inspection, and radiography have been pursued. However, this measurement is time-consuming and requires unwieldy and highly costly equipment. Therefore, the concept of **self-reporting coatings has been proposed for early warning of corrosion**, attracting interest for its potential to tackle the global issue of corrosion.[17]

Sustainability check

Material sourcing ● ●

There is a need to find environmentally friendly corrosion-detecting coatings.

Construction and operational ● ●

Self-reporting coatings can help preserve infrastructure through the early detection of corrosion.

Extended resilience and life cycle potential ● ●

Usable life of the building is increased.

Self-reporting coatings for corrosion

Self-reporting coatings are a specialised type of protective films that are able to respond to corrosion-related environmental changes through reactive fluorescent compounds or colour-changing dyes embedded within them.

The two main approaches for self-reporting coatings for corrosion are those that contain fluorescent or colour indicators. Nonetheless, fluorescence signals are not visible to the naked eye under daylight conditions. Observing fluorescence requires ultraviolet (UV) excitation at specific wavelengths, which can be impractical for everyday applications. Therefore, there has been a greater emphasis on corrosion sensing through visible colour changes. Such coatings contain **chemicals that undergo colour changes due to alterations in molecular structure resulting from environmental variations related to corrosion**. The colour transformation can occur due to changes in the pH or interactions with metal ions.[17]

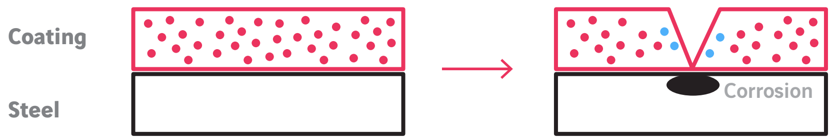


EXHIBIT 4: MECHANISM OF ACTION OF CORROSION DETECTING COATINGS

The optimal pH indicating molecule is phenolphthalein (PhPh) due to its high colour contrast during pH variation, being colourless when the pH value is lower than 8.2 but turning into bright pink at a pH range of 8.2–12.0. As for metal ion indicators, phenanthroline and its derivatives are regarded as the most efficient, displaying an intense red colour through a chromogenic reaction with ferrous ions.[17]

What makes it special?

Corrosion leads to significant deterioration in the overall properties and functionality of metallic materials, posing a great threat to structural integrity, life safety, environmental preservation, and economic progress.[17]

The estimation of corrosion loss in industrialised countries including USA, UK and Japan, has been calculated to be up to **5% of their Gross Domestic Product** (GDP). Moreover, **anti-corrosion costs of concrete structures are known to increase by a factor of 5** in each successive stage in the corrosion process (e.g., early corrosion, pitting corrosion, cracking, and severe corrosion damage, etc.). Therefore, it is crucial to promptly detect and address the initial stages of corrosion in order to minimise maintenance expenses and prevent catastrophic incidents.[18]

The most widely used method for corrosion mitigation is **protective coatings**, which serve as a physical barrier against corrosive reactions of the underlying metallic substrates. Nonetheless, these coatings are vulnerable to damage from mechanical or environmental factors throughout their lifecycle, including construction, transportation, and service. The deterioration of the protective coatings is only detected once corrosion has already appeared. Thus, the repair or replacement of the material becomes more expensive and labour-intensive. As a result, there has been a growing interest in the past decade towards the development of **smart coatings that possess self-reporting capabilities at early stages**.[19]

Through their built-in indicators, **self-reporting coatings can rapidly provide feedback on the corrosion condition** of the underlying metals and identify active corrosion sites before visible corrosion products form. Apart from directly incorporating indicators into coatings, the **micro-/nano-encapsulation of indicators is often required**. This approach provides physical isolation from the coating matrix and enables stimuli-triggered releases of the indicators.[17]

Micro- and nano-encapsulation approaches allow the combination of compounds, achieving smart coatings that include both corrosion indicators and self-healing agents.[20] The combination of self-reporting and self-healing functionalities in corrosion-detecting coatings results in a synergistic effect. This allows for early corrosion warnings and efficient suppression of corrosion activities before artificial repairs become necessary to address the damages. Consequently, the comprehensive properties of the coatings are improved, enhancing their overall performance and durability.[17]

Examples in the field

The current research goals in the development of self-reporting coatings are related to improving the sensing principles, enhancing the performance of fluorescence or coloration, and finding environmentally friendly encapsulation technologies. [17,21]

It is important to note that the technology is still in its early stages of development and has not yet become widely available in the market. Despite this, research centres and a few startups are actively paving the way for future advances and the potential commercialisation of corrosion-detecting coatings able to self-report, but with more emphasis on self-healing. As further progress is made, it is anticipated that smart coatings, including corrosion-detecting, will gain broader adoption, achieving an estimated market size of USD 26,727 Million by 2030.[22]

NASA

Corrosion poses a significant concern at NASA's Kennedy Space Center in Florida. The centre's facilities and metal structures are exposed to a combination of factors, including high humidity, salt, UV light, and exhaust emissions from rocket launches. This exposure creates an environment conducive to corrosion initiation and progression.[23]

For this reason, scientists at Kennedy Space Center, led by Dr. Luz M. Calle, the technical lead for the Corrosion Technology Laboratory in the Research and Technology Programs Directorate, have made significant strides in the **development of Smart Multifunctional Coatings for Corrosion Detection and Control in the Aerospace Industry**.[23,24]

Their patented technology consists of a **multifunctional smart coating for the autonomous control of corrosion**. It is being developed to be inherently able to detect chemical changes associated to early corrosion stages and respond autonomously to warn about and control it.[24]

DR. LUZ M. CALLE, THE TECHNICAL LEAD FOR KENNEDY SPACE CENTER'S CORROSION TECHNOLOGY LABORATORY, CHECKS OUT SAMPLE TILES AT THE BEACHSIDE CORROSION TEST FACILITY - NASA

Vuronyx Tech

BOSTON, USA
—

$2.26M TOTAL FUNDING
—

NOT YET COMMERCIALISING
—

TRL 3-4
—

Vuronyx Technologies in an early stage start-up focused on commercialising novel material science-based technologies and products. Sponsored by the Office of Nuclear Energy of the United States, in 2021, the company started a project to **develop a coating that will be able to provide early indication of corrosion in nuclear storage stainless steel casks**. For this, they are investigating the use of coatings for detection of iron and chromium ions using rhodamine based metal chemosensors.[25]

In previous research, rhodamine derivatives had been reported as complex-forming ligands with transition metal ions, leading to a phenomenon known as chelation-enhanced fluorescence (CHEF). With their investigation, Vuronyx Technologies have successfully synthesised two polymer precursors incorporating a metal ion-selective chemosensor derived from rhodamine B (RhB). X6X The technical report for the research is expected to be released as soon as January 1, 2040.[25]

LEGEND

HEADQUARTERS
—

FUNDING
—

TERRITORIAL REACH
—

TECHNOLOGY READINESS LEVEL
—

Maturity of the tech

The technology applied to the built environment is currently between experimental POC and prototype level.

TRL 0	TRL 1-2	TRL 3-4	TRL 5	TRL 6-7	TRL 8	TRL 9
Idea	Scientific validation	Experimental POC	Prototype	Minimum viable product	Industrialisation	Commercialisation

The increasing **demand for smart coatings in the market is primarily driven by their remarkable ability to detect corrosion** on various surfaces. This leading aspect is revolutionising corrosion management by minimising the need for extensive repairs in corroded areas, thereby prolonging the lifespan of components and structures susceptible to corrosion. Smart coatings exhibit a range of corrosion protection capabilities, including warning systems, sensing mechanisms, corrosion inhibition, and repair functionalities. From these four trends, the **pH triggered self-healing coatings** are the ones gaining most attention, focusing on developing multifunctional microcapsules to accomplish this. Nonetheless, the technology still finds itself under research and development, pushed by the demand from the electronics, automotive, military and aerospace industries.[22]

Key roadblocks to overcome

PROPERTIES

Incompatible with all surfaces

The effectiveness of corrosion sensing can vary depending on the compatibility between the sensing species and the composition of the metal substrate. Therefore, there is a need to find new indicators that respond to a variety of corrosion-induced environmental changes. As an alternative solution, the use of nanocontainers such as micro- and nano-capsules, offers a way to overcome compatibility issues by effectively insulating the indicators from the coating components. Furthermore, nanocontainers can also enhance the sensing sensitivity of the coating.[17,18]

Opaque coatings

Incorporating visible colour indicators in coatings requires the careful selection of a chromogenic substance that exhibits a distinct contrast to the colour of the coating surface. While chemicals such as PhPH or rhodamine have the ability to change colour within specific pH ranges, they require transparent coatings to be embedded within. However, their practical adoption in industrial or commercial settings may be hindered, as in commercial coatings it is common for the formulations to include auxiliaries, additives, or fillers, which renders them opaque. In this case, fluorescence indicators have an advantage, as they can still be effectively captured and analysed.[17,18]

Indicators with toxic components

The presence of certain toxic components within indicators or nanocontainers used in self-reporting coatings are raising concerns regarding their potential environmental and biological impacts. Numerous studies have focused on the corrosion detection capabilities of these coatings, but less have addressed the biological toxicity and overall environmental impact associated with their use. Nonetheless, due to increasingly stringent environmental regulations, many commercially available corrosion protective coatings have faced bans, pushing forward the investigation into eco-friendly alternatives. For instance, the aforementioned scientists of NASA's Kennedy Space Center have developed an environmentally friendly smart coating that could be used in the future to detect and stop corrosion in metal.[18,23,24]

SCALING UP

Only tested in controlled environments

The metal ions generated as a result of corrosion are typically present at low levels. In controlled experimental environments, synthetised coatings have demonstrated favourable detection. However, real-world conditions often involve a corrosive media with multiple chemicals that can convert metal ions into chemically inert molecules. Consequently, accurate monitoring of corrosive ions over prolonged periods becomes challenging. Moreover, in alloys where various metal ions coexist, indicator molecules must exhibit exceptional sensitivity and anti-interference capabilities. For this, employing a fluorescent indicator with exceptionally high brightness can enhance the sensitivity of corrosion detection.[18]

Short durability of the signal

Considering that self-reporting coatings will be used in harsh environments (salinity, humidity, acidity, or alkalinity), it is crucial to assess the longevity of the capsule-containing indicators in outdoor settings. Moreover, in practical applications, the duration between coating maintenance intervals can be considerable. Thus, the long-term performance must be established through research. To enhance stability and durability, researchers should first explore the prolonged activity of sensing species and carefully select appropriate fluorescent or colour indicators. Also, they should modulate the release of indicators based on pH changes or the appearance of metal ions within the corrosive environment. With this, premature leaching of indicators before corrosion occurs will be prevented, optimising effectiveness.[17]

Ecosystem & Actors

	Corrosion-detecting coatings	Corrosion-protective coatings
Commercialised	Autonomic Materials; NEI Corporation	AkzoNobel; DUPONT; NEI Corporation; BASF We create chemistry; JOTUN; PPG; DOW; BAYER; SHERWIN WILLIAMS
Not commercialised	Vuronyx Tech; BASF We create chemistry	

Entities promoting corrosion-detecting coatings

- NASA
- Department of Energy, United States of America
- European Commission
- COATALIFE

Corrosion mitigation can be tackled through corrosion-protective coatings, which serve as a physical barrier from environmental factors for the metallic substrates.[19] This approach was first suggested in 1985, and since then has been the dominant strategy for corrosion mitigation, with a market size of USD 10.1 billion in 2023.[26,27]

On the other hand, smart coatings, being advanced materials with predefined properties that allow them to sense and respond to external stimuli, require more extensive research.[22] Therefore, the **smart coatings market size is currently at USD 5.15 billion**, half of the stated value for corrosion-protective coatings.[28] Moreover, the smart coating market is further divided according to their function into: anti-icing, anti-corrosion, antimicrobial, antifouling, self-healing, self-cleaning, and others. Hence, the market size for corrosion-related smart coatings becomes even more diluted. Nonetheless, **anti-corrosion, self-cleaning, and self-healing are the leading technologies** of this segmentation.[22]

The aforementioned market data reveals why it is reasonable that large multinationals are grouped in the mapping above as those that commercialise traditional corrosion-protective coatings. Meanwhile, in the area of corrosion-detecting coatings, there is a lower density of actors. Here, the two commercialising companies, consisting of the startup Autonomic Materials and the multinational NEI Corporation, **focus on delivering self-healing coatings for corrosion**, but do not cover self-reporting coatings.[28,29]. Thus, their products are able to sense the corrosive environmental factors and respond to fluctuations through the release of healing agents, but no colour or fluorescence shift in the affected area is used. In this sense, BASF is also actively participating in research for self-healing corrosion-detecting coatings, though no product of such type has been commercialised yet.[30] The **only identified actor for self-reporting corrosion-detecting coatings is the startup Vuronyx Technologies**, whose project has been examined in the previous pages of this report.[25]

As seen with the examples in the field, **NASA is one of the key players** to develop new and sustainable corrosion-detecting coatings due to the need for them in their facilities.[23] In Europe, the European Commission is also engaged in research, financing projects such as **COAT4LIFE, which aims to develop eco-friendly multifunctional coatings** that have the ability to detect and protect from corrosion based on different mechanisms that combine nanostructured inhibiting and sensing additives.[31]

2.2 ENERGY-EXCHANGING MATERIALS

"The future of construction lies in those technologies aimed to promote resilient buildings."

Claude-Sebastien Lerbourg, Director of External Ventures Europe at Saint Gobain

The essentials of energy-exchanging materials

Energy-exchanging or “first law” materials are smart materials that produce an output energy from an input according to the first law of thermodynamics, meaning energy is converted from one type to another.[5] This property becomes especially relevant for reducing energy consumption in buildings and, therefore, improve energy efficiency.[26] Overall, energy-exchanging materials can be used to conserve energy and reduce costs associated with heating, cooling, and lighting.

In first law materials, the **energy state is altered** by the input energy, but the material composition stays the same.[5] Depending on the type of input energy these smart materials are able to receive, and the processed output energy they give as a result, there are several classes of energy-exchanging materials that transform energy from one form to another:[5,33]

	Type	Input	Output
Light-emitting	Photoluminescent	Radiation	Light
	Electroluminescent	Electric potential difference	Light
	Chemiluminiscent	Chemical reaction	Light
	Thermoluminescence	Temperature difference	Light
Reversible	Electrorestrictive	Electric potential difference	Deformation
	Magnetorestrictive	Magnetic field	Deformation
	Piezoelectric	Deformation	Electric potential difference
	Thermoelectric	Temperature difference	Electric potential difference
Non-reversible	Light-emitting diodes	Electric potential difference	Light
	Photovoltaics	Radiation	Electric potential difference

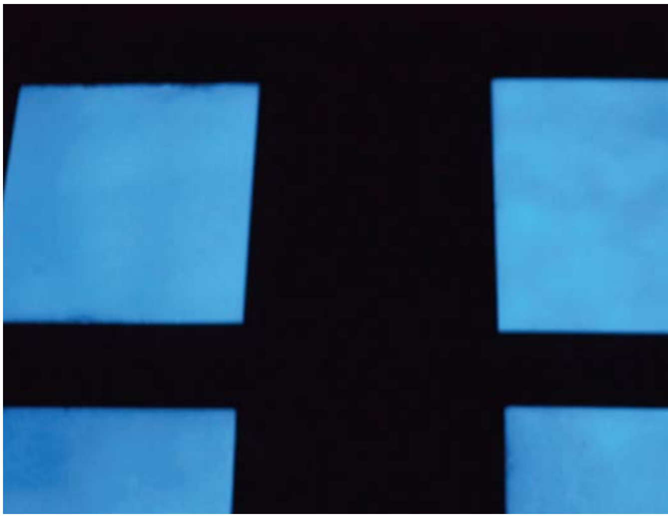
EXHIBIT 5: TYPES OF ENERGY-EXCHANGING MATERIALS

The **properties of these materials are determined by their molecular structure or microstructure**. Therefore, construction specialists must understand the material behaviour in relation to the phenomena and the environment they create. This way, the advantages these technologies have to offer will be applied to a variety of designs, including new and retrofitted buildings.[5]

Examples of energy-exchanging materials in construction

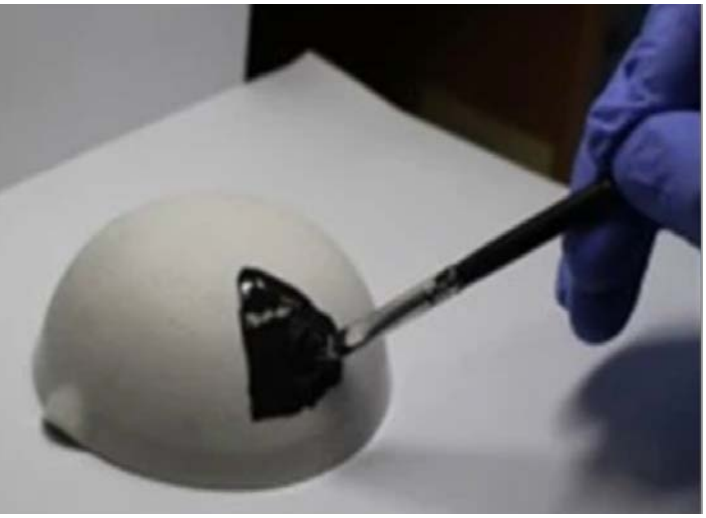
Light-emitting cement

Light-emitting cement is a smart construction material in research/development stage with a lifespan of 100 years.[34] Developed by Dr. Jose Carlos Rubio from the Michoacan University of Saint Nicholas of Hidalgo in Mexico, this cement presents an altered microstructure to enable the absorption of solar energy during daylight and the subsequent emission of light in darkness.[34,35]. Conventional cement, being an opaque material, does not permit the transmission of light through its interior. The addition of water to cement during its production triggers a hydration reaction, leading to the formation of crystal flakes which act as barriers, hindering the absorption of solar energy. In contrast, light-emitting cement has an altered microstructure that eliminates the presence of crystals, thereby allowing incoming light to deeply penetrate the cement structure.



LIGHT-EMITTING CEMENT - INVESTIGACIÓN Y DESAROLLO

Additionally, the material is rendered phosphorescent though additives that alter its optical properties, enabling it to absorb and subsequently release solar energy.[35] During daylight hours, the light-emitting cement structure functions as a storage device. The entire mass absorbs sunlight, causing the electrons within it to become excited. When night falls, these electrons transition back to their original state, resulting in the emission of light.[35] as a result, this unique cement has the capacity to provide continuous illumination for a period of 12 hours without the need for electricity.[34] Furthermore, the manufacturing process of the new material is also ecological, as the combination of its raw materials (silica, river sand, industrial waste, alkali, and water) forms of a robust mixture with a gel-like appearance from which the sole by-product is water steam.[34,36]



THERMOELECTRIC PAINT BEING APPLIED TO AN ALUMINA HEMISPHERE - PARK SH, ET AL. (2016). NATURE COMMUNICATIONS

Thermoelectric paint

Thermoelectric materials are able to convert temperature differences into electricity, and vice versa. Generally, these materials come as solid-state engineered devices, which limits their use to flat areas. However, considering that the surfaces of most heat sources are curved, heat loss becomes inevitable, reducing the heat-saving effect that the product aims to achieve.[37] To address this issue, researchers from Ulsan National Institute of Science & Technology in South Korea developed a shape-engineerable thermoelectric painting, geometrically compatible to surfaces of any shape.[37] Their end goal is to apply the technique to large-scale heat source surfaces such as buildings or even ship vessels.[38]

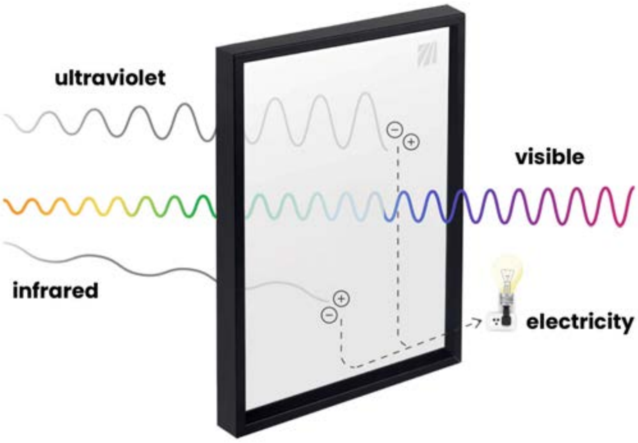
The thermoelectric paint contains particles of bismuth telluride, which is arguably known as the best thermoelectric material at near room temperature. Moreover, the formulation also includes molecular sintering aids that, when subjected to heat, prompt the thermoelectric particles to merge, resulting in higher particle density within the paint. Thus, this enhanced particle density contributes to improved energy conversion efficiency.[38]

To demonstrate the viability of the proposed technology, the researchers successfully constructed thermoelectric generators by applying the paint onto various substrates, including flat, curved, and large-sized hemispherical surfaces. This innovative approach showcased its effectiveness in collecting heat energy from diverse heat sources, achieving an exceptionally high output power density (4.0 mW/cm2). This result stands as the highest reported value among printed thermoelectric generators, highlighting the significant advancements made by this technology.[39]

Transparent solar technology[40]

Ubiquitous Energy is a next-generation technology company that develops and commercialises truly transparent solar technology for architectural glass.

Traditional solar window technologies often face trade-offs in terms of transparency, colour, obstruction of viewing area, haze, or energy efficiency, which pose challenges in their widespread adoption as direct replacements for standard windows. However, Ubiquitous Energy has pioneered UE Power™, the world's first electricity-generating alternative to traditional windows that offers both aesthetic appeal and functionality. This breakthrough innovation provides a solution that overcomes the limitations of conventional solar windows, offering a viable and visually pleasing option for incorporating solar energy generation into architectural designs.



UE POWER™ SELECTIVE HARVESTING TECHNOLOGY - UBIQUITOUS ENERGY OFFICIAL WEBSITE

As illustrated in the diagram on the right, UE Power™ is a transparent solar coating that efficiently captures 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.

This innovative coating is composed of light-absorbing dyes derived from non-toxic, abundant materials, much like the pigments commonly used in fabrics and paints. This unique formulation enables Ubiquitous Energy to seamlessly integrate power generation capabilities into windows and various everyday objects, preserving their aesthetic appeal and functionality without any compromise.

Why focus on piezoelectric materials?

Energy-exchanging materials can **recover internal energy in a usable form**. In terms of construction, this characteristic can help to reduce energy consumption in buildings, improving their energy efficiency.[33]

In that regard, a promising first law material for construction is **piezoelectric material**. These are capable of producing electric currents when subjected to mechanical stress and vice versa. Several naturally occurring materials exhibit this property, and their earliest applications date back to the First World War as radar detectors, super-sensitive microphones, sonar devices, or smart sensors in weapons. However, it has not been until recently that piezoelectric materials have shown to be applicable in the design and construction of self-sustainable buildings, through smart sensing and energy harvesting.[41] Therefore, due to their novelty and their potential impact in sustainability, this technology will be further developed in the following pages.

Sustainability check

Material sourcing ●

Raw materials must be processed and even chemically treated to become piezoelectric.

Construction and operational ●

Applying this technology to buildings can help improve the energy efficiency and the use of renewable energy sources.

Extended resilience and life cycle potential ● ●

If the piezoelectric material consists of a composite, it can be difficult to recycle.

Electrical power through mechanical stress

The term "piezoelectricity" is a combination of two words: "piezo," derived from the Greek word for pressure, and "electricity," relating to electrical charges.[42] When mechanical strain or vibration energy is applied to a piezoelectric material, it is able to turn it into an electric potential difference.[43]

The energy-exchanging property of piezoelectric materials is reversible:[41]

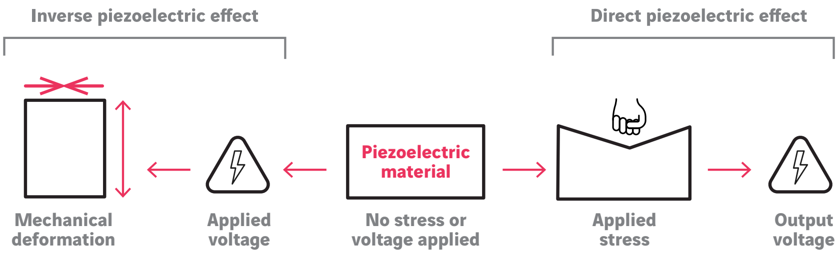


EXHIBIT 5: MECHANISM OF ACTION OF PIEZOELECTRIC MATERIALS

The direct piezoelectric effect, also known as generator or sensor effect, describes the electrical charge that is produced when a mechanical stress is exerted on the material. On the contrary, the indirect piezoelectric effect is the property of the material to develop the strain when an electrical charge is applied.[42]

These effects were first discovered in 1880 by the Curie brothers, Jacques and Pierre. Since then, it has been applied to multiple scenarios.[41] Recently, this property has shown to present opportunities for **harnessing renewable and sustainable energy through power harvesting**, and enabling self-sustained smart sensing in buildings.[43]

What makes it special?

Buildings are exposed to natural vibrations from human movements, vehicle passages, winds or machinery, that can affect the structure in the long term. With the use of piezoelectric materials, it could be possible to **obtain electric energy from this mechanical stress, at the same time that vibrations are controlled**. In this way, the building could become self-sustainable in terms of electricity, and the consumption of natural resources to produce energy would be reduced.[44]

The process of converting unused energy resources, such as mechanical stress, into electricity is known as **energy harvesting**. Due to their high power density, architectural simplicity and scalability, piezoelectric materials have emerged as the preferred option among various smart materials with energy harvesting potential.[43]

When comparing piezoelectric materials to the other two types of vibration energy harvesting approaches, electromagnetic and electrostatic, we see that piezoelectric materials produce higher power density outputs (3 to 5 fold higher power density).[43,45] Moreover, whilst electromagnetic harvesters are preferable for large and centralised equipment, and electrostatic is suitable for very small systems, **piezoelectric converters are applicable for all equipment sizes and, therefore, they are suitable for implementing within buildings**.[43]

	Power efficiency	Flexibility of implementation	Suitable for buildings
Piezoelectric	⊕	⊕ ⊕	⊕ ⊕
Electromagnetic	⊖	⊕	⊖
Electrostatic	⊖	⊕	⊖

EXHIBIT 6: ADVANTAGES OF PIEZOELECTRIC HARVESTERS

Examples in the field

To achieve self-sustainable buildings, the piezoelectric effect should be intrinsic of commonly used construction materials. Unfortunately, this is not the case for concrete, and for timber, even if the material is able to generate an electrical charge under mechanical stress, it is not very strong.[46]

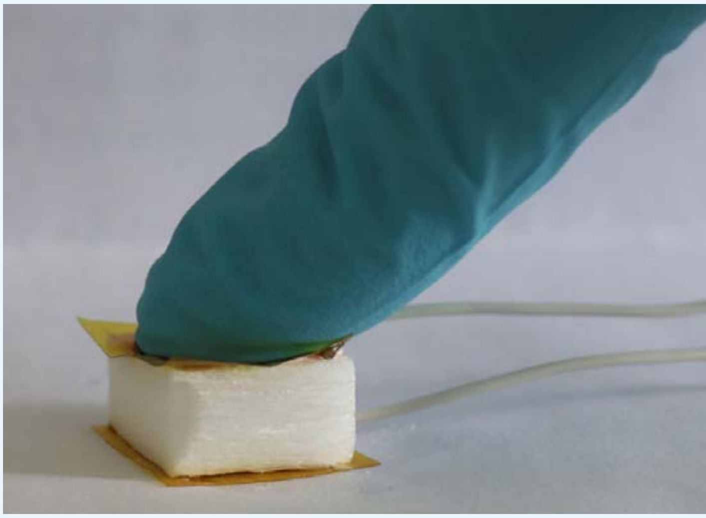
Nonetheless, research is currently underway to integrate piezoelectricity into conventional construction materials. By infusing these traditional materials with piezoelectric capabilities, it is envisioned that buildings and infrastructure could not only fulfil their primary functions but also generate electricity from mechanical stress and vibrations. This advancement has the potential to revolutionise the way we think about energy generation in the built environment, offering sustainable and self-powered structures that actively contribute to renewable energy goals.

Voltage from a wood sponge

Researchers from ETH Zurich and Empa have discovered that by removing lignin from wood, the stiff cellulose is prevented from buckling, enhancing deformability and also therefore, the piezoelectric effect.[46,47]

In a first attempt, scientists achieved this "delignification" by placing wood in a mixture of hydrogen peroxide and acetic acid.[48] However, in a follow-up study, the team aimed to produce the wooden sponge without using chemicals and found a natural solution: the fungus Ganoderma applanatum. This organism degrades the lignin and hemicellulose from wood through white rot, and is more friendly to the environmentally than chemicals.[46,48]

With the wood decay fungus, piezoelectricity from wood is increased by 55 times, meaning that after 10 weeks of infection, blocks of decayed wood can power LEDs.[48]
Currently, the group is at the demonstrator scale, with the aim of using the technology as sensors integrated into wooden floors.[46]



LITTLE PRESSURE CAN GENERATE USABLE ENERGY IN THE WOODEN SPONGE - ACS NANO / EMPA

PAVEGEN

LONDON, UNITED KINGDOM
—

$17.1M TOTAL FUNDING
—

WORLDWIDE
—

TRL 8-9
—

Pavegen Systems, founded in 2009 by Laurence Kemball-Cook, is a technology company specialising in the development of interactive floor tiles. These innovative tiles have the ability to convert footsteps into small amounts of electrical energy while also providing valuable data insights and engagement opportunities for global brands, businesses, and governments.[49] The company initially faced unsatisfactory results with their first prototype in 2009, but a significant breakthrough occurred in 2016 when they unveiled a new model of their smart floor. This updated version consisted of unique, three-sided "tiles" that could depress by a few millimetres when subjected to the pressure of footsteps and subsequently return to their original position. As individuals walk on the floor, the pressure activates three coils, initiating the generation of electrical energy. This energy is then stored in lithium batteries for later use, ensuring efficient utilisation of the harvested power.[50]

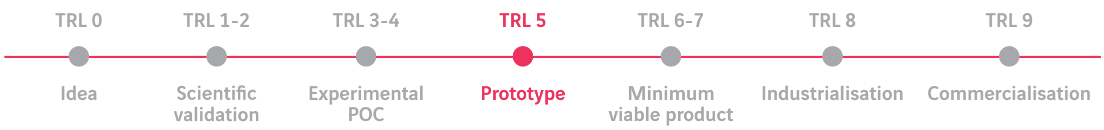
The system offers a notable advantage, as approximately 80% of its tiles are constructed using recycled materials including car tyres, truck tyres, and reclaimed concrete from structures destined for demolition. By utilising these recycled materials, the Pavegen system demonstrates a commitment to environmental responsibility throughout its production cycle while simultaneously facilitating the generation of clean energy.[50]

LEGEND

HEADQUARTERS
—
FUNDING
—
TERRITORIAL REACH
—
TECHNOLOGY READINESS LEVEL
—

Maturity of the tech

The technology applied to construction materials is currently at prototype level.



Piezoelectric materials have been demonstrated to be useful for self-powered sensing, energy harvesting and as stimulators. Nonetheless, few piezoelectric products have been realised, only in the electronics market as composites. In terms of construction, no commercialised products are available yet. However, it is anticipated that new materials exhibiting enhanced properties will find widespread applications across diverse fields in the near future. One significant example is the development of piezoelectric energy harvesters in heat transfer applications involving fluid flow. This advancement holds promising potential for extracting energy from such thermal processes. Moreover, the exploration of novel piezoelectric materials and unexplored vibration sources is also expected to drive increased attention towards piezoelectric energy harvesting.[45]

Key roadblocks to overcome

PROPERTIES

Small power density

Until now, the voltage generated by piezoelectric harvesters has proven to be adequate for sensor nodes and low-power lights, with a power in terms of milliwatts (mW). Nonetheless, this energy is not always continuous, and is too low for higher building facilities. The pursuit of materials that can produce a moderate voltage, higher current (demanding a higher piezoelectric constant), and possess satisfactory scalability and manufacturability is the key objective. Additionally, it will be desirable for these materials to be cost-effective so that they can be compared to current technologies such as solar cells. This way, their viability and competitiveness in the market will be ensured.[43,51]

Environment Susceptibility

In order to accommodate the unique mechanical energy characteristics of different working conditions, it is important to consider the specific geographic, thermal, and functional aspects of buildings. These factors contribute to the wide array of energy sources available. As a result, enhancing the properties of piezoelectric materials and the design of energy harvesters becomes essential to ensure their optimal performance in their respective environmental conditions. By tailoring these materials and designs to suit specific contexts, the efficiency and effectiveness of piezoelectric energy harvesting systems can be maximized.[43]

Unknown long-term

Enhancing the long-term stability, mechanical strength, and chemical durability of piezoelectric generators is crucial. Buildings have a lifespan that can extend over several decades, and the durability of materials may be affected by factors such as weathering, creep, aging, and chemical reactions. Therefore, further research is recommended to gain a better understanding of the long-term performance of piezoelectric building components. This knowledge will contribute to the development of robust and reliable piezoelectric materials and systems that can withstand the rigours of extended service life in buildings.[43]

Lack of building applicability

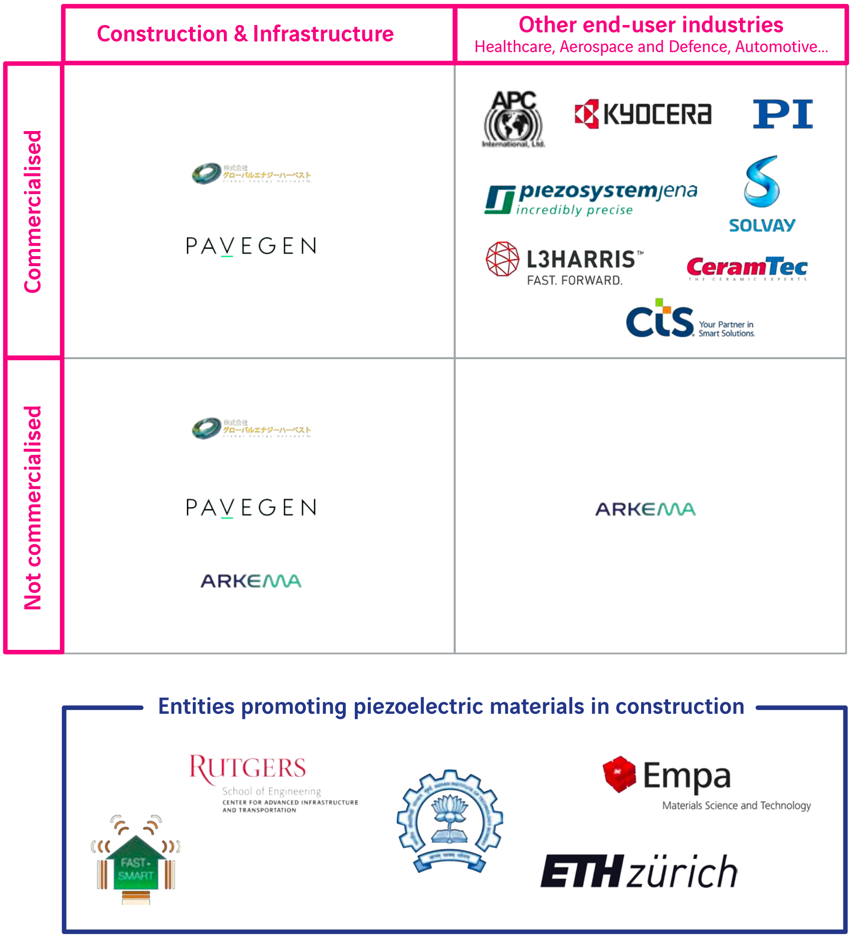
Building structures that are compatible with the integration of piezoelectric materials can serve as a viable platform for improving energy conversion efficiency. Therefore, efforts should be directed towards optimising building structural designs to enhance the efficiency of electromechanical conversion. Additionally, there is a need for further studies from the perspective of building designers, exploring innovative approaches and strategies to maximise the benefits of piezoelectric materials in building design and construction. By considering the unique requirements and opportunities presented by buildings, designers can contribute to the advancement of piezoelectric technologies and their seamless integration into the built environment.[43]

SCALING UP

Poor market applicability

As the technology is still in very preliminary phases, its application in the construction industry has yet to be well defined. A possible way to enter the market more easily is by finding niche applications. Considering areas such as harsh environments, inaccessible locations, emergency situations, extreme conditions, or military applications is an important task for the future of energy harvesters. For instance, the niche field of engineering structural health monitoring has shown to be promising.[51]

Ecosystem & Actors



Currently **commercialised piezoelectric materials come in the form of sensors or actuators**, meaning they are embedded in an electronic device as part of a broader composite. The most widely used material for this application is lead zirconate titanate. However, due to the presence of lead in the compound, which is poisonous to humans, regulations such as the Restrictions of Hazardous Substances (RoHS) Directive 2002/95/EC limit their use. Therefore, to find alternative polymers with piezoelectric properties is an ongoing research area in order to have compliant materials.[52]

As seen in the mapping above, **piezoelectric material products are mostly found in end-user industries that are not related to construction** and infrastructure. For those, the automotive segment is the major contributor, largely due to the increasing demand for electric vehicles.[53] Moreover, piezoelectric applications for healthcare have seen an exponential growth since the COVID-19 pandemic as, in combination with healthcare electronics, they served to study the coronavirus and its traits. For instance, PI Ceramics developed piezoceramics that enabled precise liquid handling for an early in vitro diagnosis of the disease. Also, defence activities have experienced an increase in budget, with governments investing in missile guidance systems, drones, and radars. Thus, piezoelectric research and applicability toward armed forces have been heavily boosted.[52]

Note that this mapping aims to showcase the difference that exists between an almost inexistent piezoelectric materials market for construction, and a developed market for other applications. Therefore, not all existent companies for other end-user applications are included here, as our research focus in this report is the construction industry.

The main **actors responsible for the development of piezoelectric applications in construction are research institutions**. We can take as an example the already explored piezoelectric wood research from ETH Zurich and Empa, or the Indian Institute of Technology, where they are also developing a technique to enhance the power output of piezoelectric materials. Here, the applications with the most interest from the scientific community are those that seek to take advantage of the electrical energy produced from the mechanic pressure in floor tiles as humans walk on them.[53]

2.3

ALTERNATIVE RAW MATERIALS FOR SUSTAINABLE CONSTRUCTION

"Without a safe and sustainable supply of critical raw materials, there will be no green and industrial transition."

Margrethe Vestager
Executive Vice-President for a Europe Fit for the Digital Age

Alternative raw materials in construction today

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 contributes significantly to global carbon emissions.[53] 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. The **extraction, transportation, and manufacturing of raw materials have frequently resulted in the depletion of resources** and loss of biological diversity, impacting both fauna and flora. The fossil fuel **energy consumption associated with these processes produces emissions that contribute to climate change** and acid rain. Moreover, **construction waste often contaminates air and water**, posing significant health and safety risks.[54]

Increasing concern over such harmful impacts is translated into a rising popularity of alternative materials for construction. Consequently, the value of the global green building materials market is projected to skyrocket from **USD 422.27 billion in 2023 to a whopping USD 951.15 billion by 2030**, signifying a CAGR of 12.3% during that period.[55]

A few tangible examples of alternative materials are already in use today. For example, **plant-based polyurethane rigid foam is a type of foam** made from plant-based materials (a combination of bamboo, hemp and kelp) that can be used as insulation. Also, cork is a renewable resource that can be used as insulation, flooring, and wall coverings. And even recycled plastic can be used to produce concrete, reducing the need for new components.

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.[55]

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. This energy conservation can result in lower utility bills and a reduced carbon impact.[56]

From a financial perspective, **alternative materials can also be more cost-effective**. Using salvaged materials, for example, can bring down the overall construction cost and make construction projects more accessible to a wider range of people.[57] Embracing **alternative materials can contribute to waste reduction**. For instance, 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.[55]

Nevertheless, these promising alternatives are not fully at scale yet. As it has already been seen with new cement, the construction industry is **slow to adopt new materials and technologies**, preferring to stick to traditional materials that have been used for decades.[58] This is because new construction materials and technologies may require the whole manufacturing process to change or adapt, becoming difficult to apply in the short term.

Some examples of alternative construction materials

Bamboo

There are over 1,500 species of bamboo, but only a **few have the potential to be used as structural construction** materials.[59] It is very versatile and has been used in construction for centuries, particularly in countries where it grows abundantly such as in Asia, South America and Africa.

Bamboo is lightweight, strong, and flexible, making it **suitable for structures like bridges, scaffolding, and housing**.[60] Indeed, it can have a similar strength-to-weight ratio as steel and higher strength than some types of wood. Its high levels of flexibility makes it resilient to environmental forces like wind and earthquakes.[61]

Beyond its physical properties, bamboo is also a sustainable material. It grows very fast (some species can grow up to a meter a day), **absorbs carbon dioxide at a high rate**, and when harvested, regrows from its root system. This makes it an environmentally friendly alternative to concrete and steel which are resource-intensive materials with high energy requirements for production.[62]

Nevertheless, the adoption of bamboo in construction has been **hindered by a lack of standardisation** and building codes.[59]

Recycled Plastic

According to a Plastic Europe report, nearly **half of the post-consumer recycled plastic in Europe has been repurposed in the construction sector**.[63] Some of the most common applications of recycled plastics in construction include roofing tiles, concrete, indoor insulation, structural lumber, and PVC windows.[64]

In comparison to conventional building materials, plastics present an array of **benefits due to their lightweight nature**. They are considerably more manageable to transport, handle, and install, thereby streamlining the construction process. Additionally, they retain the requisite mechanical properties needed for robust construction applications, making them an efficient alternative.[65]

Despite its remarkable attributes, the adoption of plastic as a construction material has been relatively slow. This is predominantly due to a combination of factors: a **lack of awareness regarding its suitability in the building sector**, and **misconceptions regarding its potential hazards and toxicity in the event of a fire**.[66]

Ferrock

Developed by a former Ph.D. Student at the University of Arizona, this technology is based on **iron carbonate that uses almost entirely recycled materials to create an alternative to concrete** that is carbon-negative.[56]

It is manufactured using **waste steel dust generated from industrial processes**, which is combined with silica and other recycled materials.[67] The material is then bound with atmospheric CO_2, and assumed to **absorb 8-11% of CO_2** by weight from the environment.[68]


A DOMED STRUCTURE UNDER CONSTRUCTION MADE ALMOST ENTIRELY OF FERROCK. IMAGE © DAVID STONE

The formulation of Ferrock has low embodied energy, lower consumption of natural resources, and minimal climate impact, a scale from one to ten versus Ordinary Portland Cement.[69] Despite all the pros of Ferrock, the cons include its **high cost and the need for further research** to determine its long-term durability and structural properties. However, it is still an interesting alternative to traditional concrete due to its potential to reduce the environmental impact of construction.

Timber

Cross-laminated timber (CLT) is an engineered wood product that is made by **gluing together layers of lumber boards at right angles to one another to form structural panels**.[70] CLT is particularly well suited to multistory, taller wood construction as it stands out with a strength-to-weight ratio that is equivalent to that of concrete, yet it weighs only one fifth as much.[71]

With its **incorporation into the International Building Code in 2015**, CLT has emerged as an environmentally friendly alternative material for constructing walls, roofs, floors, and even ceilings, showcasing its versatility and utility in modern construction.

The use of CLT in construction is promising due to its sustainability, versatility, and cost effectiveness compared to traditional housing materials. CLT is a **carbon-negative material that stores carbon** and has a smaller environmental footprint than traditional materials. However, **feasibility, as well as cost competitiveness, can vary greatly depending on the type and complexity of the project**.[73]

Similarly to CLT, the french startup Woodoo developed the SOLID technology. It is a process that transforms wood into a material with the mechanical strength of steel but with a better weight-strength ratio. The process involves removing lignin, which is the natural "glue" between wood fibers, and replacing it with a binding agent that creates much stronger molecular bonds. This makes the wood completely inert to its environment. The result is a lightweight yet strong structural material that could be used by the construction sector as an alternative to steel.

Construction projects using alternative raw materials

Insulating with algae

In Hangzhou, China, architects have innovated a tower design featuring an algae biofacade, enhancing both the city's **green aesthetics and carbon absorption**. This design also **insulates the building**.

In Paris, a similar design, The Algo House, showcases a biofacade cultivating microalgae for medical research. It also integrates photobioreactors within its facade, which in turn **reduce energy consumption by repurposing the heat collected for domestic hot water and heating**. This aligns with Paris' climate plan, exemplifying innovative, sustainable architecture.

XTU ARCHITECTS. © XTUXTU_INVIVO

BYBLOCK STUCCO BOUNDARY WALL

Building with plastics

ByBlock has been developed by ByFusion, a pioneering product dedicated to sustainable construction and environmental stewardship. ByBlock is an innovative, eco-friendly **building material made entirely from unsorted, unprocessed plastic waste**, showcasing the company's commitment to recycling and reuse.

These blocks are modular, lightweight, and resilient, offering architects and builders a new degree of design flexibility. Additionally, ByBlock provides **superior insulation, is fire-resistant, and withstands extreme weather conditions**, making it a reliable choice for diverse climates.[74]

Why zoom in on Mycelium?

Mycelium, the root structure of mushrooms, possesses a unique composition making it a prime candidate for creating sustainable and eco-friendly insulation material. It exhibits remarkable **natural properties such as self-assembly and self-healing**, which provide significant advantages over traditional insulation materials. More importantly, it's **renewable and completely compostable**, addressing the mounting concern of construction waste. Furthermore, mycelium-based insulation demonstrates **exceptional thermal and acoustic performance**, rivalling synthetic counterparts while avoiding associated environmental costs.

The **technology used to grow and form mycelium into insulating products is not energy-intensive**, reducing the carbon footprint of its production. With these attributes, mycelium holds tremendous potential for revolutionising the insulation sector within the construction industry, offering a sustainable and high-performance alternative that aligns with the future goals of green building.

Sustainability check

Material sourcing

The product is made of renewable resources and waste streams.

Construction and operational

The manufacturing process consumes 90% less water, utilises 40% less energy and emits 60% less CO_2 than polystyrene.

Extended resilience and life cycle potential

Proper waste management and recycling are ensured with this technology, as mycelium composites are renewable and appropriate for circularity.

Insulating with fungi

Mycelium is a network of fungal threads that can grow underground or in substrates such as wood, fusing into a solid material. When combined with a natural filler, it creates mycelium composites, a biodegradable and non-toxic material that provides good insulating, acoustic and fire performance.[75]

Mycelium composites' manufacturing is comprised of six tuneable steps:[76]

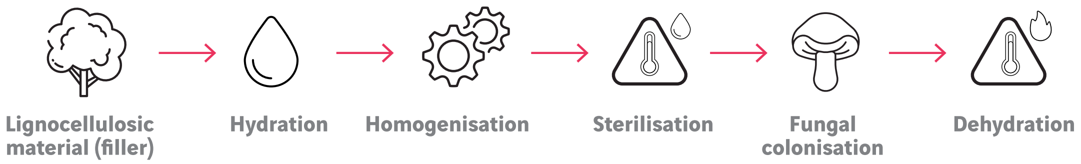


EXHIBIT 7: PRODUCTION PROCESS OF MYCELLIUM COMPOSITES

The process starts with **any material that can sustain fungal growth**, usually being lignocellulosic material. This substrate is first soaked in water to hydrate, as moisture is important for fungal growth. The hydrated raw material is then homogenised to increase the growth surface area, and later sterilised to remove the existent microbial competition. Composite assembly itself is completed using a natural fungal growth process, which **binds the lignocellulosic material into 3D geometries mirroring the mould shape** that the substrate is packed into. Following the growth period, the composite materials can be removed from the moulds and hot-pressed, oven or air dried to dehydrate the material and neutralise the fungus.[76]

What makes it special?

Mycelium composites offer a range of **material properties that can be tailored** to specific needs through their composition and manufacturing process. They have the potential to serve as **alternatives to foams, timber, and plastics** in various applications including insulation, door cores, panelling, flooring, cabinetry, and other furnishings.[76]

Most importantly, mycelium composites show particular **promise as thermal and acoustic insulation material**, due to their low density and thus lower thermal conductivity, and to their porous and fibrous texture, respectively.[76,77]

In terms of insulation properties, mycelium composites are **competitive with the most conventional materials**, those being synthetic foam (polystyrene, polyurethane, and phenolic formaldehyde resin) and wood products (plywood, softwood, and hardwood). Therefore, they can be compared as follows:[76]

	Competitive pricing	Fire resistance	Thermal conductivity	Acoustic absorption	Biodegradation
Mycelium composites	+	+	+	+ +	+ +
Synthetic foams	+	− −	+ +	+	− −
Wood products	+	−	−	−	+ +

EXHIBIT 8: ADVANTAGES OF MYCELIUM COMPOSITES

As seen in exhibit 8, mycelium composites are **cost competitive** with both synthetic foam and wood products, and show a significant **advantage in terms of fire safety** over traditional synthetic insulation materials such as polystyrene foams, which is very flammable. Moreover, lignocellulosic agricultural or forestry by-products or wastes are commonly used as fibrous fillers, which facilitates the **waste upcycling and circular economy**, ensures the biodegradability of the material, and contributes to its low cost.[76]

Regarding manufacturing, the material is fabricated using a **low-energy, natural manufacturing process, which sequesters carbon**. The values on the right show that **mycelium composites act as a CO_2 sink**, helping achieve net zero or even carbon-negative buildings, in contrast with conventional construction materials which do not fix CO_2.[78]

860 MJ/m³
Embodied energy
1.5 - to 6-fold reduction compared with common construction materials

-39,5 kg/m³
Embodied carbon
In contrast with positive results in common construction materials

EXHIBIT 9: EMBODIED ENERGY AND CARBON OF MYCELIUM COMPOSITES [78]

MYKOR PRODUCT - OFFICIAL WEBSITE

Examples in the field

ecovative
We grow materials.

NEW YORK, USA
—

$91.1M TOTAL FUNDING
—

WORLDWIDE
—

TRL 8-9
—

Ecovative is a mycelium technology company that designs and grows sustainable materials from the **leftovers of agriculture** that would otherwise go to waste. They aim to provide sustainable alternatives for packaging, building materials, and leather, and are developing technologies for the use of mycelium in the food and beauty industries. Currently, their commercialised products are related to packaging, and the rest are under research. With regards to construction, with their **AirMycelium Technology, they produce their high-performance foam, Forager**, that replaces plastics and polystyrene.[79]

BIOHM

LONDON, UNITED KINGDOM
—

$1.73M TOTAL FUNDING
—

WORLDWIDE
—

TRL 8-9
—

Biohm is a research and development led biomanufacturing company. Their aim is to revolutionise construction and create a healthier, more sustainable, built environment. They have produced a **mycelium insulation panel, and they sell mycelium-based lampshades** for interior design. Their entire manufacturing process is completely regenerative, estimated to be carbon negative by **sequestering at least 16 tonnes of carbon per month**.[80]

GROWN bio

HILVERSUM, NETHERLANDS
—

N/A
—

EUROPE
—

TRL 8-9
—

GROWN bio is a biotechnology company, harnessing nature's intelligence to grow sustainable and compostable protective packaging, building material and interior design items from natural, regenerative and waste materials. They launched mushroom ® packaging in Europe and have collaborated with designers to introduce a range of interior items and artwork. Currently they are working on an innovation: **an insulation panel that can be used to transition the building industry to bio-based products**. They have realised wall panels to separate spaces or block out sounds.[81]

LEGEND
HEADQUARTERS —
FUNDING —
TERRITORIAL REACH —
TECHNOLOGY READINESS LEVEL —

Maturity of the tech

The technology applied to construction materials is currently between prototype and minimum viable product.

TRL 0	TRL 1-2	TRL 3-4	TRL 5	TRL 6-7	TRL 8	TRL 9
Idea	Scientific validation	Experimental POC	Prototype	Minimum viable product	Industrialisation	Commercialisation

The **potential of mycelium composites has been demonstrated in numerous research studies**, specifically in the areas of packaging[79 ,82,83,84,85], thermal insulation [82,86,87,88,89], and acoustic absorption foams[90,91,92]. Even if they are not completely adopted by the market, **acoustic and thermal insulation panels are already available as wall claddings**, where they do not carry the weight of the building.[91] This is because there is no current accreditation for mycelium composites' insulation panels as structural components in the professional industry, and they are only used when an exemption from the building regulations is obtained, or as wall cladding.[81] Thus, industrial traction in building materials is scarce, mostly limited to **small-scale prototypes and exhibition installations**.[77] Nonetheless, the global mycelium market is expected to grow at a CAGR of 7.4% until 2032, which forecasts a wider use of the technology in the future.[77,93]

Key roadblocks to overcome

PROPERTIES

Low strength for construction

A clay brick has a compressive strength of 69–140 MPa, while mycelium composites have a compressive strength of 0.35–0.75 MPa. Therefore, the conventional construction techniques used with self-supporting structures cannot be applied to mycelium composites, limiting their applicability in large-scale projects. Though, with appropriate computational design tools, stability can be achieved through geometry rather than material strength.[94]

Moisture uptake

One of the biggest issues limiting the use of mycelium composites is their tendency to absorb large amounts of water, increasing its weight by ~40–580 wt% when in contact with water for 48–192 hours. This is much higher than polystyrene (0,03-9 wt%) or other conventional synthetic foams, and can be a serious problem in leaking wall or roof cavities. Nonetheless, there are already alternatives under research to tackle water absorption. For instance, the use of particulate substrate fillers, such as beech sawdust, makes mycelium composites less susceptible to water uptake (20 wt%). Hot or cold pressed mycelium composites also experience less than half the water uptake (~250 wt%). Moreover, many bio-based coatings have also shown promise in reducing water absorption in natural fibre composites and could be applied to mycelium composites.[76]

Termite susceptibility

Like untreated wood products, mycelium composites have no termite resistant properties of their own. However, this can be improved through substrate selection. For example, hemp-based mycelium composites have high termite resistance, exhibiting high termite mortality rates. Moreover, natural termiticides such as guayule resin or vetiver oil can also be applied.[76]

SCALING UP

Slow manufacturing

The production steps of mycelium composites are comprised of a biological process with long cycles of production, risk of contamination, and an overall lack of consistency and reproducibility.[94] Due to this, the manufacturing process is slow and can take days or even months to complete, compared to synthetic foams and wood products which can be produced in minutes to days.[76] Ultimately, the scaling up of mycelium in both size and quantity to reach an industry-standard level of product certification is hindered. It must be noted that companies such as Ecovative and Biohm have started to address some of these considerations using genetic engineering, optimisation of fungal strains, and introduction of additional micro-organisms in the fabrication loop.[94]

Lack of information

There are still gaps in material properties' documentation which limits the application and usage of mycelium materials.[76] Patents are monopolised by a few startups and this prevents the distribution of knowledge to successfully mass-produce high-quality, standardised mycelium-based materials. The public's lack of general knowledge about the materials contributes to their lack of awareness regarding their existence and undermines confidence in their potential for large-scale applications beyond packaging alternatives and consumer products. Luckily, as mycelium-based research expands, its accessibility and visibility will increase, facilitating information dissemination across disciplines.[94] For instance, the Centre of Expertise Biobased Economy is promoting knowledge sharing through the Mycelium on Board Project, which aims to bring mycelium composites a step closer to the market, giving them visibility and increasing the possibility of a commercial breakthrough.[95]

Ecosystem & Actors

	Thermal insulation Wall panels	Acoustic insulation Wall cladding	Other applications Packaging, textiles...
Commercialised		mogu, GROWN bio, MYCEEN, MYCELIUM	MYCL, BOLT THREADS, MYCOWORKS, biomyc, BIOHM, MAGICAL MUSHROOM, GROWN bio
Not commercialised	BIOHM, biomyc, ecovative, mykor, MYCL, GROWN bio		ecovative

Entities promoting mycelium in construction

CLEANTECH BULGARIA · Centre of Expertise Biobased Economy (CoE BBE) · EIT Climate-KIC · stowa

As previously mentioned, the mycelium composites technology has been well explored in terms of research but is still missing accreditation in the professional construction industry.[81] For this reason, the **market trend is to commercialise products outside of construction** (e.g., packaging or textiles), or related to the interior design of the building (e.g., wall panels for insulation or furniture).

Taking a closer look at the mapping above, we see that BIOHM, MYCL, BioMyc, GROWN bio and Ecovative appear as companies that commercialise products for other applications, and also as companies with products for thermal insulation that have not yet been marketed. They follow this strategy in order to **expand their reach and take advantage of their expertise to meet the needs of more developed markets** from which they can obtain revenue. In the case of BIOHM and MYCL, their products, besides thermal insulation, are related to interior design and the textile industry, respectively. On the other hand, BioMyc, Grown.bio and Ecovative work with mycelium composites for the packaging industry, being the two latter big players in the field. For instance, back in 2016, Ecovative announced a partnership with IKEA to aid the furniture giant transition from polystyrene to the organic, mushroom-based packaging.[96] In the case of GROWN bio and

Ecovative, both companies have other applications of the technology in their pipeline, being interior design articles for Grown.bio, and not yet commercialised leather alternatives for Ecovative.

Notably, those **companies that only specialise in mycelium composites for construction are startups**, whilst the ones that diversify their products are more likely to become scaleups. Accordingly, entities are promoting research and aiding these startups to grow and gain financing, as they value the potential of the technology in construction and, above all, the fact that it is a sustainable alternative to conventional building materials. For instance, **EIT Climate KIC and Cleantech Bulgaria supported BioMyc** through the EIT Climate-KIC Regional Innovation Scheme Accelerator in Bulgaria in 2017, with mentoring, support and 92.000€. Thanks to this, the startup was able to form its core team, including a leading biotechnology professor, and produced its first prototypes. This same company was also honoured as the best green European startup at the Start-up Europe Awards 2018 by European Commissioner for the Environment, Karmenu Vella, and took second place and 10.000€ at the Sustainable Future Forum clim@ competition a month earlier.[97]

2.4

BIOMIMICRY FOR SUSTAINABLE CONSTRUCTION

"Innovation is alive – in both the figurative and literal sense. Bio-sourced materials are championing a return to low-tech, natural solutions and biomimicry."

Leonard
The three mutations of construction materials

The essentials of biomimicry

In an era marked by the growing emphasis on enhancing industrial sustainability and production processes, biomimetics is emerging as a promising avenue for boosting the energy efficiency of infrastructure. 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.[99]

In a few words, biomimicry is infusing biological strategies in the design of man-made structures. When doing so, three components are taken into account in every aspect of the approach:[98]

1 **Emulate**
The scientific, research-based practice of learning from and replicating nature's forms, processes, and ecosystems to create regenerative designs.

2 **Ethos**
The philosophy of understanding how life works and creating designs that support and create conditions conductive to life

3 **Re(connect)**
The concept that we are nature and find value in connecting to our place on Earth as part of life's interconnected systems

It is important to specify that the term "bioinspired design" is an umbrella concept for design and engineering approaches that use biology as a resource for solutions, including biomimicry. Nonetheless, while biomimicry is a type of bioinspired design, not all bioinspired design is biomimicry.[98]

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.[98]

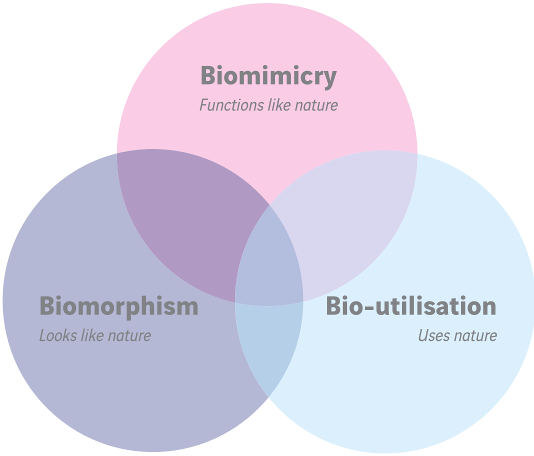


EXHIBIT 10: DIFFERENCE BETWEEN BIOMIMICRY, BIOMORPHISM AND BIO-UTILISATION

In contrast, biomorphism refers to designs that visually resemble elements from life, and bio-utilisation to the use of biological material or living organisms in a design or technology.[98]

Biomimicry in 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.[100] A direct result is a growing trend to prioritise sustainability and respect for the environment in professional approaches, which is led by the Sustainable Development Goals (SDGs).[99] 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**.[101]

Using nature as inspiration for creating architectural works is not something new. Take the Crystal Palace of Joseph Paxton as an example, or the works of Antoni Gaudí. Both renowned architects turned to nature to design buildings, featuring repetitions of shapes found in living organisms to optimise efficiency.[99,101]

However, **recent research has also demonstrated the applicability of biomimicry in construction and its materials**. Now, the aim is to maximise the potential of this field in order to build structures that are more efficient, develop zero-consumption systems, optimise resource management, enhance thermal comfort control, generate energy for buildings and finally, manufacture materials with improved properties, which is what we will focusing on in this chapter.[99]

Biomimicry in construction materials

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.[102] 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.[103]

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.[102] Here are some noteworthy examples:

Gecko-inspired adhesives[104,105]

Many species of gecko can walk up smooth surfaces like stone walls or glass. This is because their toes have microscopic hairs that help them stick to these surfaces. By mimicking gecko toes, researchers and companies have developed adhesives for a range of applications, including construction. For instance, geCKo Materials use the adhesives to move smooth, large or heavy objects with confidence or ensure stone slabs (e.g., marble, granite) or tiles are able to set and cure with coplanarity. With their directional dry adhesives, they eliminate toxic, noisy, energy-consuming vacuum pumps and increase safety in construction sites.

WOODFLOW, STRONG BY FORM - OFFICIAL WEBSITE

Wood-based composites[106,107]

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.

Lotus leaf

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 can help to reduce the amount of maintenance required to keep a building looking clean, and it can also help to prevent the growth of mould and mildew.

Why zoom in on self-healing concrete and self-cleaning surfaces?

In addition to the aforementioned examples, two particular biomimetic solutions possess transformative potential to shift towards a more sustainable and resilient construction. With the main aim of reducing building maintenance, self-healing concrete and self-cleaning are establishing a strong foothold in their markets.

On the one hand, self-healing concrete is gaining traction as a viable and easy to deploy alternative to conventional Portland Cement. This is noteworthy considering that concrete ranks as the second most consumed substance on earth after water. It accounts for **60% of the materials used in construction**, and its industry emits over **4 billion tonnes of CO_2 annually**.[108,109]

On the other hand, self-cleaning surfaces represent a novel integration of material science, nanotechnology, and architecture. When utilised on building facades, they have shown to **reduce maintenance costs over 50%**. In indoor environments, the technology ensures air quality comparable to that of a hospital, achieving an **85% reduction in harmful volatile organic compounds**.[110]

Following on, we will delve further into the particularities of each approach to portray their relevance within the industry.

Sustainability check

Material sourcing ●●

The product elements are intrinsically the same as Portland cement.

Construction and operational ●●

Building durability is increased and costs are reduced.

Extended resilience and life cycle potential ●●●

Time to end-of-life is increased as maintenance becomes self-sustained.

Self-healing concrete

Self-healing concrete is defined as able to repair its cracks autonomously.[111] The material is infused with dormant, limestone-producing bacteria that are triggered by the presence of air and moisture upon fissure formation. Once activated, bacteria metabolise the calcium lactate present in concrete, consuming oxygen in the process. As a result, the soluble calcium lactate is converted into insoluble limestone, effectively sealing the cracks.[112]

The self-healing mechanism of concrete can be compared to that of biological systems:[112]

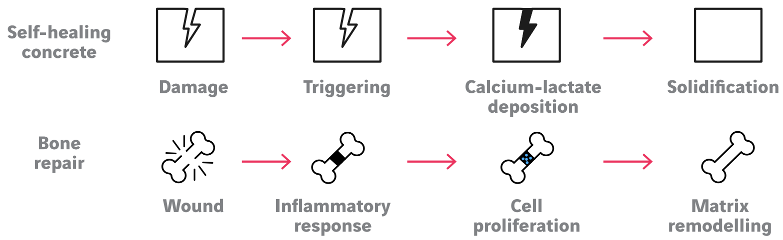


EXHIBIT 11: COMPARISON OF BONE REPAIR TO SELF-HEALING CONCRETE

Biological systems, such as bones, respond to injury in three basic steps: inflammatory response, cell proliferation, and matrix remodelling. Synthetic systems mimic this process more simplistically and at an accelerated rate.[112]

What makes it special?

Self-healing concrete possesses the inherent ability to undergo autonomous healing, thereby **reducing the need for external intervention** to identify and repair internal damage. This remarkable property effectively limits issues such as reinforcement corrosion and concrete deterioration, as well as their associated costs, and simultaneously **enhances the overall durability of the material**.[113]

With bacteria-infused concrete, even the smallest cracks can be reached. Additional benefits of this advanced material versus conventional concrete are as follows:[114]

	Durability	Permeability	Compressive strength	Maintenance	Eco-friendly
Self-healing concrete	+ +	+ +	+ +	+ +	+
Conventional concrete	+	+	+	−	−

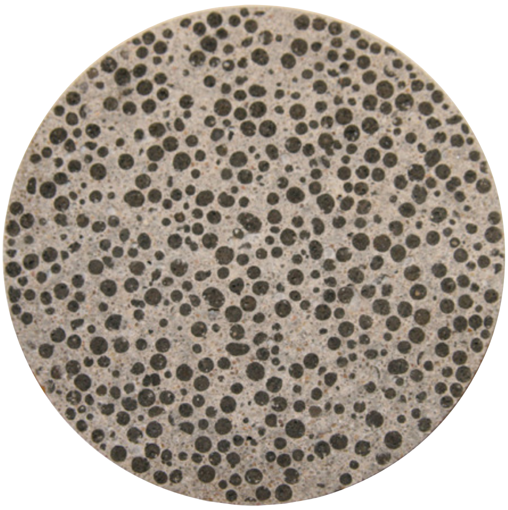
EXHIBIT 12: ADVANTAGES OF SELF-HEALING CONCRETE TO PORTLAND CEMENT

According to the Portland Cement Association, durability of concrete is defined as its ability to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties.[115] In the case of self-healing concrete, it is predicted that it **extends the service life of a structure by 20 years** more than conventional concrete.[114]

Permeability defines the rate of flow of a fluid into a porous solid, and it is a crucial property of concrete, determining its performance when subjected to aggressive environments. With low permeability, there is less chance of external agents attacking the material and its steel reinforcement. Thanks to the carbonation process of the infused bacteria(production of limestone), self-healing concrete shows a **64.3% reduction in porosity and a 41.07% reduction in water absorption**. This indicates a substantial positive effect of the biotic self-healing agent on the permeability of concrete. However, this percentage is specific for the Bacillus Substilis bacteria, and may ultimately vary depending on the formulation.[114,116]

The carbonation process also increases the **compressive strength of the self-healing concrete by up to 30%** more than conventional concrete. Therefore, the limestone produced by the bacteria not only acts as a binding agent, but also fills the pores.[114,117]

Most importantly, it is estimated that the use of self-repairing concrete **saves up to 50% of concrete's lifetime cost** by eliminating the need for repair.[118] Lower repair and maintenance needs also contribute to reducing the production of new concrete, resulting in lower carbon dioxide emissions.[114] According to the self-healing concrete manufacturer Basilisk, adding their healing agent leads to a potential reduction of **7 billion tonnes of CO_2 per year due to service life extension, and an additional 3 billion tonnes of CO_2 per year due to more effective crack control**.[119]



MICROSCOPIC VIEW - CAPSULE WITH AN INTERNAL DIAMETER RANGING FROM 0.8 TO 4MM

Examples in the field

Basilisk self healing concrete

DEFT, NETHERLANDS —
N/A —
WORLDWIDE —
TRL 8-9 —

Basilisk is a spin-out of Delft University of Technology, where self-healing concrete was first discovered by Professor Dr. Henk Jonkers. They manufacture a range of bio-based self-healing concrete products that make the material more sustainable, durable and waterproof. Their technology is based on **micro-organisms that produce limestone and as a result, crack formation in concrete structures can be autonomously repaired**. The autonomous repair system is implemented in several products that are applicable for both new constructions and existing structures.[120]

Biozeroc

CAMBRIDGE, UNITED KINGDOM —
£350K RAISED IN 2022 —
NOT YET COMMERCIALISED —
TRL 3-4 —

BioZeroc is a climate-tech startup that uses biotechnology and scalable process technology to create carbon negative construction materials. Their patent pending solution aims to remove cement in the concrete manufacturing process by replacing it with a **bacterial process that binds together the aggregate**. Therefore, not only do they use bacteria to create a self-healing concrete, but they also leverage it for the manufacturing process.[121]

BIOMASON

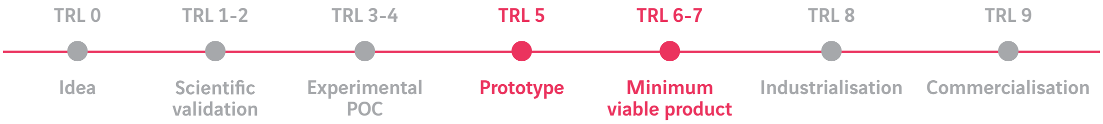
RALEIGH, USA —
$67M TOTAL FUNDING —
WORLDWIDE —
TRL 8-9 —

Biomason is a biotechnology company that commercialises cement produced through biology. Their biocement product, Biolith, is manufactured through limestone-producing bacteria, which are retained in the material after production but are not used for self-healing. As well as Biolith, the company has also developed a **prototype of Engineered Living Marine Cement**. This biocement is **seeded with natural marine microorganisms that the source required nutrients from seawater** for calcium carbonate precipitation, resulting in sustained structural integrity, self-healing abilities, and helping to anchor it to the marine sediment floor.[122]

LEGEND: HEADQUARTERS — FUNDING — TERRITORIAL REACH — TECHNOLOGY READINESS LEVEL —

Maturity of the tech

The bacteria-based self-healing concrete technology is currently between industrialisation and commercialisation:



Most of the techniques for bacteria-based or biotic self-healing concrete have been presented in academic literature and still only experimentally proven under laboratory conditions or relevant environments. Few technologies have been tested in upscale conditions, and even fewer are commercialised.[123] Nonetheless, **Delft University of Technology pioneered the application and established the first patent** in 2011.[124] After that, Basilisk was founded as a spin-out in 2015, and **self-healing concrete became available in the construction industry for the first time in 2017**.[125] As of today, the company has developed multiple construction projects with their products, such as a Japanese water purification plant or retention walls for the Dutch railway market leader ProRail.[126]

The self-healing concrete market is currently dominated by abiotic repair techniques in which chemical compounds, such as sodium silicate, are used as a catalyst in the crack-healing process instead of bacteria.[127] Tendency shows that the **global self-healing concrete market will register a revenue CAGR of 36.8% by 2030**.[128] This, together with the rising demand for sustainable construction materials which have a forecasted CAGR of 12,7% by 2031[129], will ultimately increase the adoption of self-healing concrete in the market.

Key roadblocks to overcome

PROPERTIES

Skilled labour

Working with bacterial concrete requires labourers to possess specialised expertise and technical knowledge for proper mixing and handling. This adds additional expenses and time to the construction process, consequently complicating the overall workflow and potentially causing delays.[114]

Environment dependent

Incorporating bacteria into concrete to enhance its durability by repairing cracks is indeed valuable. However, it is important to recognise that their environment significantly influences this process. Initially, the bacteria face challenges when introduced into the harsh conditions of the concrete matrix, posing a threat to their survival. Moreover, factors like high temperature, alkalinity, and limited oxygen supply further impact their ability to thrive. As a result, it becomes crucial to consider aspects such as the survival characteristics of microbes and the establishment of optimal conditions in the development process of this material.[114] Nonetheless, bacteria that can survive in this harsh environment have been identified, the most well-known being Bacillus megaterium. This one can precipitate the largest amount of limestone compared to other bacteria, which results in increased compressive strength and higher crack-healing efficiency.[130]

Human health

It is important to note that some bacteria used for infusion within concrete are harmful to human health. Their use must be limited to structures that are not purpose-built to support human life, avoiding houses or apartments, for example.[117] However, Bacillus subtilis has promising self-healing results and is non-harmful.[131]

SCALING UP

High cost

In addition to its widespread availability, the affordability of concrete is a key factor contributing to its global acceptance.[114] However, in the case of self-healing concrete, it carries a higher price tag. In fact, the cost of bacterial concrete is 7% to 28% higher than the conventional one.[117] Although the returns on investment are significant due to its beneficial properties, the initial higher cost of self-healing concrete often dissuades businesses from adopting the technology. Companies have yet to recognize the long-term financial gains and environmental advantages associated with the adoption of self-healing concrete.[131]

Lack of guidelines

The self-healing concrete design mix lacks standardised guidelines to achieve optimum performance. The appropriate quantity and specific type of bacteria can vary significantly depending on the intended application. Thus, there is a constant need for adaptability and flexibility when determining the optimal dosage and selecting bacteria for different use cases.[131] Fortunately, entities such as Resilient Materials 4 Life are paving the way for guideline standardisation, by developing bacteria-based self-healing cementitious composites together with industrial partners across the supply chain, and engaging with complementary initiatives.[132]

Ecosystem & Actors

Based on the type of self-healing technology, the market can be segmented into biotic and abiotic.[128] Despite the fact both segments are still evolving, abiotic **self-healing technology is currently accounting for the largest revenue**.[128] This trend is clearly portrayed by the mapping above, where the highest percentage of big companies commercialising products is found on the right-top quadrant. A potential reason for this market stratification is the fact that biotic self-healing systems, involving living organisms, can be more complex and challenging to control, as the viability and activity of bacteria are influenced by various environmental factors.[130] In contrast, abiotic self-healing systems offer easier control and predictability, being precisely engineered to consistently and reliably heal cracks. However, it is difficult to compate this technology to **bacteria-based solutions, which are able to heal cracks as small as one millimetre**, as well as lie dormant in the concrete for up to 200 years before activating. Also, abiotic integrated admixtures lose part of their healing ability during the concrete mixing phase. By using chemicals instead of bacteria, a crystalline structure is formed when the concrete is mixed to be placed, leaving potential for unhealed cracking after the product is set. Thus, this technique is more of a waterproofing admixture than a self-healing one, as the crystalline expansive property is aimed at blocking water leakage through pores.[133]

Biotic self-healing concrete is relatively nascent, for which there is **only one commercial player with a genuine self-healing approach utilising bacteria embedded within the concrete mix: Basilisk**.[134] As mentioned before, Basilisk is a spin-out of Delft University of Technology, where the new material was first discovered by Professor Dr. Henk Jonkers.[120] They co-created the bio-based solution together with Corbion, who provided their SENTIALL® technology, a copolymer that released the substrate when a crack occurred without affecting the setting time or the strength of the concrete.[135] In 2017, Basilisk brought the product to market, and since then, no competitor has reached commercialisation yet.

Sustainability check

Material sourcing ●●

Clarification needs to be done toward toxicity of the most used catalyst TiO_2.

Construction and operational ●●

Reducing water use, and improving environmental quality by reducing the need for chemical cleaning agents.

Extended resilience and life cycle potential ●●

Limited reuse, recycling, and upcycling potential due to their specialty coatings.

Photocatalytic self-cleaning surfaces

Self-cleaning surfaces are a class of materials with the inherent ability to remove any debris or bacteria from their surfaces in a variety of ways. The self-cleaning functionality of these surfaces is commonly inspired by natural phenomena observed in lotus leaves, gecko feet, and water striders, to name a few.[136] There are several ways to make self-cleaning surfaces, including photocatalytic coatings, hydrophobic coatings, and hydrophilic coatings.

Self-cleaning surfaces/coatings in the construction sector are especially remarkable for their innovative fusion of material science, nanotechnology, and architecture. Three types of self-cleaning surfaces have been developed and used in construction:

1. **Superhydrophobic surfaces are defined by their extreme water repellence, which causes water to form spherical droplets that roll off the surface, taking dirt and debris with them.**

2. **Superhydrophilic surfaces, on the other hand, are characterised by their extreme water attraction, which causes water to spread out evenly across the surface, forming a very thin layer of water.**

3. **Photocatalytic surfaces are designed to leverage the power of light to catalyse a chemical reaction. In nature, the process that most closely mirrors this, is photosynthesis in plants:**

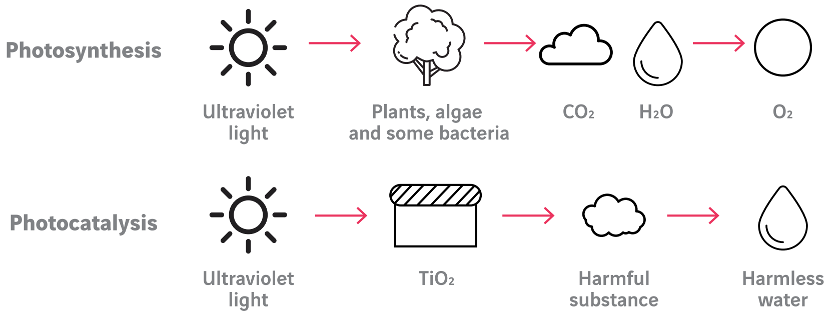


EXHIBIT 13: COMPARISON OF PHOTOSYNTHESIS AND PHOTOCATALYSIS

Photosynthesis is the process through which plants, algae, and some bacteria absorb sunlight (ultraviolet light) and use that energy to convert carbon dioxide and water into glucose (a type of sugar) and oxygen (O_2). Photocatalysis, on the other hand, employs a photocatalyst (often titanium dioxide – TiO_2 – or other semiconductors) that is energised by light, like how chlorophyll is activated in photosynthesis. Once activated, this **photocatalyst can interact with water and carbon dioxide** (or other substances) in the environment and cause a reaction.

	Self-cleaning	Water-adhesion	Resistance to damage	Air purification
Photocatalytic	+	+	+	+ +
Hydrophobic	+ +	− −	− +	− −
Hydrophilic	−	+ +	+	− −
Normal type	− −	− +	+ +	− −

EXHIBIT 14: ADVANTAGES OF PHOTOCATALYTIC SURFACES

What makes it special?

The most fascinating aspect of photocatalytic surfaces lies in their **ability to 'clean' themselves** and their surroundings. These surfaces are coated with substances such as titanium dioxide, which under the influence of light (usually sunlight), can **break down organic dirt into harmless substances like water and carbon dioxide**.

Buildings can then remain clean and new-looking for longer, reducing the need for resource-intensive cleaning processes. These technologies offer solutions to long-standing challenges, such as the cost and environmental impact of maintenance[110], **extending the lifespan and improving the appearance of buildings**.

TiO_2 is the most deeply studied photocatalytic material in the field of green building. The potential of TiO_2 as a photocatalyst was first discovered by Fujishima and Honda in 1972.[137] Moreover, these surfaces have demonstrated the **ability to neutralise harmful pollutants and bacteria in the air and in water**[138,139], thus helping to improve air quality and water purification. It stays the most widely used photocatalyst in construction materials due to its low cost, chemically stable nature, and absence of toxicity.[140]

Photocatalysis emerges as a promising approach to address current environmental and climate challenges. It holds the **potential to transform or even remove harmful greenhouse gases from the atmosphere**. Among various options, TiO_2 stands out as a particularly effective agent for converting both mineral and organic compounds, thereby contributing significantly to climate change mitigation strategies.[141]

Examples in the field

pureti
Soluciones sostenibles ... por un Mundo Limpio

NYC, USA
—

N/A
—

WORLDWIDE
—

TRL 9
—

PURETi has developed a **light-activated, water-based, surface treatment spray applied to transform virtually any surface into a self-cleaning material**. In consequence, the material becomes able to eliminate grime and foul material buildup, improves air quality, and eradicates organic malodors. The spray is developed by water-based UV-PCO (ultraviolet photocatalysis) technology which uses light, not chemicals to create sustainable, clean surfaces. It improves indoor and outdoor air quality by continually eliminating VOCs and harmful greenhouse gases such as Methane and NOx and eliminates stubborn organic malodors such as smoke or human and agricultural waste.

GREEN EARTH NANO SCIENCE INC.
We Make Nanotechnology Work For You

MISSISSAUGA, CANADA
—

N/A
—

WORLDWIDE
—

TRL 8-9
—

Green Earth Nano Science is a Canadian company that produces photocatalytic coatings for a variety of applications, including building facades, roofs, and windows. Their award-winning **Gens Nano photocatalyst coatings can eliminate bio-contamination caused by Listeria, Salmonella, E. Coli, Swine Flu, Bird Flu, SARS, and mold spores**. The product is based on a proprietary formula that includes titanium dioxide and can improve indoor air quality when installed together with UV-C air filtration systems. Moreover, not only do they offer an installation service to apply the coating, but they also sell a "do-it-yourself system".

SAINT-GOBAIN

PARIS, FRANCE
—

$1,5B
—

WORLDWIDE
—

TRL 9
—

Saint-Gobain is one of the world's largest manufacturers of building materials, construction products, and innovative solutions. Founded in 1665, the company has a long history of providing materials for various industries including construction, automotive, aerospace, and more. They provide the self-cleaning **SGG BIOCLEAN glass, a clear glass on which a transparent layer of a photocatalytic and hydrophilic mineral material is deposited.** The product uses the combined action of rain with ultraviolet rays from the sun to eliminate dirt. It allows for clear vision to be maintained even in rainy weather and the risk of condensation on the outer face of the insulating glazing is almost completely gone.

LEGEND

HEADQUARTERS
—

FUNDING
—

TERRITORIAL REACH
—

TECHNOLOGY READINESS LEVEL
—

Maturity of the tech

Photocatalytic self-cleaning technology is currently between industrialisation and commercialisation:

TRL 0	TRL 1-2	TRL 3-4	TRL 5	TRL 6-7	TRL 8	TRL 9
Idea	Scientific validation	Experimental POC	Prototype	Minimum viable product	Industrialisation	Commercialisation

Photocatalytic materials primarily composed of **TiO_2 have been the subject of rigorous research for several decades**, with substantial progress being made in understanding their properties and mechanisms. However, the **transition from lab-scale research to full-scale applications in the construction industry has been a more recent development**. In that regard, the company PURETi has been in the forefront of the advancements, being the partner in charge of the European Union's iSCAPE project. This initiative started in 2016, aiming to enhance and unify efforts within European cities to tackle poor air quality and carbon emissions in the face of climate change. The idea was to promote sustainable and passive strategies for mitigating air pollution, implementing effective policy interventions and fostering behavioural change initiatives. According to the report on technical advances for photocatalytic coatings developed by iSCAPE, PURETi's state-of-the-art TiO_2 technology for transparent films has been crucial for technical progress in photocatalytic coatings that could be utilised in areas with hight exposure to natural light.[142,143]

Today, the applications of photocatalytic technology in construction have **extended to include air purification and deodorisation, antimicrobial surfaces, and water purification systems**. The materials have been applied in various formats such as paints, plasters, tiles, glass, and concrete. The maturity of this technology for other applications will differ depending on the field of applications, ranging from basic research for H_2 production to mature, market-ready solutions for self-cleaning, air purification and water treatment.[144]

Key roadblocks to overcome

PROPERTIES

Limited durability

As good as they are, the surfaces can lose their effectiveness over time. They are vulnerable to physical wear and tear, weathering, and abrasion. The balance of light transmittance, durability, and self-cleaning performance of the coating film is a significant issue that hinders the wide application of photocatalytic self-cleaning coatings on glass exteriors for buildings.[145] Fortunately, research is finding alternative production processes to deliver highly durable coatings. For example, a self-cleaning photocatalytic coating has recently been developed by applying a fluorinated dual-scale TiO_2 onto an inorganic lithium silicate adhesive. This innovative approach ensures exceptional durability and sustains photocatalytic degradation performance over extended periods, even when exposed to natural light. Specifically, the coating maintained a minimal long-term quality loss rate of less than 0.3%, effectively mitigating the risk of nanoparticle leakage and eliminating the potential for secondary environmental pollution.[145]

Environmental and health impact

The potential environmental and health implications of nanomaterials used in self-cleaning surfaces are a cause for concern. Nanoparticles could potentially contaminate the environment or harm living organisms if not properly contained. For instance, research has shown that TiO_2 coatings with low photocatalytic activity are well-suited for domestic applications due to their minimal leaching of photoactive material. On the other hand, mesoporous TiO_2 coatings, initially highly active, experience a substantial decline in self-cleaning performance and a notable release of nanoparticles into the surrounding environment upon exposure to chemical solutions commonly found in domestic settings.[146] As TiO_2 has been demonstrated to impact soil microbial function and sea ecosystems, nanoparticle leakage from self-cleaning coatings can pose a threat to the environment.[147,148] Nonetheless, PURETi's 'Evaluation of the Environmental Impacts of Titanium Dioxide Photocatalyst Coatings for Pavements Using Life-Cycle Assessment' has shown that the use of TiO_2 coatings has a positive effect on four main environmental categories: acidification, eutrophication, criteria air pollutants, and smog formation. According to the study, the environmental performance of the product's overall life cycle assessment has a negative score of -0.70, indicating that the addition of this surface layer has a potential positive effect on the environment.[149]

Deactivation in diverse conditions

The efficient and uninterrupted operation of photocatalyst systems will require the substantial challenge of system deactivation to be addressed. This deactivation commonly happens during the photocatalytic reaction, primarily caused by irreversible adsorption of recalcitrant by-products or the obstruction of active sites on the catalyst surface by carbon residues or dust particles. In gas-phase photocatalysis, where the absence of a water solvent hinders the removal of by-products and intermediates from the surface, the issue of deactivation becomes even more crucial compared to the liquid phase. Fortunately, numerous approaches have been suggested to reactivate the photocatalyst, including techniques such as water vapor treatment, high temperature treatment, hydrogen peroxide oxidation, and UV irradiation. Employing a more oxidizing atmosphere and enhancing mass transfer have shown promising results in mitigating deactivation. Additionally, simple methods like washing with water or utilizing reagents and organic solvents can effectively regenerate deactivated photocatalysts.[150]

Key roadblocks to overcome

SCALING UP

High costs

Producing such surfaces and coatings involves complex processes and materials that can be more expensive. The exact cost of these coatings can vary depending on the specific product and application method. This becomes a significant barrier when considering large-scale applications in construction. However, this is to be balanced, because it's also suggested that photocatalytic self-cleaning tiles could stay clean for more than 20 years, compared to the common tile-covered building which needs to be cleaned every 5 years.[151]

Technical complexities

Scaling up from laboratory scale to full-scale industrial applications involves dealing with technical complexities, like achieving a uniform distribution of photocatalytic particles on large surfaces. Their effectiveness can be reduced in real-world conditions like the presence of interfering species, complex water matrices, and low pollutant concentrations.[150] This could limit the application of the product to specific areas of the globe due to weathering conditions, for example.

Regulatory challenges

The regulatory landscape for nanotechnology and related materials is still developing. This can create uncertainty and delays in product approval and market introduction, hindering the industry's ability to scale up. As of today, France and the European Union (EU) are contesting the toxicity of TiO_2 in court. On February 18th, 2020, the official EU Journal published the Regulation (EU) n. 2020/217. Also known as the 14th ATP (Adaptation to Technical Progress), the regulation introduced amendments to Annex VI of Regulation 1272/2008 (CLP). These amendments encompassed the addition, removal, and modification of harmonised classifications for specific substances. Of the updated substances, the most controversial classification update regarded the TiO_2 (CAS: 13463–67–7), which received a classification as carcinogenic via inhalation of category 2 due to the toxicity of respirable particles.[152]

However, in November 2022, The EU General Court reached a verdict on the matter, issuing a judgment that nullified the portion concerning TiO_2. Consequently, the French Government, which was at the origin of the project to classify the substance as carcinogenic, announced the filing of an appeal challenging the decision to annul the carcinogenic classification. Since then, the update has been temporally suspended, and the harmonised classification as carcinogenic via inhalation of category 2 for TiO_2 still applies.[152] After the resolution of this situation, it is expected that the European Union and its member states will definitely establish comprehensive standards and regulations for the coatings, which will represent a crucial step towards widespread adoption.

Ecosystem & Actors

	Hydrophobic	Hydrophilic	Photocatalytic
Corporations	SAINT-GOBAIN	ABRISA TECHNOLOGIES HEF PHOTONICS; TEKRA	Italcementi HEIDELBERGCEMENT Group; ALCOA; PILKINGTON; SAINT-GOBAIN
SME & Startups	lotusleaf COATINGS	lotusleaf COATINGS	nano hygiene; greenmillennium; nanoSeptic; pureti; GREEN EARTH NANO SCIENCE INC.; Advanced MATERIALS

Entities promoting self-cleaning surfaces

スペースシステム創造研究センター Research Center for Space System Innovation; NASA; Fraunhofer ISE; The University of Texas at Austin; University of Science and Technology of China

For self-cleaning surfaces, the journey from taking inspiration from nature to market reality is lengthy, but teeming with potential. A dynamic ecosystem of large companies, research centres and startups are currently navigating this journey. Their efforts have become particularly critical given the burgeoning demand for eco-friendly, low-maintenance and efficient materials in various sectors such as construction, automotive, textiles, and aerospace.[153]

At the **forefront of innovation is PURETi**, a US-based startup specialising in the development of photocatalytic surface treatments. They have pioneered solutions that can be **retroactively applied to existing structures**, thereby endowing them with self-cleaning and air-purifying properties.[154] Alongside these young enterprises, established corporations are also playing a significant role. For instance, the **Italcementi Group**, a leading cement manufacturer, has been **instrumental in integrating photocatalytic technology within the construction industry**, with their groundbreaking product "TX Active", a self-cleaning cement utilised in prominent projects such as the Dives in Misericordia Church in Rome.[155]

Meanwhile, **academic institutions** such as the University of Science and Technology of China are also making strides in their **development of a self-cleaning concrete, specifically tailored for the construction industry**.[156] Further broadening the ecosystem's scope are companies like NanoSeptic that have embarked on establishing innovation centres.[157] These **hubs are focused on the conception and development of smart materials**, including self-cleaning surfaces, exemplifying the ongoing momentum within this vibrant, sustainability-focused ecosystem.

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.[157] This, combined with the necessary drive towards sustainable construction, has fostered a growing interest in materials 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.[18] Likewise, **energy-exchanging materials,** with their unique capacity t**o recover internal energy in a more usable form,** are gaining momentum to boost efficiency in urban environments.[32,51]

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. As previously mentioned, 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 t**he 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 this 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.**[5] 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.[31] Also, materials such as phase-changing or piezoelectric could be deployed in public locations, visible to consumers, serving to foster a broader interest.[13]

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.[158] For instance, when using timber, it's vital to ensure sustainable production to avoid potential deforestation caused by excessive demand.[159] 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.[99]

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.[160] In this context, governments should consider **implementing initiatives and promotional strategies that will contribute to costs reduction** in the long term.[161,162] 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 utilization will ensue, **facilitating economies of scale and mass production**.[5] 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.

PICTURES GALLERY

Cover page - Fahroni - ENVATO

Page 09 - Exhibit 1: The net zero pathway - GCCA

Page 09 - Exhibit 2: construction value chain - Hello Tomorrow

Page 10 - Tobias Weinhold – Unsplash

Page 11 - Antoine Dupré

Page 15 - Max Van Den Oetelaar – Unsplash

Page 16 - Calvin Chin – Unsplash

Page 17 - Mathew Schwartz – Unsplash

Page 20 - Exhibit 3: Types of structure-changing materials

Page 21 - Brightlands materials center's thermochromic glass - TNO innovation for life / Material prototype using shape memory alloys - Tactile Architecture

Page 23 - Exhibit 4: mechanism of action of corrosion detecting coatings

Page 24 - Zsolt palatinus - Unsplash

Page 25 - Dr. Luz M. Calle - NASA

Page 32 - Joel filipe - Unsplash

Page 32 - Exhibit 5: Types of energy-changing materials

Page 33 - Light-emitting cement - investigación y desarollo

Page 33 - Thermoelectric paint being applied to an alumina hemisphere - park sh, et al. (2016). Nature communications

Page 34 - UE Power™ selective harvesting technology - Ubiquitous energy official website

Page 36 - Exhibit 5: Mechanism of action of piezoelectric materials

Page 37 - Exhibit 6: Advantages of piezoelectric harvesters

Page 38 - Little pressure can generate usable energy in the wooden sponge - Acs Nano / Empa

Page 45 - Eleonora Albasi - Unsplash / Marc Newberry - Unsplash

Page 46 - A domed structure under construction made almost entirely of ferrock. Image © David Stone

Page 46 - Ernesta Vala - Unsplash

Page 47 - XTU ARCHITECTS. © XTUXTU_INVIVO / Byblock stucco boundary wall / Exhibit 7: Production process of mycellium composites

Page 49 - MYKOR PRODUCT - OFFICIAL WEBSITE

Page 56 - Exhibit 10: Difference between biomimicry, biomorphism and bio-utilisation

Page 57 - Crystal Palace by Joseph Paxton / Sagrada Familia by Antoni Gaudí - Photograph by Bernard Gagnon

Page 58 - Michaela Klikova - Unsplash / Woodflow, Strong By Form - Official website / Anna Sushok - Unsplash

Page 60 - Exhibit 11: Comparison of bone repair to self-healing concrete

Page 61 - Exhibit 12: advantages of self-healing concrete to portland cement / Microscopic view - capsule with an internal diameter ranging from 0.8 to 4mm

Page 68 - Exhibit 13: Comparison of photosynthesis and photocatalysis / Exhibit 14: Advantages of photocatalytic surfaces

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About us

Leonard is the name of the VINCI Group's foresight platform and fast track for innovative projects, launched in July 2017. Why Leonard? To respond to some of the biggest challenges facing VINCI's businesses: digital revolution, faster innovation cycles and environmental transition. Within a transforming world, Leonard detects new trends, supports innovation and brings together all the players involved in shaping the future of cities and regions.

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Hello Tomorrow is a global initiative that connects deep tech entrepreneurs with businesses and investors, and provides consulting services in strategy and innovation. Over the course of nine editions, the Hello Tomorrow Global Challenge has received 30,000 applications from 132 countries, partnering with universities and research institutions worldwide to identify deep tech solutions that are advancing human and planetary health. Hello Tomorrow then connects these pioneers with industry, investors, researchers, and regulators through international events, consulting services and startup programs to harness the potential of their solutions.

hello-tomorrow.org

TO GO FURTHER

In part two, an array of novel materials are portrayed, most of which intend to increase the efficiency of the building over its use life, without forgetting about its production and appropriate disposal.

In the first part of the report, the most promising technology trends tackling the production phase of the concrete industry has been assessed.

Available here

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