Scientific Advice Mechanism
to the European Commission

April 2026

SAPEA Evidence Review Report

Advanced Materials

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to the European Commission

Advanced Materials

SAPEA Evidence Review Report

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Foreword

Advanced materials are and will be everywhere in our daily life. They are defined as materials designed with new or enhanced properties, leading to specific or improved functional performance in all possible fields of application. Their development has a continuing impact on the progress of humankind and on the world economy. To cite a few examples, they are of paramount importance in areas such as building, energy, healthcare, electronics, mobility, as well as the environmental and digital transition.

With this in mind, Europe has recognised advanced materials as key enablers for the competitiveness of European industries and for the green and digital transitions. Several initiatives have been launched in this field, including the prioritisation of the "Advanced Materials for Industrial Leadership Manifesto" in the State of the Union address.

Yet, Europe faces challenges in the advanced materials research and innovation (R&I) landscape. These include the fragmentation of R&I ecosystems, the gap between EU and US or Asian private investment in the area, low digitalisation levels in the design and development of advanced materials, insufficient industrial support to inventors to cross the "valley of death", and a lack of the necessary skills for the future. Several initiatives are being launched to target these gaps, which aim to set Europe up as a leader in advanced materials as the demand for them continues to grow worldwide.

Still, questions remain, and in March 2025 the College of Commissioners asked the Scientific Advice Mechanism, through the Group of Chief Scientific Advisors, to answer the following:

> 1. What contribution can advanced materials bring to the EU's strategic autonomy?
> 2. How can the cross-fertilisation of innovation in advanced materials be enhanced?

To address these questions, SAPEA assembled a working group of experts, nominated by academies of science and engineering across Europe. The team was coordinated by Euro-CASE acting as the lead Academy Network on behalf of SAPEA. Between June and December 2025, the working group, composed of 22 members, reviewed and compiled the latest evidence on the subject to create this evidence review report. Seventeen stakeholders from the advanced materials industry and innovation chain participated in an industry and innovation workshop; 13 experts reviewed a preliminary draft of the report in an expert workshop; and four peer reviewers revised the final version. Building on these contributions, the report informed the Group of Chief Scientific Advisors to assist them in delivering their Scientific Opinion.

We warmly thank all experts and stakeholders for their paramount and complementary contributions throughout the evidence-gathering and quality assurance processes, with a special mention to the co-chairs, Prof. Anke Weidenkaff and Prof. Olli Ikkala, and the working group. Finally, we also express our sincere gratitude to the European academies of science and engineering for being so active in bringing together such an outstanding panel of experts.

Ad Honorem Professor **Eloy Álvarez Pelegry**, President of Euro-CASE
Dr. **Patrick Maestro**, Secretary General of Euro-CASE
Professor **Donald Dingwell**, Chair of the SAPEA Board

Preface

We often take the different materials around us for granted, without ultimately appreciating that they make our lifestyle possible and contribute to our welfare. These include the semiconducting materials that facilitate energy supply, a healthy environment, and solar and electronic devices; optical materials that enable optical fibres for internet connections; high-quality metals for jet engines and lightweight constructions for vehicles; pigments provide different colours; and engineered nanostructures that facilitate several critical aspects in healthcare. Such materials have typically already required extensive research and development to reach their current subtle and refined properties and technological importance. Today such materials are generally engineered and produced using sophisticated processes from raw materials, which are typically derived from oil or mined minerals, processes that sometimes involve high energy consumption and generate polluting waste.

On the other hand, one might ask: Could materials in the future offer profoundly new properties and technologies to further transform societies? Such materials are referred to as advanced materials, which already exist in different stages of research—some at very early conceptual levels, while others are already transitioning from laboratories to technology. Inevitably, some advanced materials concepts ultimately fail for various reasons, which is characteristic of any ambitious effort to generate novelties. To avoid major failures, we must create suitable innovation ecosystems.

Developments in present-day advanced materials are led by several driving forces, both global and characteristically European ones. A globally relevant driver is the quest for sustainability —that is, using renewable raw materials, energy-efficient processing, and developing infrastructure for renewable energy sources and storage. Another global driver is the pursuit of a circular economy, which aims to use waste as a raw material source, for example by recirculating materials from the discarded electronic devices or using inedible fractions of food production to create new polymeric materials. Notably, large-scale recirculation is directly linked to securing the availability of critical rare materials within the EU. These, and several other issues require rethinking how to promote advanced materials development in the EU, from successful basic research to strategies that can foster technological translation.

In relation to the importance of advanced materials, the Group of Chief Scientific Advisors to the European Commission were asked to provide a Scientific Opinion with policy recommendations concerning the EU's strategic autonomy and the enhancement of cross-fertilisation of innovation. This evidence review report first discusses what advanced materials are and provides examples. Defining them precisely is a challenge, as they encompass a wide variety of emerging concepts at different development stages and with varying potential. In general, the report focuses on advanced materials for mobility, energy, construction, electronics, health sectors alongside cross-cutting aspects.

The report is divided into seven chapters, including key messages and suggestions:

- **Chapter 1** introduces advanced materials at a general level, their potential, and their definitions.
- **Chapter 2** addresses sustainability, including assessment methods, recirculation, raw materials, and best practices.
- **Chapter 3** covers advanced materials production and the need for innovation ecosystems to enable technological translation.
- **Chapter 4** discusses the importance of high-quality basic research to innovate fundamentals for advanced materials, including biotechnical production, as well as selected examples.
- **Chapter 5** emphasises the fundamental transition to data-driven materials science, exploiting large data libraries to address complex materials properties, automated laboratories and production, and integration with simulations.
- **Chapter 6** discusses legislation and governance.
- **Chapter 7** provides the summary, analysis of EU strengths and weaknesses, and policy options.

As with any emerging science, it is challenging to predict the exact materials that will ultimately enable major technological breakthroughs, as it may strongly depend on unforeseen individual scientific findings. Still, we believe that the Report describes the required EU ecosystem and processes to foster such breakthroughs from fundamental research to technological translation.

Finally, we would like to thank the highly professional team of experts for their commitment to identifying necessary platforms for future material developments and anticipating potential future directions. Last but not least, we are deeply grateful for the SAPEA team for making this report possible, despite the presence of several, occasionally differing, expert opinions, and for keeping to the tight schedule.

Professor **Anke Weidenkaff**
Professor **Olli Ikkala**

Members of the working group

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The above experts were identified with the support of:

- **Academy of Engineering**, Portugal
- **British Academy**
- **Council of Finnish Academies**
- **Danish Academy of Technical Sciences**
- **Hungarian Academy of Engineering**
- **Latvian Association of Young Researchers**
- **National Academy of Science and Engineering (acatech)**, Germany
- **Royal Academy of Engineering**, Spain
- **Royal Academy of Sciences, Fine Arts and Letters of Belgium**
- **Royal Irish Academy**
- **Slovenian Academy of Engineering**

Executive summary

Our lives depend on advanced materials. Modern technologies have enabled scientists to manipulate and create powerful advanced materials, such as semiconductors, nanomedicine, photovoltaic cells, and many more, transforming the industrial, medical, electronics, space and aviation, automotive, and energy sectors. Given their influence in practically all sectors, advanced materials are critical to the competitiveness, autonomy, and resilience of European industries.

Therefore, the Group of Chief Scientific Advisors to the European Commission were asked to provide a Scientific Opinion, with policy recommendations, on the following questions as stated in the Scoping Paper (European Commission, 2025c):

1. **What contribution can advanced materials bring to the European Union's (EU) strategic autonomy?**
   This question seeks to identify specific research areas in advanced materials that reflect the EU's core strengths and have the highest potential impact on industrial competitiveness. This includes cross-cutting research challenges for developing safe and sustainable advanced materials for the circular economy, focusing on material design, development, characterisation, processing, production, and product integration. In addition, it aims to identify gaps in research areas for critical sectors where the EU can put additional efforts and resources to achieve strategic autonomy.
2. **How can the cross-fertilisation of innovation in advanced materials be enhanced?**
   This question seeks to identify mechanisms that can capitalise on the potential of new innovative functionalities of advanced materials across sectors and applications, and to stimulate new business models and innovation markets. To achieve cross-sector innovation and support its uptake by industries, it is also imperative to facilitate alignment and feedback loops between basic research and industrial needs for advanced materials.

As requested, the evidence on the above questions remains within the scope of the European Commission Communication on Advanced Materials for Industrial Leadership (European Commission, 2024b), which focuses on sectors such as mobility, energy, construction, and electronics, with cross-cutting aspects, and also includes health.

To address these scoping questions, SAPEA assembled an interdisciplinary working group of independent experts to develop this comprehensive evidence review report, which the Group of Chief Scientific Advisors used to inform their Scientific Opinion and policy recommendations.

The structure of the report

In the report, we highlight the following main themes that will deepen understanding of advanced materials and inform their discovery, design, development, and production:

1. Chapter 1 defines advanced materials and identifies the main reasons to achieve strategic autonomy in advanced materials within the EU, with a specific focus on the construction, energy, mobility, electronics, and health sectors.
2. Chapter 2 illustrates why developing sustainable, safe, and efficient advanced materials is vital to aligning with the EU's green transition. The chapter further highlights perspectives and opportunities to consider in advanced materials development that can directly alleviate the environmental, economic, and societal challenges of our times.
3. Chapter 3 discusses the role of emerging technologies and infrastructure in the development and manufacturing of advanced materials. The chapter also emphasises the need for academia-industry networks and industrial synergies in the manufacturing and scaling up of advanced materials.
4. Chapter 4 presents new perspectives and avenues in basic research that will either improve or replace traditional materials with new advanced materials, highlighting research projects focused on delivering specific functionalities and sustainable properties.
5. Chapter 5 reviews the current practices in digitalisation, particularly dissecting how comprehensive and high-quality databases, simulations, and artificial intelligence (AI)[1] will transform advanced materials design, production, and circularity to align with the EU's digital transition.
6. Chapter 6 analyses the policy and regulatory frameworks required to ensure that advanced materials are safe and sustainable from the outset, and that their applications do not cause harm to human health and the environment.
7. Chapter 7 summarises the EU's key strengths and weaknesses in advanced materials and identifies new opportunities for policymakers to establish research endeavours, innovation systems, and markets to propel Europe's success in advanced materials.

What are advanced materials?

The term "advanced materials" is a very broad and inclusive term, and many different definitions exist (European Commission et al., 2016). Importantly, the Organisation for Economic Co-operation and Development (OECD) offers a working description of advanced materials as:

> *...materials that are rationally designed to have* ***new or enhanced properties,*** and/or ***targeted or enhanced structural features*** *with the objective to achieve specific or improved functional performance. This includes both new emerging manufactured materials, and materials that are manufactured from traditional materials. This also includes materials from innovative manufacturing processes that enable the creation of targeted structures from starting materials, such as bottom-up approaches* (OECD, 2023).

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[1] The term AI is used throughout the report to refer to AI/ML (artificial intelligence/machine learning) technologies – see Glossary.

Other synonyms are conceivable, including terms like "manufactured", "enhanced", "targeted", "rationally designed" or "improved", "specifically engineered", "superior", "novel". It should also be noted that what we consider to be advanced materials also changes over time. It depends both on how technologies develop and mature, and on the changing problems they are intended to address. In this light, we consider the following criteria relevant for any present or emerging materials to qualify as advanced materials:

- Advanced materials are new materials that are designed to have novel or enhanced properties and/or structural features for specific or improved functional performance in comparison to existing materials. This includes both new emerging manufactured materials and materials that are manufactured from traditional materials.
- Emerging advanced materials increasingly form part of complex multi-component systems consisting of several constituent materials that are developed using breakthrough techniques and are underpinned by robust scientific understanding.

Advanced materials have transformative roles across sectors, including:

- Polymers, ceramics, and composites in construction, mobility, and aviation
- Semiconductors, magnets, sensors, and batteries in energy and electronics
- Quantum materials for disruptive applications
- Biomaterials and nanomaterials in health applications.

All these advanced materials are instrumental for the EU's competitiveness and resilience. In this context, it is crucial that basic research that leads to new advanced materials remains a priority for European funding programmes and innovation frameworks.

Advanced materials for promoting sustainability

Sustainability is an important consideration in developing advanced materials. In fact, environmental and human safety criteria are paramount in the design and development of any emerging technology and materials.

This report recognises raw material sourcing as a key geopolitical challenge for the EU—it entails significant environmental, societal, and economic burdens. Many important raw materials, including rare earth elements, are mined, processed, and transported, causing pollution and contributing to harmful emissions. These activities also frequently harm vulnerable communities, with disproportionate impact on women. Therefore, efforts are underway to improve the sustainable sourcing of critical minerals and develop safer alternatives that reduce dependence on geographically limited raw materials.

Circular economies aim to minimise waste and maximise product use by promoting reuse, repair, refurbishment, and recycling of materials and products. This approach strives to tackle global challenges, such as climate change, pollution, and habitat loss. Advanced materials are increasingly engineered using the safe and sustainable by design (SSbD) framework and tested using holistic assessments that integrate circular economy principles along with environmental, social, economic, and multi-criteria life cycle considerations, producing more sustainable advanced materials. In a nutshell, the overarching goal of these holistic approaches is to support responsible innovation and ensure a meaningful shift towards global sustainability objectives.

The report highlights the need for industrial symbiosis that aims to develop synergy across different industries to minimise material sourcing, processing, and waste. Policies and ecosystems that allow industries to support material and waste transfer will help the EU to achieve its sustainability goals.

More importantly, the report underscores the need to put sustainability and the climate crisis at the forefront of advanced materials innovation, offering evidence on how advanced materials will contribute to the reduction in emissions, the removal of greenhouse gases, the repair of our climate systems, and building resilience to deal with climate impacts and threats. Advanced materials should also maximise resource efficiency and reduce the impacts associated with quarrying and mining activities, as well as the import of raw materials.

The EU research community is rapidly shifting towards sustainability in materials discovery and development, with many EU flagship projects addressing contemporary challenges by placing sustainability at their core. From tackling e-waste to developing durable and low-carbon-dioxide (CO_2) cement, this report highlights recent progress in sustainable advanced materials.

Emerging technologies and new solutions

Developing and manufacturing advanced materials requires new technologies and industrial synergy. Europe needs strong capabilities in new technologies, and manufacturing plants must make use of tools such as biotechnology, AI and machine learning (ML) to seriously achieve dominance in advanced materials. This report highlights how advanced materials are manufactured and which extant and emerging technologies and production systems can enhance efficiency in manufacturing.

Manufacturing challenges often relate to scalability and circularity. Advanced manufacturing technologies, such as biotechnology, 3D printing, and robotics powered by digital AI applications, increase production capabilities. In addition, several advanced materials are directly incorporated into manufacturing technologies to improve scalability and sustainability.

Materials discovery and manufacturing are often insular processes, with sectors either developing technologies and materials in isolation or sometimes competing with other sectors. It is in Europe’s interest to develop cross-cutting innovation pipelines and integrate data-driven approaches to accelerate materials discovery and manufacturing. This report outlines important feedback loops, interdisciplinary collaborations, and shared infrastructure that can accelerate the adoption and market readiness of advanced materials across multiple sectors. In addition, innovation sandboxes, learning factories, and science parks can help bridge the gap between academic research and industry. Actively learning about cross-cutting challenges in these innovation ecosystems can help scale-up and make existing production systems more efficient.

Fundamental research and the quest for more advanced materials discovery

One of the main messages of the report is that high quality fundamental (also called basic or frontier) research is indispensable for the EU to achieve strategic autonomy in advanced materials. New material discoveries often come from new scientific theories and explorations, because they lead to a better understanding of materials and their properties. In addition, basic and applied research go hand-in-hand to turn exciting research discoveries into viable products ready for market adoption.

The report showcases numerous exciting research areas in biomaterials, nanomaterials, quantum materials, metal oxides, and many other materials with unique properties and functionalities in addition to their manufacturability. While many of these materials are slowly entering the market, it is evident that they are already addressing challenges in sustainability, raw material sourcing, and green energy transition, and transforming critical sectors, such as health, energy, and electronics.

Interdisciplinary research institutes, state-of-the-art infrastructure, and funding mechanisms, such as the Horizon Europe where the European Research Council (ERC) is placed, are the EU's biggest strengths. The report promotes leveraging these strengths to attract and retain research talent to develop future advanced materials.

Leveraging digital tools to design and manufacture advanced materials

Advanced materials are often derived from existing materials. Therefore, digitalisation, together with AI and ML technologies, can have a profound impact on how material properties are studied and modified. When it comes to materials design and exploration of new properties, simulation-driven or data-driven approaches, or a combination of the two can indeed accelerate materials discovery. Simulations are particularly useful since they can predict numerous structural and functional properties and develop new configurations for testing and development. AI/ML can also be applied to design entirely new materials with desired properties. However, integrating AI/ML approaches into advanced materials discovery remains challenging due to limited high-quality data. While existing databases support new research, the lack of highly specialised datasets for specific applications restricts the use of simulations and computational methods to design and develop new advanced materials.

Europe is a leader in simulations, particularly in first-principles modelling, where computational workflows and codes generated by European scientists are used worldwide. The report summarises (1) the generation of these simulation codes by pan-European scientists using open-source frameworks, (2) their role in accelerating basic research toward industrial applications, (3) the interoperability of codes across different sectors and applications, (4) their contribution to strengthening reproducible research practices, and (5) their role in advancing new materials research.

In addition, the report showcases how industrial manufacturing that uses automation and robotics will not be possible without simulation codes and AI. Autonomous laboratories and self-driving labs facilitate material synthesis, manufacturing, and characterisation using advanced AI models. Furthermore, these systems continuously generate new data and model parameters, helping model refinement and the generation of digital twins to create *in silico* models of new materials and their functionalities.

Building a governance framework for advanced materials

Europe needs a robust policy framework to strengthen and maintain competitiveness in advanced materials. Most advanced materials are governed by a general product safety framework and sector-specific regulations. However, advanced materials are complex and general safety frameworks often hinder their adoption in new applications. The report uses evidence and lessons learned from nanomaterials—an important class of advanced materials—to show how the regulatory landscape changes over time and the challenges associated with making new regulations for complex material classes. Therefore, socio-economic research on advanced materials policy and innovation should become part of advanced materials research.

While this report presents a technical definition of advanced materials, the European Commission does not have a definition established for legal and regulatory purposes. This represents a significant initial hurdle because regulations are interpreted, enforced, and fulfilled based on legally binding definitions. Therefore, the EU needs to define advanced materials to develop a comprehensive policy framework for them.

Conclusions of the report and supporting evidence-based policy options

The report concludes that advanced materials are critical to the EU's strategic autonomy and strengthening and maintaining its competitiveness. The report gathers evidence on the EU's strengths and weaknesses in all aspects of advanced materials, from design and discovery to manufacturing and market adoption, for applications in construction, mobility, energy, electronics, and health sectors. It is evident that the EU boasts excellence in research programmes and infrastructure, supported by robust funding and policy frameworks. The EU also remains a global leader in selected fields of sustainability compared to other bigger economies, such as the US and China. At the same time, fragmented cross-border economic and strategic ecosystems and markets make it difficult to drive industrial innovation and scale-up in advanced materials to directly compete with China and other manufacturing hubs. The report emphasises the roadblocks for innovation in advanced materials: lack of skilled workers and resources for scaling up, slow adoption of AI and other emerging technologies, and a complex regulatory landscape.

In addition to pinpointing challenges, opportunities, and future directions in advanced materials across all stages—from research and discovery to introducing new products to the market—this report outlines potential policy options that can support policymakers in strengthening the EU's strategic autonomy and capabilities in advanced materials. The report specifically identifies challenges and opportunities in five key cross-cutting domains that require attention. These domains are:

- **Sustainability:** To successfully achieve the EU's objectives of safe and sustainable advanced material development, policymakers and stakeholders should make holistic life cycle assessments a standard practice, incorporating environmental, social, and economic perspectives into materials discovery. In addition, circular economy principles should take centre stage in research and education, workforce and infrastructure development, and funding mechanisms.
- **Manufacturing, scaling, and infrastructure development:** Given the geopolitical constraints within the EU, it is evident that it needs regional hubs and innovation clusters that operate between member states to support industrialisation and scaling up, material and waste processing, and harmonising regulatory approvals.
- **Vision and opportunities for basic research:** While the EU remains committed to basic research, it can continue to support and strengthen basic research programmes in biotechnology, nanotechnology, AI, and other emerging fields of materials science, such as quantum materials, metamaterials, advanced composite materials, and neuromorphic materials, through research and innovation funding programmes, such as the currently active Horizon Europe.
- **Digitalisation:** Funding AI and ML education in materials science and implementing findable, accessible, interoperable, and reusable (FAIR) data practices in all aspects of EU research and innovation is vital to accelerating materials discovery through robust databases, cutting-edge simulation codes, and building AI-driven self-driving labs and manufacturing hubs.
- **Policy and governance:** As the EU gears up for the forthcoming Advanced Materials Act, it needs to establish a dedicated coordination mechanism for advanced materials within the European Commission. These efforts can draw on the lessons learned from nanomaterials legislation to build a systematic government framework that not only guides assessment of hazard, exposure, and risks, but also accelerates materials discovery while fulfilling the EU's commitment towards sustainability.

In conclusion, this report provides a comprehensive review of what advanced materials are, where they can benefit society, and how we can design and manufacture them in a safe and sustainable manner. Within this context, this report identifies a range of policy options that can support the EU's mission to advance green and digital transitions, address cross-cutting challenges in advanced materials innovation, and benefit multiple sectors to strengthen the EU's competitiveness in advanced materials.

Key messages

- Incorporate the SSbD framework in advanced materials design and discovery.
- Promote scalable manufacturing infrastructure to achieve lab-to-market for advanced materials.
- Promote synergies between materials research and innovation pipelines in Europe, which are driven by evidence-based approaches.
- Enforce FAIR data principles along with AI-driven materials discovery and design.
- Establish policy and regulation frameworks that take the diversity and unique properties of advanced materials into consideration.

Chapter 1: Introduction

1.1. Scope of the report

The Group of Chief Scientific Advisors to the European Commission has been asked to provide a Scientific Opinion with policy recommendations on the two scoping questions addressed in this evidence review report. As requested in the Scoping Paper, the evidence on these questions remains within the scope of the European Commission Communication on Advanced Materials for Industrial Leadership (European Commission, 2024b), focusing on sectors like energy, construction, mobility, and electronics, along with cross-cutting aspects, with the addition of health:

1. **What contribution can advanced materials bring to the EU's strategic autonomy?**
   To address this question, we focus on research areas in advanced materials that can improve sectors, such as energy, construction, mobility, electronics, and health, which are essential to improving Europeans' wellbeing. Throughout the report, we pinpoint key research areas and applications that reflect the EU's core strengths. We also identify cross-cutting research challenges, including aspects of resource-efficient reuse of materials and end-of-life products, aimed at producing safe and sustainable advanced materials guided by circular economy principles. We further highlight current best practices supported by case studies and discuss pitfalls and roadblocks that could hinder the introduction of advanced materials and their products to the European market. In addition, we pinpoint factors and gaps that can impact industrial competitiveness, where the EU may need to increase efforts.
2. **How can the cross-fertilisation of innovation in advanced materials be enhanced?**
   To address this question, we highlight strengths and weaknesses in the five sectors identified as being critical, namely energy, construction, mobility, electronics, and health, with particular emphasis on cross-cutting aspects. Through this approach, we identify best practices, pitfalls, and potential solutions that can accelerate cross-fertilisation of innovation.

In addition, this report discusses why advanced materials are central to Europe's future and strategic autonomy. Here, we outline three important factors that are bringing new perspectives to advanced materials and will propel the EU towards strategic autonomy. These are:

1. **The geopolitical situation:** Changing geopolitical dynamics fundamentally affect the sourcing of raw materials and resources, since Europe largely imports them. Critical raw materials, such as metals and rare earth elements, will shape Europe's ability to achieve autonomy in advanced materials. While the importance and strategic value of critical raw materials are recognised globally, Europe is geopolitically vulnerable due to its resource constraints.
2. **Sustainability and health:** Europe's commitments to sustainability and environmental responsibility require that chemicals, materials, and products exert minimal impact on health, the environment, and the climate. Consequently, innovation in advanced materials will be driven

by a focus on sustainability, ensuring that resource efficiency becomes standard practice across sourcing, production, use, and end-of-life processes.

3. **Information or data-based materials:** Europe has established significant expertise in developing information-based materials, utilising data- and information-driven methods to identify the most suitable materials for specific applications. By integrating AI and ML modelling into advanced materials discovery, Europe can strategically develop sustainable, eco-friendly, and efficient materials, thereby reducing dependence on imported raw materials.

1.2. What are advanced materials?

Materials reshape humankind

Material discoveries have revolutionised humankind throughout history. The Bronze Age witnessed the advent of new tools and technologies that incorporated metals in stone tools, thereby increasing productivity in agriculture, warfare, and trade. In ancient Roman times, the invention of Roman concrete improved the strength and stability of structures, which have lasted for thousands of years to date. In modern times, the invention of the Haber-Bosch process 100 years ago made it possible to trap atmospheric nitrogen to create synthetic fertilisers that increased global crop production, preventing famine. In recent decades, semiconductor materials have facilitated the electronics and information revolutions, new polymer technologies have helped a new mass production industry of consumer products to flourish, and new metal alloys have made jet engines possible.

At its core, these were all disruptive technologies and as such related to advanced materials *at that time*. These examples illustrate how disruptive material inventions have changed the course of human history. While many recent advanced materials have resulted from profound, often curiosity-driven, scientific explorations, sporadic and accidental scientific findings have also led to breakthroughs. For example, semiconducting materials were initially undervalued, but they are now ubiquitous in all electronics. In some cases, it takes years of sustained research efforts to improve the properties of a given material to create breakthrough advancements. For example, it took decades-long efforts to create the renewable energy converter materials, such as photovoltaics, magnets, and electrocatalysts, that are vital to the modern world.

Advanced materials

What are advanced materials among the broader class of materials? The OECD defines advanced materials as follows:

> Advanced materials are materials that are rationally designed to have (i) new or enhanced properties, and/or (ii) targeted or enhanced structural features with the objective to achieve specific or improved functional performance. This classification includes both new emerging manufactured materials and materials that are manufactured from traditional materials.

In addition, we consider that advanced materials should follow this overarching criterion: advanced materials are expected to have a potential for a disruptive impact on technology based on their purposefully engineered functions (Box 1). Historically, the development of advanced materials has typically been focused on achieving excellent mechanical, electrical, optical, magnetic, and medical properties for use in construction, electronics, devices, sensing, energy, and health. However, sustainability, resource efficiency, and limited reliance on rare and critical resources have increasingly become central. In this context, we consider the following criteria as relevant to any present or emerging materials as advanced materials:

Box 1: Criteria to consider in present and emerging advanced materials.

Advanced materials are new materials that are designed to have novel or enhanced properties and/or structural features for specific or improved functional performance in comparison to existing materials. This includes both new emerging manufactured materials and materials that are manufactured from traditional materials. In this light, what we consider to be "advanced" changes over time as technology develops and matures and the social and economic problems that they are expected to address also change.

Emerging advanced materials increasingly form part of complex multi-component systems consisting of several constituent materials, are developed using breakthrough techniques, and are underpinned by robust scientific understanding. This is significant because constituent materials with differing properties may need to be fine-tuned and engineered, balancing competing requirements.

The multi-component nature invariably involves a large number of possible structural possibilities of the constituent components. This involves mastering structural information in materials synthesis and optimisation, wherein data-based AI/ML and synthetic biology approaches are becoming essential, especially in relation to sustainability.

Following these criteria, Box 2 presents several classes of advanced materials that exist based on different starting materials, manufacturing processes, and intended applications (see also Table 1).

Box 2: Classes of advanced materials

Based on the emerging international consensus (the Innovative Advanced Materials Initiative/IAM-I[2], the EU Advanced Materials Communication, the SSbD framework, and national strategies such as the UK's National Materials Innovation Strategy), the following 10 broad classes of advanced materials are suggested. These materials are typically designed to deliver enhanced performance and to be safe and sustainable by design, taking into account the renewability of feedstocks, environmental degradability, durability, circularity, and recyclability over the full cycle:

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[2] https://www.iam-i.eu/our-work/#sria

- **Biomaterials:** Materials intended to interact with biological systems to evaluate, treat, augment, or replace tissues, organs, or physiological functions. They encompass polymeric, metallic, bio-ceramic, composite and natural bio-derived materials engineered for biocompatibility, controlled bioactivity, and (where appropriate) resorbability (easy breakdown or dissolution and reabsorption by a biological organism). Applications include implants, prostheses, tissue engineering scaffolds, wound dressings, drug and gene delivery systems, and biosensors that support improved health and wellbeing over the full life cycle of the device.
- **Ceramic materials:** Inorganic, non-metallic materials with high hardness, thermal stability and chemical resistance, including structural ceramics, technical ceramics, and bio-ceramics. They are used in high-temperature and wear-resistant components (engines, turbines, cutting tools), electronic substrates and insulators, and solid electrolytes.
- **Electronic, photonic, and quantum materials:** Materials designed for information processing, communication, sensing and quantum technologies, including semiconductors, superconductors, dielectrics, magnetic and spintronic materials, optical and photonic media, and selected quantum and topological materials. They underpin low-loss power electronics for data centres and telecommunications, quantum and neuromorphic computing, sensors, imaging systems, and integrated photonics. Current development focuses on higher energy efficiency, extended device lifetimes, reduced dependence on critical elements, and circular approaches to component and module design.
- **Energy materials:** Materials engineered to store, convert, harvest or distribute energy efficiently and safely, spanning electrodes and electrolytes for batteries and supercapacitors, fuel-cell and electrolyser components, hydrogen storage media, thermoelectrics, catalysts for power-to-X processes (power to chemicals or heat processes), and materials for solar, wind, and nuclear technologies. They are critical enablers of the clean-energy and net-zero transition, targeting reduced carbon footprint, extended lifetime, improved recyclability and safe, low-impact processing across the entire energy system.
- **Advanced metallic materials:** Multi-element and microstructure-engineered alloys, including high-entropy and compositionally complex alloys, advanced steels, intermetallics, nanocrystalline and amorphous alloys, and additively manufactured metals, which are designed for superior combinations of strength, toughness, corrosion resistance, fatigue life, and temperature capability. These materials are key to lightweight and durable components in transport, energy, manufacturing, and health technologies, with a growing emphasis on resource efficiency, repairability, remanufacturing and high-value recycling.
- **Hybrid materials:** Materials combining organic, inorganic and/or bio-derived components at molecular, nano- or micro-scale to achieve multifunctional properties not attainable by individual constituents. Examples include organic–inorganic hybrids, metal–organic frameworks (MOFs), bio-hybrids, and multi-phase catalysts, sensing or separation media. They enable advanced performance in energy conversion and storage, catalysis, separation and purification, environmental monitoring, and healthcare.

- **Nanomaterials:** Materials that exhibit at least one dimension in the nanoscale (typically 1–100 nanometres (nm)), including nanoparticles, nanoclusters, nanotubes, nanowires, quantum dots, and ultra-thin sheets of 2D materials, such as graphene and related systems. Their size-dependent optical, electronic, catalytic, and/or mechanical properties enable innovations in electronics and optoelectronics, energy, sensors, medicine, environmental remediation, and structural reinforcement. Current policy frameworks place strong emphasis on robust metrology, exposure, and risk assessment for nanomaterials.
- **Polymeric materials:** Synthetic and bio-based macromolecules, including functional and high-performance polymers, elastomers, biodegradable and recyclable plastics, and polymer precursors for advanced processing (e.g. 3D printing, coatings, membranes). They are used in packaging, mobility, construction and infrastructure, electronics, healthcare and medical devices, textiles and wearables, and agriculture. New generations of polymers are explicitly designed to reduce environmental footprint through bio-based feedstocks, depolymerisation, and reduced release of micro- and nano-plastics.
- **Smart, responsive, and multifunctional materials:** Materials that respond to stimuli (temperature, light, electric/magnetic fields, chemical environment, mechanical stress) with reversible and controllable changes in properties, often combining several functions in a single system. This class includes phase-change materials, shape-memory alloys and polymers, stimuli-responsive gels, adaptive surfaces and interfaces, meta-materials and "animate" materials capable of self-healing or repair, or of self-adaptation. Applications span healthcare and biomedical devices, soft robotics, adaptive optics, energy systems, construction, automotive and aerospace, and high-value consumer products. Design is increasingly guided by robust metrology, durability under real operating conditions, and compatibility with circular business models.
- **Structural materials and advanced composites:** Materials engineered for mechanical performance—strength, stiffness, toughness, fatigue, and environmental resistance— often combining multiple phases in composite architectures (e.g. fibre-reinforced polymer composites, metal-matrix and ceramic-matrix composites, laminates, architected and lattice materials). They are central to aerospace and aviation, automotive and transport, construction and infrastructure, marine and offshore structures, and heavy industry. Current research and innovation (R&I) focuses on sustainable fibres and matrices, reduced use of critical materials, low-carbon manufacturing, and structural health monitoring.

The examples in Box 2 underline that two fundamentally different types of advanced materials exist, depending on the intended application and engineered properties. The first ones are primarily inorganic materials, mostly humanmade, which allow unique structural and functional (optical, electromagnetic, thermal, and other) properties. These materials contain elements, such as lithium, cobalt, rare-earth ones, and silicon, which are typically mined from the earth (instead of obtained from recycling); therefore, their sourcing comes with many geopolitical challenges. These materials also need to be processed to remove impurities before they can be used in applications, where they are often used in hybrid systems. For example, many materials are embedded in polymers. Developing alternative solutions for these critical materials would be of great value, requiring extensive fundamental research.

The other type contains organic components often found in nature, either pure or as part of composites. Biological materials, such as silk, elastin, and nanocellulose, exhibit extraordinary mechanical properties comparable to some metals. Many plant and animal composites show self-cleaning, adhesive, and tensile properties, making them excellent advanced materials in a range of applications. Importantly, biological and bio-synthetic materials are largely based on a handful of abundant elements available in nature, such as nitrogen, hydrogen, oxygen, carbon, phosphorous, sodium, and chlorine. Additionally, as biological processes are sustainable, bioinspiration is emerging as a major platform for advanced materials. Exploiting synthetic biology and potentially avoiding the use of rare critical materials in selected applications is crucial. Finally, biological systems are inherently adaptive to changing environmental conditions, which can inspire the design of advanced materials in the longer term. This would be particularly valuable for healthcare and other application areas.

1.3. The need for advanced materials

Why do advanced materials matter to Europe today? Conventional material production approaches are largely based on energy- and chemical-intensive extraction, short-term usage, and fast depletion of non-renewable geologic resources, particularly fossil fuels, and minerals. These practices are increasingly recognised as unsustainable in the light of growing environmental, economic, geopolitical, and societal pressures.

In response, there is a global shift towards circular economy principles, which promote prolonged material lifespan, reuse, regeneration, and efficient recycling. Within this context, advanced materials play a central role. The development of materials is currently experiencing a profound transformation driven by sustainability and resource-efficiency considerations. Further, new capabilities in AI, ML, simulation, and digitalisation of experimental explorations have the potential to accelerate materials discovery and design.

The strategic importance of advanced materials is particularly evident in Europe, where natural resources are comparatively limited. This factor makes it imperative to ensure secure and efficient access to primary raw materials and shift focus towards innovations that extend product lifespans through repair, regeneration, self-healing, improved material flows, and sustainable recycling. Concomitantly, the increasing integration of simulation and data-driven methodologies, from high-throughput computational modelling and ML in materials discovery to automated synthesis and characterisation, demands a coordinated framework that supports scientific research, industrial innovation, and policy development.

At the same time, Europe is facing challenges in manufacturing products and systems to serve a plethora of applications. Citizens demand improved quality of life and comfort while insisting on upholding sustainability standards. This means that we should start by properly eco-designing our needs, with sustainable choices of raw materials and reuse and/or biodegradability in mind. This should be complemented by selecting energy- and materials-efficient techniques where recyclability also should be considered.

To achieve this sustainable transition, emerging and critical technologies, such as sustainable technologies (also termed green chemistry), AI, and biotechnology (including synthetic biology), are essential. Recognising this, European policy initiatives have already started to emphasise two key goals. The short-term goal of the Net-Zero Industry Act aims to achieve net-zero manufacturing capacity to meet at least 40% of the EU's annual deployment needs by 2030 (Regulation (EU) 2024/1735, 2024). The critical role of advanced materials in the green transition, under the broader umbrella of the European Green Deal, has a long-term view targeting climate neutrality by 2050 (European Commission, 2024c). Achieving these ambitions requires materials that are resource-efficient and low-carbon, placing advanced materials at the core of the green and digital transformation (European Commission, 2023b).

1.4. Advanced materials of our times and their applications

At present, major efforts are underway to translate research into manufacturing technologies and viable products. As summarised in Table 1, current developments in the field of advanced materials are geared towards meeting the needs of humanity. These include: nanostructure materials for light-weight construction, electronics, sensing, and healthcare; sustainable biodegradable packaging materials; biosynthetic skin; materials that respond to stimuli for autonomous systems; materials that can heal or show dirt-repellence; coloured materials without oil-based chemistry; bio-derived materials; and advanced materials for lightning, photovoltaics, and energy harvesting, storage, and management.

While not all of these promising advanced materials are expected to lead to societal transformation, sustained investment in high-level fundamental research can facilitate breakthroughs and strengthen the EU's capacity to manage technological and commercial translation.

Advanced materials	Possible applications
2D materials (e.g. graphene, transition metal disulfides, MXenes)	Ultra-thin and flexible electronics, high-mobility transistors, transparent conductors, advanced membranes for gas and water purification, next-generation batteries, supercapacitors.
Nanoparticles, nanoclusters and quantum dots	Photovoltaics and LEDs (Light Emitting Diodes), bio-imaging and medical contrast agents, catalysts with high surface area, tunable optical and electronic materials.
Nanowires, nanotubes and 1D structures	High-sensitivity sensors, miniaturised interconnects and contacts, thermoelectric devices, reinforced composites, structural components.

Engineered nanostructured surfaces and coatings	Self-cleaning and anti-fouling surfaces, anti-icing and anti-fogging coatings, low-friction tribological layers, passive thermal management for buildings and devices.
Functional polymers and elastomers (including electro-active polymers)	Biodegradable and recyclable plastics, flexible and stretchable electronics, vibration and noise damping, soft actuators and artificial muscles, encapsulation, barrier layers.
Hydrogels, ionogels and gels	Tissue-engineering scaffolds, wound dressings, controlled drug delivery, soft robotics and wearable sensors, solid and quasi-solid electrolytes for batteries.
Bio-based materials (cellulose, lignin, bio-composites)	Sustainable construction and insulation, lightweight panels and packaging, textiles and fibres, bio-derived electrodes, membranes for energy storage and filtration.
Proteins, peptides, DNA/RNA, and virus-like particles	Biocompatible coatings and adhesives, programmable nanocontainers for drugs and genes, biosensing and diagnostic platforms, templated nano-electronics, nano-photonics.
Advanced semiconductors and oxide electronics	High-efficiency photovoltaics, power electronics for grid and transport, LEDs, laser diodes, photoelectrochemical water splitting, gas, and chemical sensors.
Structural and functional ceramics and glass-ceramics	High-temperature and corrosion-resistant components, thermal barrier coatings, biomedical implants, electronic substrates and packaging, protective armour, wear-resistant parts.
Porous materials and membranes (zeolites, MOFs, ceramic membranes)	Selective gas separation and carbon capture, water purification and desalination, catalytic reactors, regenerative filters for air quality and industrial emissions control.
Thermoelectric and caloric materials	Waste-heat harvesting in industry and transport, solid-state cooling without greenhouse gas emissions, local thermal management of electronics and sensors.
High-entropy and compositionally complex alloys	High-strength and corrosion-resistant components for turbines, aerospace, nuclear and chemical plants, structural parts in extreme environments, long-lived and recyclable infrastructure.
Advanced steels and ultra-high-strength steels	Crash-resistant automotive structures, rail and pipeline systems, offshore platforms and civil infrastructure, protective and blast-resistant components.
Superalloys and refractory alloys	High-temperature components for jet engines, gas and steam turbines, concentrated solar power receivers, nuclear fission and fusion devices, high-temperature tooling.

Lightweight metals and metal-matrix composites (Al, Mg, Ti)	Weight reduction in vehicles, aircraft and drones, portable electronic devices and wearables, robotic systems, sporting goods, personal transport.
Metals for hydrogen and other energy systems	Hydrogen storage and transport, fuel cell bipolar plates, corrosion- and embrittlement-resistant pipelines and tanks, durable electrodes, current collectors for batteries and electrolysers.
Quantum materials (strongly correlated, topological, 2D quantum magnets)	Low-power and ultra-fast logic devices, spintronic and neuromorphic components, robust interconnects and memory, novel sensing concepts based on quantum phases.
Superconductors (low- and high-temperature)	High-field magnets for fusion, particle accelerators and MRI/NMR, lossless power cables and fault-current limiters, ultra-sensitive detectors, quantum electronic circuits.
Multiferroics and magnetoelectric materials	Voltage-controlled magnetic memory and logic, highly efficient actuators and sensors, tunable RF and microwave devices, compact and low-energy components for communication systems.
Quantum photonic materials and colour centres in solids	Single-photon sources and detectors, secure quantum communication, integrated quantum photonic circuits, nanoscale magnetometry and thermometry, ultra-precise timekeeping, navigation.

Table 1. Advanced materials and their possible applications[3].

1.5. Thinking ahead: Future-focused research and innovation of advanced materials

Advanced materials are at the heart of innovation for most technological areas. This underscores the need for their systematic development. The European Commission's request identified five sectors that rely on advanced materials, introduced here. In each section, we highlight emerging technologies that could focus on serving today's technology and application demands.

1.5.1. Energy

Energy is among the EU's focal points, as the EU aims to decrease greenhouse gas emissions by 55% by 2030 and increase renewable energy sources to 42.5% of total energy consumption (European Commission, n.d.-d). In 2004, the EU generated ~2 700 TWh/year; nearly half of it came from renewable resources and the rest from fossil fuels and nuclear sources (Figure 1).

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[3] See also the table in Annex 1.

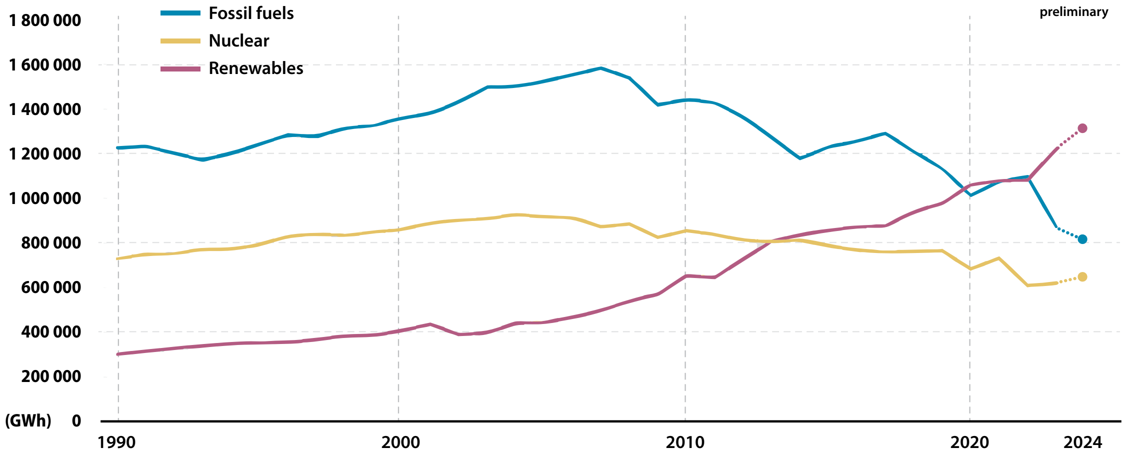

Figure 1. Electricity production in the EU, 1990-2024.
Source: Adapted from Eurostat (2025a). Licensed under CC BY 4.0.

To expand its capacity in renewable energy, the EU aims to increase renewable ("green") hydrogen production from some 50 thousand tonnes in 2024 (see Figure 3) to 10 million tonnes per year by 2030 (European Commission, n.d.-c; EY & Hyvolution, 2025). Under the hydrogen economy, hydrogen produced through water electrolysis without greenhouse gas emissions will generate electricity using entirely renewable sources instead of fossil fuels. This is achievable using advanced storage systems to manage hydrogen transport and surplus hydrogen (Oliveira et al., 2021).

Advanced materials and infrastructure play a key role in energy production, energy storage, and energy management to increase energy efficiency. The following key materials, particularly focused on clean and renewable energy, are anticipated to lead to innovation in the energy sector:

1. Large-scale green hydrogen production, storage, transport, and production materials, including pipelines, infrastructure, containers, adhesives, and cryogenic-resistant alloys.
2. High-atom energy efficiency materials for electrochemical converters.
3. Magnets.
4. Piezoelectrics and high-temperature superconductors.
5. Catalysts.
6. Materials for batteries, such as solid-state and sodium-ion batteries, and redox batteries.
7. Materials for CO_2 capture and valorisation.
8. Photovoltaics for solar and wind energy converters, such as advanced solar cells.
9. Advanced composites for wind turbine blades and generators.

1.5.2. Electronics

The electronics sector faces an emerging challenge: the need to develop sustainable, ultra-low-power-consuming devices that can meet the versatile and growing needs of future technologies, such as data centres and high-performance computing facilities. This can be realised by exploiting new semiconductors, quantum materials, materials involving topological effects, and other low-dimensional materials, which respond to the demands of utilising materials performance at a nanoscale.

A major bottleneck in electronic materials today is related to solving the problem of thermal budgets. New device designs and architecture and local efficient cooling and processing can address these limitations. Moreover, exploiting topological effects in quantum materials**,** like spintronics, will enable new capabilities and levels of performance, such as ultra-high-speed electronics and quantum sensing.

Looking ahead, miniaturisation is expected to continue, for example, in exploiting three-dimensional device integration. The following key focus areas are anticipated to innovate electronics:

1. Sustainable, high-performance, including radiation-hardened, materials for electronics with extended functional lifetimes, novel materials for ultra-scaled transistors (lower dimensional, i.e., sheet or line-like, 2D or 1D materials) and materials for spintronics (e.g., 0D quantum dots).
2. Low-waste production and rare elements recycling.
3. Alternatives to high-purity silicon for semiconductor circuits for use in AI and the Internet of Things (IoT) applications.
4. Recyclable and/or biodegradable materials for substrates and packaging.
5. Rare metal resource efficiency strategies for energy converters.
6. Defect engineering for next-generation information storage and processing material.
7. Flexible and printed electronics, especially stretchable materials for wearables, IoT, and advanced displays.
8. Quantum and neuromorphic materials for low-energy and more complex computing.
9. Additive manufacturing of advanced polymers, metals, and ceramics for 3D printed electronics.

1.5.3. Construction

The present evidence suggests focusing on reducing the CO_2 footprint of building materials, improving energy efficiency in buildings, enhancing structural robustness and longevity, enabling better monitoring of structural integrity, and promoting greater occupant wellbeing. The EU should exploit novel materials to enhance environmental and structural performance—especially in harsh environments—and reduce energy consumption, while incorporating new functionalities in electronic components for smart buildings.

Using the novel materials that enable smart, durable buildings and associated structures, the key innovation focus areas for the construction sector are:

1. Development of environmental recyclable sensor materials with long lifespans, and eco-friendly construction materials, such as low-carbon cement, steel with a low carbon footprint, timber composites, and thermally efficient (bio-based) insulation.
2. Self-healing and climate-resilient materials, such as self-healing concrete, and adaptive building materials.

3. Earthquake- and corrosion-resistant materials, such as flexible fibre-reinforced composites, advanced coatings for offshore wind-tower foundations, bridges, and tunnels.
4. Smart surface coatings and nanomaterials for enhanced targeted properties, such as self-cleaning, anti-icing, and pollution-reducing for urban infrastructure.
5. Materials with heating and cooling properties for adjustment withstanding climate change.

1.5.4. Health

Advanced materials are becoming game changers in the health and biomedical sectors, where therapies and diagnostics routinely use viral capsids, deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) nanostructures, nanoparticles, nanoclusters, vaccines, biosensors, and gels.

The following key focus areas are anticipated to innovate the health sector:

1. Qualification and lifetime prediction of materials for medical device design.
2. Advanced materials for regenerative medicine, tissue engineering, cell therapy, drug delivery, and biosensing.
3. Engineered materials for implants and devices, such as antibacterial surfaces and ergonomic customisation.
4. Recycling of biocompatible materials for implants and devices.
5. Incorporation of digital technologies, such as bioimprinting, laser writing in theranostics, biosensing, and bioimaging.

1.5.5. Mobility

The concept of enhancing quality of life in urban areas is closely linked to rethinking mobility. Teleworking can reduce the need for travel, contributing to more sustainable cities. Achieving sustainable transportation involves more than just reducing CO_2 emissions and energy consumption; it requires a holistic approach that promotes liveable cities, green habitats, and citizen-friendly living environments. This entails reimagining multi-modal mobility with less car ownership, fewer parking spaces, and a focus on environmentally friendly personal autonomy.

In electrical transportation, advanced sensors and communication materials will be crucial for the widespread adoption of smart mobility solutions. EU efforts should therefore focus on developing advanced energy storage systems, including solid-state batteries, alternative fuels, and high-performance materials suited for demanding transport environments.

The following key focus areas—that not only enhance sustainability and reduce environmental footprints, but also expand mobility opportunities for vulnerable groups such as people with disabilities or illnesses, children, and older people—are anticipated to innovate the mobility sector:

1. Lighter materials, such as bio-based polymers and corrosion-resistant coatings for magnesium and aluminium alloys.
2. Thermal barrier coatings, supercapacitors for energy storage, and metamaterials for noise reduction are vital for both low- and high-mobility applications.
3. Fast, comprehensive, and affordable sensors all around the vehicle to ensure the safety of (semi-) autonomous vehicles.

1.6. Our approach to this report

In this report, we focus on the following main themes that align with the current public view and the EU's policy goals:

- Sustainability and green chemistry principles (Chapter 2)
- Production (Chapter 3)
- Basic research to accelerate advanced materials discovery for societal transformations (Chapter 4)
- Data-driven and simulation-guided manufacturing of advanced materials (Chapter 5)
- Policy and regulation (Chapter 6).

Sustainability and green chemistry principles (Chapter 2)

Achieving sustainability is a grand challenge of our time. Sustainability was first defined as the principle of meeting present human needs without compromising the ability of future generations to meet their own needs (Brundtland, 1987). This concept is often understood as a balance between environmental, social, and economic pillars. However, sustainability is often reduced to the environmental sphere, where sustainable chemistry is only discussed in terms of the so-called green principles of chemistry (Anastas & Warner, 2000). Among these principles one can find: the use of renewable resources and renewable energy; low carbon footprint; controlled product life cycles with effective waste recycling; reducing greenhouse gas emissions; preventing waste; minimising environmental hazards and toxicity; promoting safety; maximising the content of raw materials in the product; resource effectiveness; reducing needs to use organic solvents; high-energy efficiency in manufacturing and in applications; and clean and lean production processes. However, sustainability also affects social and economic conditions. Therefore, holistic life cycle assessment (LCA) is needed where the deployment of advanced sustainable materials into the market is based on a quantitative and standardised approach for the estimation of environmental, social, and economic implications

One goal of introducing advanced materials is that they will reduce dependence on raw materials when combined with circular strategies, extend product lifetimes, and improve energy and resource efficiency. There is evidence that bio-derived raw materials (feedstock) can be used for several types of advanced materials, including biotechnological production. Biorefineries (analogous to oil refineries), in which renewable bio-based feedstocks will be used for product manufacture through various technologies, are being developed, and there is still a long way to go in this area. Energy efficiency, the use of waste as starting materials, and scalability are emerging focal points, for example, the utilisation of inedible food waste and other industrial or municipal biowaste, and electronics waste.

Production (Chapter 3)

Advanced manufacturing technologies, including additive manufacturing, AI-driven designs, recycling and biotechnology, are essential for producing next-generation materials with enhanced properties, sustainability, and enabling circularity. There exists firm evidence that biotechnology and synthetic biology will increasingly allow bio-based production of some chemicals, polymers, and other biosynthetic products as substitution materials. Even though large-scale industrial biotechnological processes exist, the development of many more new processes from laboratory to industrial scale is still a bottleneck for increasing the market of biosynthetic materials. New technology developments need reconsideration of certifications and sufficient infrastructure scale-up to overcome process inefficiencies. Innovation sandboxes and learning factories provide low-risk environments for testing and scaling materials and processes. These environments foster collaboration between academia, industry, and regulators. Innovation ecosystems and networks are vital for bridging the lab-to-market gap and fostering cross-sectoral collaboration when developing new types of materials and their markets. The design of sustainable alloys and electro-ceramics can profit from composition-based to microstructure-driven approaches, integrating AI, robotics, and circularity principles.

Basic research to accelerate advanced materials discovery for societal transformations (Chapter 4)

Fundamental research is vital for innovation, which involves systematic knowledge development and often leads to landmark inventions. Advanced materials are no exception in this respect; developments in many scientific and technological fields are culminating in advanced materials that will reshape the world. There are a variety of ways basic research can drive innovation in materials science, and the examples and case studies showcase advanced materials that will enable the green transition and empower the EU's energy, transport, and electronics industries. The European Research Council, the EU's core strength in basic research, provides a powerful funding platform to perform such vital science.

Data-driven and simulation guided manufacturing of advanced materials (Chapter 5)

Broad and firm evidence shows that high-throughput workflows and automated laboratories will revolutionise the experimental approaches for materials synthesis, processing, and characterisation, and data- and simulation-driven approaches will become dominant in materials design and discovery. Combined with powerful first-principles and multiscale computational methods, ML and AI techniques, coupled with vast materials data repositories and powerful computing platforms, will enable unprecedented exploration of the materials space. At present, the lack of high-quality datasets and insufficient databases makes it still challenging to implement reliable computational approaches. There should be concrete efforts to generate new high-quality databases to expand materials research.

Digital twins[4]—digital models that emulate the behaviour of a real-world system—specific to materials development and manufacture, will be needed in automated processes.

Policy and regulation (Chapter 6)

Most categories of advanced materials are typically governed by the general product safety framework and sector-specific regulations, wherever applicable. It remains unclear how to ensure sustainability and circularity for advanced materials. There is a fundamental problem with how we approach risk governance related to emerging materials and technologies, such as nuclear power, biotechnology, nanotechnology, and now advanced materials. There is a recurring and concerning pattern where stakeholder collaboration and consultation are encouraged to discuss policy and governance. However, the recommendations are either forgotten or often ignored for decades.

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[4] A digital model of a real-world system or process, used for purposes such as, optimising, testing, monitoring, and maintenance (see Chapter 5 and Glossary).

Chapter 2: A primer on sustainability: Concepts, processes, and best practices

2.1. Introduction and scope of the chapter

Global challenges, such as climate change, pollution, biodiversity loss, and limited natural resources, require sustainable solutions for innovation, including advanced materials. Sustainability is also vital to Europe's strategic autonomy, since the production of advanced materials may introduce challenges related to critical raw material sourcing, with social, economic, and environmental implications. As the EU is implementing its ambitious policy framework to achieve sustainability within Europe, we focus on all aspects of sustainability. The goal of this chapter is to provide a comprehensive understanding of why advanced materials are key to a sustainable EU.

Throughout the chapter, we describe sustainability via two critical concepts:

1. **Circular economy or circularity:** a circular economy refers to maximising resource value from production to consumption in a way that ensures nothing gets wasted. It involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products for as long as possible.
2. **Cross-fertilisation:** cross-fertilisation is a business strategy that involves bringing and mixing ideas from different places, industries, markets, and people to produce better products and services.

Using these two underlying approaches, we first outline raw material sourcing, circular strategies, urban mining, and industrial symbiosis approaches and how they will contribute to the EU's autonomy in the commodity-sourcing needed for advanced materials production (Sections 2.2., 2.3. and 2.4.). We then discuss how holistic assessments are essential for developing sustainable advanced materials, which are rooted in identifying and avoiding unwanted environmental, economic, and social impacts across a material's entire life cycle (Sections 2.4. and 2.5.). Lastly, we emphasise the sustainability challenges common to different sectors, with particular focus on sustainable materials, which will drive cross-fertilisation of innovation (Section 2.6.).

2.2. Raw materials sourcing and the need for sustainability

Deploying a European strategy aimed at safeguarding leadership in advanced materials requires mapping the distribution of locally and globally available resources. Monitoring fluctuations in supply chains of both primary raw materials and secondary raw materials recovered from waste and recycling has become a priority particularly due to global events and changing geopolitical scenarios.

Eurostat classifies raw materials in four categories: non-metallic minerals, metal ores, organic biomass, and fossil fuels (Eurostat, 2025b). The EU has also defined a list of *critical* and *strategic* raw materials, mostly consisting of non-metallic minerals, metal ores and chemical elements extracted from them, as well as fossil fuels, such as coking coal (Regulation (EU) 2024/1252, 2024).

The global demand for raw materials has more than tripled over the past five decades, driven by urbanisation, technological progress, rising incomes, population growth, and shorter product lifespans. Between 1970 and 2020, global material extraction rose from approximately 30 billion to over 95 billion tonnes. Without significant intervention, it is projected to increase by another 60% by 2060, potentially reaching 160 billion tonnes annually (UNEP, 2024; Krausmann et al., 2018).

Such a sharp increase is mostly associated with the dramatic increase in extraction of non-metallic minerals (Circle Economy, 2025). This category is also termed as *development minerals* and described as "minerals and materials that are mined, processed, manufactured, and used domestically in industries such as construction, manufacturing, infrastructure, and agriculture. In comparison to minimally processed export minerals, they have closer links with the local economy with a more direct impact on poverty reduction" (Franks, 2020).

Within this category, sand represents the most extracted commodity and has become one of the most critical resources globally. Depending on its specific nature and purity, sand can be used in the production of strategic materials in the construction and electronics sectors, which are considered research and development (R&D) priorities for the EU (European Commission, 2025c). While most of the extracted sand is incorporated into the construction sector to produce concrete, sand enriched in quartz is essential to produce silicon wafers, a critical component in semiconductors. We witnessed the disruption of the semiconductor supply chains during the COVID-19 crisis.

Similarly, the European ceramics industry was strongly affected by the Ukraine conflict, leading to a shortage in the supply of high-grade kaolinitic clay —another non-metallic mineral of primary importance for the construction sector— that is largely sourced from the Donbas region (Gualandri, 2023).

According to the United Nations Environment Programme (UNEP) Global Resources Outlook 2024, the extraction and processing of raw materials are responsible for over 60% of global greenhouse gas emissions and more than 90% of biodiversity loss and water stress (UNEP, 2024). They are also associated with major economic challenges and social risks, including low wages, hazardous working conditions, child labour, land-use and geo-economic conflicts, mine waste, and the displacement of indigenous communities (Hecht, 2023). In addition, women often face even greater risks than men, particularly in informal or small-scale mining, processing, and agricultural commodity chains, where they are disproportionately exposed to insecure employment, lower wages, gender-based violence, and limited decision-making power (UNEP, 2024; Mancini et al., 2018).

In response, industries have been called on to adopt more sustainable practices. Circular strategies aimed at reducing raw material extraction, such as reuse, remanufacturing, and recycling, can all play pivotal roles in this transition. According to a business-as-usual scenario, the total amount of extracted raw materials in a year can rise by more than 50% in about three decades and the percentage of materials sourced from cycling[5] is still well below 10% (Circle Economy, 2021).

Given these broader economic, environmental, and societal problems associated with raw material sourcing, the focus should shift to adopting holistic sustainability measures for the entire value chain. In addition, it is fundamental to concentrate efforts on the systematic mapping and creation of databases that lead to the extraction of secondary resources from industrial side-streams (Peys et al., 2025), particularly aimed at feeding into the European advanced materials industry.

2.3. The 4R Planet Strategy (reduction, removal, repair, resilience)

The Climate Crisis Advisory Group (CCAG), a consortium of experts in climate science, carbon emissions, energy, the environment, and natural resources, works to proactively respond to the climate emergency. It has proposed a 4R Planet Strategy[6], a comprehensive approach to secure humanity's future. In this section, we discuss how advanced materials may contribute to addressing the 4R Planet principles, involving reduction of emissions, removal of greenhouse gases, repair of our climate systems, and resilience to deal with climate impacts and threats (CCAG, 2023).

2.3.1. Reduction

As we defined at the beginning of the chapter, material circularity is a simple idea that aims to ensure that nothing gets wasted. In this concept, materials are simply not consumed and discarded, but are continuously circulated through reuse, repair, remanufacturing, and recycling. Like any product, the goal is to design advanced materials that are durable, separable, and most importantly, recyclable.

Implementing material circularity is a complicated task that requires handling production waste and end-of-life waste containing either single material or multi-material components. Technological and logistical solutions can often be implemented directly at the production site for their cycling. However,

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[5] "Cycling" is often used as an umbrella term to include both upcycling and recycling (or either of the two).

[6] https://www.ccag.earth/news/ccag-4r-planet-strategy

when production waste involves complex or multi-material compositions, it becomes more challenging to handle and recycle it.

End-of-life waste, on the other hand, presents greater challenges. It typically requires multiple steps before reuse, repair, or recycling can even begin. The actual recycling can only begin after the numerous steps starting with sorting consumers, followed by collection, then further sorting, dismantling, or shredding. These steps are resource-intensive and prone to material loss, especially when dealing with inseparable composites or contaminated materials.

While advanced materials often enable high performance during use, their complex structures or bonded multi-material forms can effectively hinder recyclability. To align with circular principles, advanced materials should be designed for durability, disassembly, and compatibility with existing recycling systems.

2.3.1.1. Renewable biomass resources as feedstock

One key aspect of reduction is the reduction in greenhouse gas emissions to limit global warming. Materials that replace fossil fuels are energy- and carbon-efficient and they will be crucial for a sustainable future. Therefore, prioritising production processes that minimise fossil-based energy and raw material use throughout the value chain process—from feedstock sourcing to product manufacturing, reuse, and recycling—is becoming a norm for advanced materials.

Bio-based systems are becoming alternatives to fossil raw materials because they leverage fundamental sustainability hallmarks of nature. A benefit of using renewable biomass and the products derived from it is that they eventually degrade efficiently, replenishing and recycling materials back into the earth and atmosphere as happens in nature or for reuse as feedstock. There are serious ongoing efforts to create advanced materials using bio-based systems and researchers use two main approaches to use biomass in manufacturing:

1. Extracting useful materials from biodegradable sources, such as cellulose, lipids, or other polymers and converting them into a final product using various technologies.
2. Using biotechnology (discussed in detail in Chapters 3 and 4) to build new material components using biomass and waste fractions as feedstock.

Using these approaches, new processes based on waste valorisation are developing to substitute oil refineries. For example, biorefineries are created for the use of non-edible feedstocks, like corn stover, straw, and wood chips to produce either biofuels, electricity, and heat or bio-based products, such as cellulose fibres and other material products.

2.3.2. Removal

Advancing carbon removal technologies to permanently remove CO_2 from the atmosphere is another critical strategy. Advanced materials can contribute to the removal of greenhouse gases produced by industrial processes by integrating with carbon capture and utilisation (CCU) approaches.

Carbon in biomass primarily originates from photosynthesis by plants and prototrophic microbes that harness energy from sunlight. In addition, certain microbes fix CO_2 using hydrogen. Biotechnological CO_2 conversion (bio-CCU) into materials is an emergent but promising field. For example, the US-based company Lanzatech demonstrates commercial feasibility to convert CO_2 or other C1 compounds such as CO and methane into building blocks for polyethylene terephthalate (PET) and polyethylene using microbial biotechnology, with prospects for broader product portfolios (F. Liew et al., 2016).

Thermochemical and electrochemical technologies can convert CO_2 into formaldehyde, methanol, and olefins, and building blocks for material production, akin to fossil-derived chemicals (Okoye-Chine et al., 2022). Biomass can also be gasified to synthetic gas consisting of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2), to produce ammonia or methanol. These technologies aim to replace fossil-based feedstocks with sustainable alternatives. This is sustainable from the carbon-emission point of view since these processes actually use CO_2 rather than generate it. While direct air capture of CO_2 remains difficult, using concentrated flue gases from industrial exhausts offers a scalable circular economy route to move towards carbon neutrality or negativity.

Actions oriented at abating methane are also needed, given its huge greenhouse impact. These can include engineering advanced catalysts, adsorbents (e.g., MOF, ZIF - Zeolitic imidazolate framework, biochars) and biotechnological solutions. For example, materials with advanced methane capturing capabilities will be needed to overcome the inherent challenges in the capture process, due to the higher dilution of methane as compared to CO_2 (Lackner, 2020). This will also require advanced design at the molecular level, which could potentially be assisted by AI methods (Y. Song et al., 2025).

2.3.3. Repair

Materials that last significantly longer by self-repairing or autonomously self-healing damage can significantly extend product lifetimes and reduce waste, offering a promising pathway to enhanced sustainability in advanced material design. Self-repair involving external energy or materials has been observed in some polymers, metals, and cement (Cahen & Lubomirsky, 2017; Tan et al., 2018). Well-known historical examples of cement-based structures are Rome's Pantheon (Italy) and the Pont du Gard near Nimes (France), which are witness of the fact that cement can self-repair cracks by interaction of unreacted particles with water.

Autonomous self-healing, where damage autonomously disappears without external intervention, occurs in a variety of materials. These include: molecular organic solids such as bipyrazole piezoelectric organic crystals (Bhunia et al., 2021; Commins et al., 2025); organic polymers and biopolymers like DNA, often by re-forming hydrogen bonds after rupture; thermoreversible rubber (Cordier et al., 2008); shape-memory metals, such as nickel-titanium alloys (Ghosh, 2008); Li-doped silicon for detectors (Pell, 1960); $CuInSe_2$ (Guillemoles et al., 1999) and $MaPbBr_3$ solar cells (Cahen et al., 2021; S. Kumar et al., 2020; Ceratti et al., 2018).

As an example, lead-halide perovskites are being developed for high efficiency solar cells and for LEDs, as well as for detectors. All three types of materials can self-heal due to mobility of ions. In halide perovskites, self-healing is further aided by strong anharmonic lattice dynamics. In general, such semiconductors are important as more electronics are sent into space and require radiation-resilience.

2.3.4. Resilience

Circular sourcing strategies are critical in ensuring supply chain resilience in the development of advanced materials. The transition to clean energy and electrification is driving a sharp increase in demand for critical elements, such as lithium, cobalt, and rare earth elements. However, extracting these minerals from primary sources poses significant geopolitical risks and adverse environmental and social impacts. Currently, China dominates the market for the extraction of commodities such as graphite, silicon and rare earth elements (REE), and for the processing of resources such as cobalt, manganese and lithium (United Nations, 2024). This near-monopoly creates strategic vulnerabilities for the EU as a whole and individual countries in the EU, which currently has low resilience due to limited domestic production and high dependency on imports from China and other suppliers (Regulation (EU) 2024/1252, 2024; OECD, 2025).

In response, the EU has introduced the Critical Raw Materials Act, aiming to diversify supply sources, increase domestic extraction, processing, and recycling capacities, and reduce overreliance on single external suppliers (Regulation (EU) 2024/1252, 2024; Zabala Innovation, 2025). The European Critical Raw Materials Act poses challenges and opportunities, some of which are discussed in Hool et. al (2024). Nevertheless, the EU's resilience remains challenged by its dependence on external supply chains.

Circular strategies, including urban mining, component reuse, and regional material loops, can reduce reliance on virgin extraction and enhance supply chain resilience. Moreover, designing advanced materials for local recovery and reuse supports building regional capacity and reduces vulnerability to global supply shocks. Collectively, the 4R Planet Strategy applies to all aspects of advanced materials research and innovation. In turn, many advanced materials will contribute to fulfilling the core principles of remove, reduce, repair, and resilience for a sustainable future.

2.4. Holistic sustainability assessments for advanced materials

2.4.1. Life-cycle perspective

Because advanced materials are complex and heterogeneous in nature, evaluating sustainability over their whole life cycle and applications requires multi-faceted approaches. These approaches need to deal with integrating environmental, social, and economic dimensions along the life cycle starting from raw material extraction and processing to manufacturing, use, and end-of-life.

Life cycle assessment (LCA) is the foundational method initially developed for environmental impact assessment. However, these assessments have evolved over time to include social and economic aspects in the analysis. Therefore, we now have broader sustainability frameworks, including social LCA (S-LCA), life cycle costing (LCC), material flow cost accounting (MFCA), and others, that we discuss in greater detail. These holistic and highly accurate frameworks go beyond limited environmental indicators and embrace expertise of stakeholders from a variety of socio-economic backgrounds to improve sustainability across the entire value chain.

The overarching goal of LCA is to accomplish holistic sustainability assessments supporting responsible innovation and ensuring a meaningful shift towards global sustainability objectives. Therefore, it has become imperative for industries to identify processes that deliver high levels of sustainability when developing or using advanced materials.

2.4.2. Environmental sustainability and green chemistry

By embedding green chemistry principles (Anastas & Warner, 2000), such as atom economy, waste prevention, energy efficiency, use of renewables, minimising toxicity, and life cycle management, into advanced materials development, we can achieve high-performance products that meet technological demands while advancing a sustainable and safer future.

Of the environmental evaluation methods, many focus on the 'carbon footprint' by measuring greenhouse gas (GHG) emissions either at the organisation or product level, as depicted in Table 2. These methods assess the GHG balance based on which organisation is the source of emissions, the energy source that created emissions, and indirect emissions that occur upstream and downstream of the value chain of the company creating emissions (Young-Ferris et al., 2025).

Besides GHG-oriented methods, environmental LCA (E-LCA) deals with potential environmental impacts throughout the life cycle. Using an inventory of all inputs—such as energy, raw materials, land use—and outputs—such as waste, emissions, toxicity—LCA returns a series of quantitative impact indicators. Specifically, the European Consumption Footprint method envisages 16 specific indicators (Commission Recommendation (EU) 2021/2279, 2021).

Method	GHG only	Multicriteria	Product level	Organisation level
GHG protocol	*x*		*x*	*x*
Bilan carbone®	*x*		*x*	*x*
ISO 14064	*x*		*x*	
ISO 14067	*x*			*x*
TfS Guidelines	*x*		*x*	
CO_2 performance ladder	*x*			*x*
LCA		*x*	*x*	*x*

Table 2. Greenhouse gas emission assessment methods.

However, when a measure becomes a target, it ceases to be a good measure. The proliferation of companies' environmental claims may amount to greenwashing, particularly considering that factors such as calculation methods, the life-cycle stage, the geographical scope of the claim, the range of issues excluded from the assessment, and whether results undergo independent verification, are not always specified (Léonard et al., 2026). The EU's Green Claims Directive (European Commission, 2023a) addresses these challenges by requiring that such claims be backed by scientific evidence and verified by third-parties, and multicriteria tools such as E-LCA are essential in this context and encouraged by the EU through the environmental footprint method (Commission Recommendation (EU) 2021/2279, 2021) (Léonard et al., 2026),

2.4.3. Economic sustainability

MFCA, LCC, and criticality assessment under the EU Critical Raw Materials Act (Regulation (EU) 2024/1252, 2024) are key methodologies for the economic evaluation of advanced materials. MFCA provides a detailed accounting of material and energy flows in monetary terms, revealing hidden costs associated with waste and inefficiencies during production. This method is particularly valuable for advanced materials, which often involve complex and resource-intensive manufacturing processes, enabling companies to identify cost-saving opportunities and improve resource efficiency (International Organization for Standardization, 2025; UNEP, 2024). Complementing this, LCC assesses all costs incurred throughout the life cycle of a product, including acquisition, operation, maintenance, and end-of-life, providing a holistic economic perspective that is critical for advanced materials embedded in long-lived or high-value applications.

Together, these tools enable a comprehensive economic evaluation of advanced materials by accounting for production inefficiencies, life cycle costs, and supply chain vulnerabilities, supporting informed decision-making for economically sustainable material development.

2.4.4. Social sustainability

In addition to environmental and economic dimensions, social life cycle assessment (S-LCA) evaluates the social impacts along the entire value chain, from raw material extraction and processing to manufacturing, use, and end-of-life. It addresses aspects such as working conditions, occupational health and safety, access to education, and respect for human rights (UNEP, 2020; Benoît & Mazijn, 2009).

S-LCA uses quantitative, qualitative, and semi-quantitative data, including generic databases, stakeholder interviews, and site-specific assessments. Many social risks, such as child labour or forced labour, cannot be meaningfully assessed based on quantities, since their occurrence is considered unacceptable regardless of extent. Therefore, S-LCA often involves contextual and normative judgments, demanding the contribution of qualitative social scientists and stakeholders.

Indicators are linked to key stakeholder groups involved along the life cycle, such as workers, consumers, local communities, society, and value chain actors. For example, metrics such as locally appropriate wages or the presence of grievance mechanisms can be used to assess risks and benefits for specific groups.

A major strength of S-LCA is its ability to identify differentiated risks for specific population groups and to account for diversity factors such as gender, age, or nationality. Depending on the process step, region, or sector, individuals may face varying degrees of exposure to discrimination, job insecurity, or lack of representation. By highlighting these group-specific vulnerabilities, S-LCA contributes to a more inclusive and comprehensive sustainability assessment, particularly in global and complex supply chains. When systematically applied to advanced materials, S-LCA can help reduce social risks worldwide by informing responsible sourcing, fair value-chain management, and socially conscious innovation.

2.4.5. Eco-design

The word eco-design comes from the fusion of ecology and design. It refers to integrating environmental considerations from the product design phase by considering all stages of the life cycle and a range of environmental impacts.

Brezet and Van Hemel (1997), proposed the so-called eco-design strategy wheel, consisting of eight axes as per Figure 2 below:

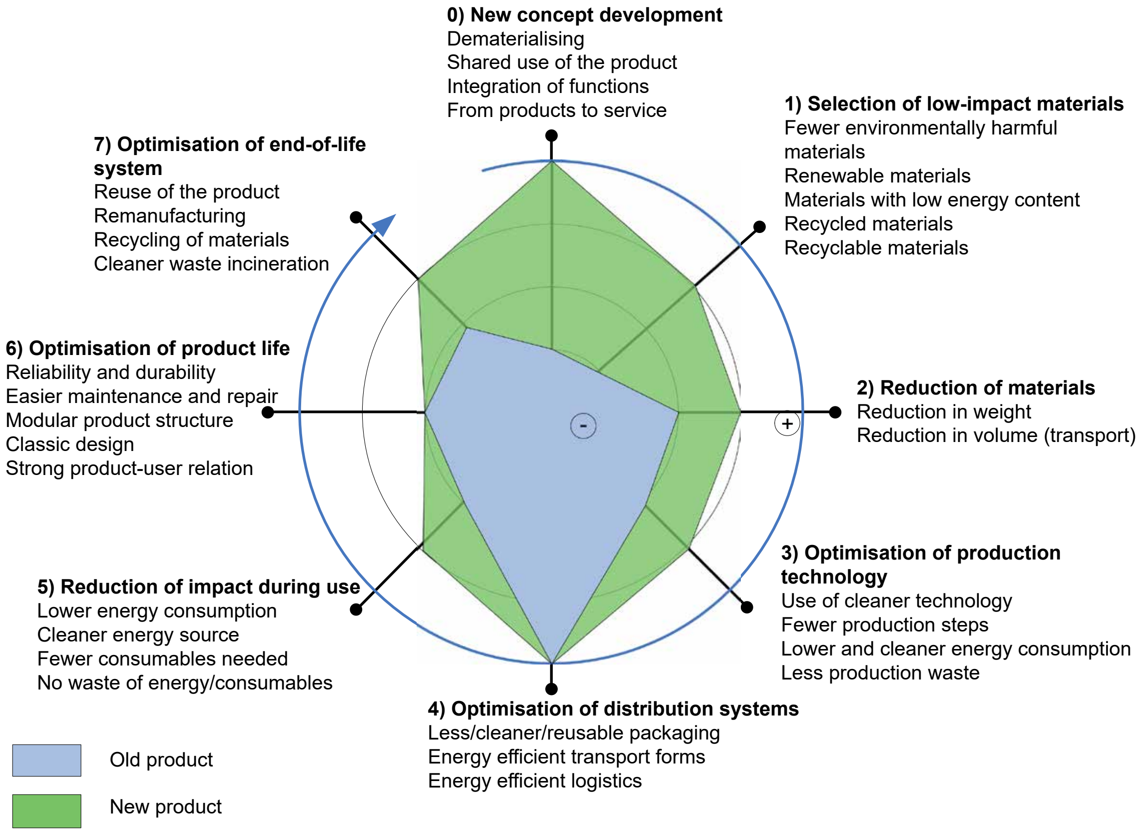

Figure 2. The eco-design strategy wheel. Source: Huulgaard & Remmen (2012), based on Brezet & van Hemel (1997).

In this context of eco-design, LCA is a very useful tool to verify how the chosen strategy will be beneficial from an environmental point of view and to help in taking decisions.

2.4.6. Safe and sustainable by design framework

Safety is a paramount feature in any product design. To address emerging gaps in safety and sustainability, the European Union has introduced the SSbD. SSbD specifically guides the development of materials, products, and processes that are inherently safer for human health and the environment, while simultaneously fostering innovation and industrial competitiveness (Commission Recommendation (EU) 2022/2510, 2022).

SSbD provides a critical roadmap for advanced materials, which often involve novel chemistries and complex production processes. The framework is structured into two main phases:

1. The first design phase integrates eco-design principles—that evaluate environmental impacts through the life cycle—with explicit safety considerations, identifying and minimising hazardous properties at an early stage by selecting safer alternatives. This includes chemical risk assessments to evaluate potential health and environmental risks related to the materials themselves.

2. The second phase focuses on performance validation and implementation, ensuring that both sustainability and safety objectives are met throughout the entire life cycle of the product or process. This holistic approach is particularly important for advanced materials, where life cycle impacts, including resource use, toxicity, recyclability, and social implications, must be assessed comprehensively (UNEP, 2024).

The EU defines the following five key steps in the SSbD process: hazard assessment of the chemical or material (chemical risk assessment, CRA); evaluation of human health and safety during production and processing; assessment of health and environmental aspects in the final application; environmental sustainability assessment; and social and economic sustainability assessment (Commission Recommendation (EU) 2022/2510, 2022).

2.4.7. Multi-criteria decision analysis

Multi-criteria assessment methods offer the advantage of simultaneously considering ecological, economic, and social aspects of sustainability. While less detailed than classical methods such as E-LCA, LCC, and S-LCA, multi-criteria assessments can efficiently highlight key sustainability hotspots. This multi-criteria approach, as summarised in Table 3, serves as a practical decision-making tool, helping stakeholders prioritise actions and guide sustainable development effectively (Rycroft et al., 2019; Lindfors, 2021).

Life cycle perspective
⬢ Perspective across all stages in a material life cycle: extraction, processing, production, use, end-of-life (with re-strategies or disposal).
Environmental sustainability
⬢ Green chemistry principles applied: resource efficiency, clean production, energy efficiency, renewable feedstocks, toxicity reduction. ⬢ Environmental LCA quantify impacts: GHG emissions and multi-impact approaches. ⬢ Environmental Product Declarations (EPDs) support transparent communication.
Economic sustainability
⬢ MFCA identifies monetary costs and inefficiencies in material and energy flows. ⬢ LCC assesses total life-cycle costs. ⬢ EU Critical Raw Materials Act fosters resilient supply chains through sourcing, processing, and recycling incentives. Criticality assessments monitor economic importance and supply risks of raw materials.
Social sustainability

⬢ S-LCA addresses social aspects such as labour conditions, human rights, health, education, and fairness across supply chain for different stakeholders. ⬢ Can highlight group-specific risks related to gender, age, nationality. ⬢ Supports responsible sourcing and socially conscious innovation contributing to Sustainable Development Goals one to five.
Eco-design
⬢ Integrates environmental considerations into design of materials, products, and processes. ⬢ Eco-design strategies: new concept development, low impact materials, material efficiency, optimisation of production process and distribution systems, reduction of impact during use, optimisation of product life, optimisation of end-of-life systems. ⬢ LCA helps evaluate and verify environmental benefits of design choices.
Safe and sustainable by design (SSbD)
⬢ Extends eco-design by integrating explicit safety and hazard evaluations early in material development (chemical risk assessment). ⬢ Structured into two phases: design (hazard assessment, safer alternatives) and validation (performance, life-cycle sustainability). ⬢ Covers chemical, health, environmental, social, and economic assessments. ⬢ Supports regulatory compliance and sustainable innovation aligned with global goals.
Multi-criteria decision analysis
⬢ Evaluates ecological, economic, and social sustainability aspects simultaneously. ⬢ Less detailed than individual LCA or LCC but effective for prioritising sustainability hotspots. ⬢ Provides practical decision-making tools to guide sustainable development actions.

Table 3. Multi-criteria life cycle assessment strategies to achieve sustainability in advanced materials.

2.5. Industrial symbiosis: Drivers, barriers, and opportunities

Industrial symbiosis is a circular strategy defined as using one company or sector's underutilised resources—including waste, by-products, residues, energy, water, logistics, capacity, expertise, equipment, and materials—by another sector, aimed at keeping resources in productive use for longer (Comité Européen de Normalisation, 2018). This strategy reduces the dependency on primary unused raw materials and has the potential to stimulate positive feedback between different industrial sectors (Lippi et al., 2025) and promote the development of symbiotic industrial networks (Sellitto et al., 2025).

It is a subfield of industrial ecology, that studies materials and energy flows in society. Drivers of industrial symbiosis include reduction of primary raw materials and associated costs, particularly related to their transport, savings in waste disposal fees, and revenue generation from by-products. In terms of raw materials consumption, currently nearly eight gigatonnes (Gt) of materials are processed every year in the EU, of which only approximately 10% are sourced as secondary materials from side-streams (Figure 3). The implementation of industrial symbiosis policies at the EU level can potentially improve these figures and reduce the dependency on primary resource extraction and import of raw materials, which account for approximately 70% and 20%, respectively, of the overall stock of processed materials (Figure 3). However, barriers to industrial symbiosis, mainly the lack of technology, infrastructure, and regulation and fluctuations in the quality, supply, and cost of by-products need to be addressed to see full benefits of the strategy (Department for Energy Security & Net Zero, 2024; Nugroho et al., 2025). A recent report has introduced the concept of Symbiosis Readiness Level (SRL), which attempts to assess the maturity of a specific industrial symbiosis project (Sommer, 2020). Using this approach, industrial symbiosis partnerships can be evaluated based on both the achieved technological level as well as other indicators, including business planning, quantitative sustainability assessment, and regulatory aspects of the partnership.

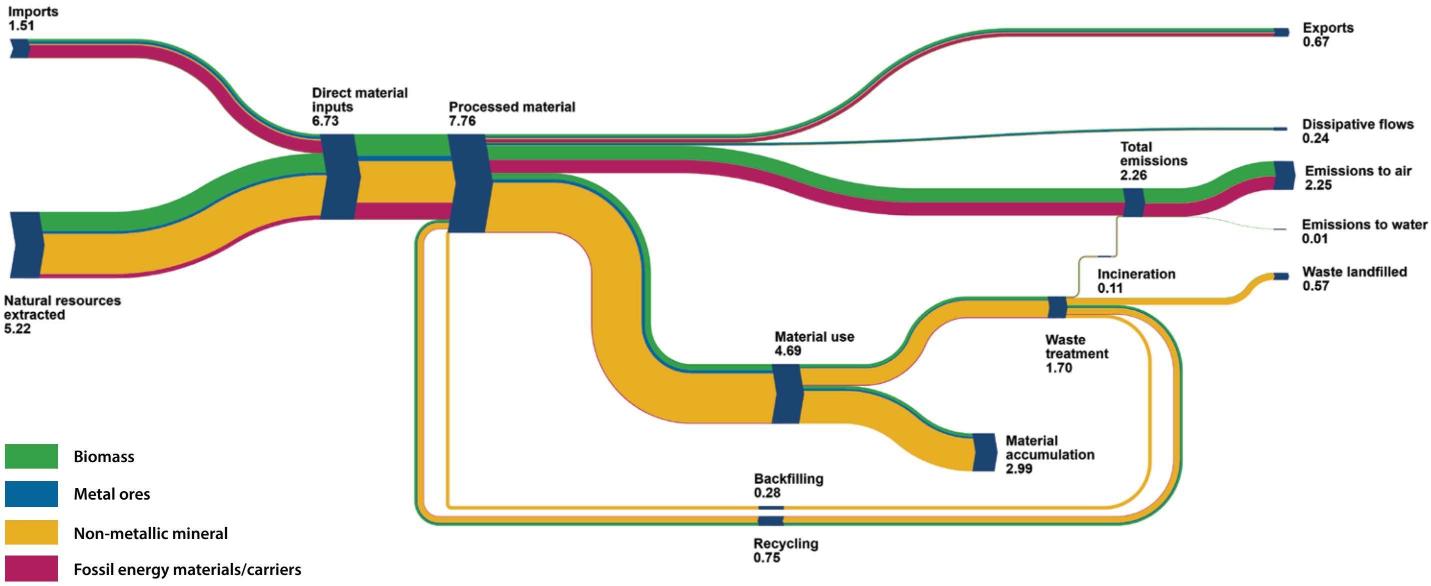

Figure 3. Sankey plot displaying material flows for the EU in 2023 (in gigatonnes).
Source: Eurostat (n.d.), Interactive visualisation. Data sources : Adapted from ENV_AC_MFA; ENV_AC_SD; ENV_WASSD. Licensed under CC BY 4.0.

2.6. Best practices and case studies

There is a growing need for sustainable advanced materials because of environmental, societal, and economic concerns as we emphasised in this chapter. Therefore, the sectors responsible for contributing to sustainability challenges, such as construction, energy, and electronics, can benefit from advanced materials that mitigate the harmful effects on health and environment. In this section, we describe several new advanced materials, their functionalities in critical sectors, and ongoing discovery efforts in the field that used sustainability as a core principle. We also describe advanced materials and projects that incorporate holistic life-cycle assessments, showcasing how they promote sustainability. Our goal is to present the achievements and developments listed below as evidence of sustainable advanced materials.

2.6.1. Advanced electronics: Tackling e-waste and transitioning to eco-electronics

The rapid growth of digital technologies has greatly increased electronic waste (e-waste), as many devices have short lifespans and are rarely recycled (Martins, 2021). At the same time, digital innovation continues to expand, making it essential to design digital devices and electronic interfaces that are both sustainable and affordable by employing circular strategies and using eco-sustainable components. This would align with sustainable principles and respect the Green Deal concept, as promoted by the European Commission (Martins, 2021).

This technological revolution supports a range of emerging applications, including interfaces that transform mobile platforms into smart systems—such as energy-autonomous sensor networks for the Internet of (Intelligent) Things (Io(I)Ts). This is a crucial and rapidly growing field of modern science and technology, as well as a vital node in the manufacturing and services value chain.

2.6.2. Advanced structural materials for construction

The construction sector is one of the most CO_2-emissions intensive sectors (Figure 4) and it also accounts for an enormous amount of raw materials consumption (Figure 5).

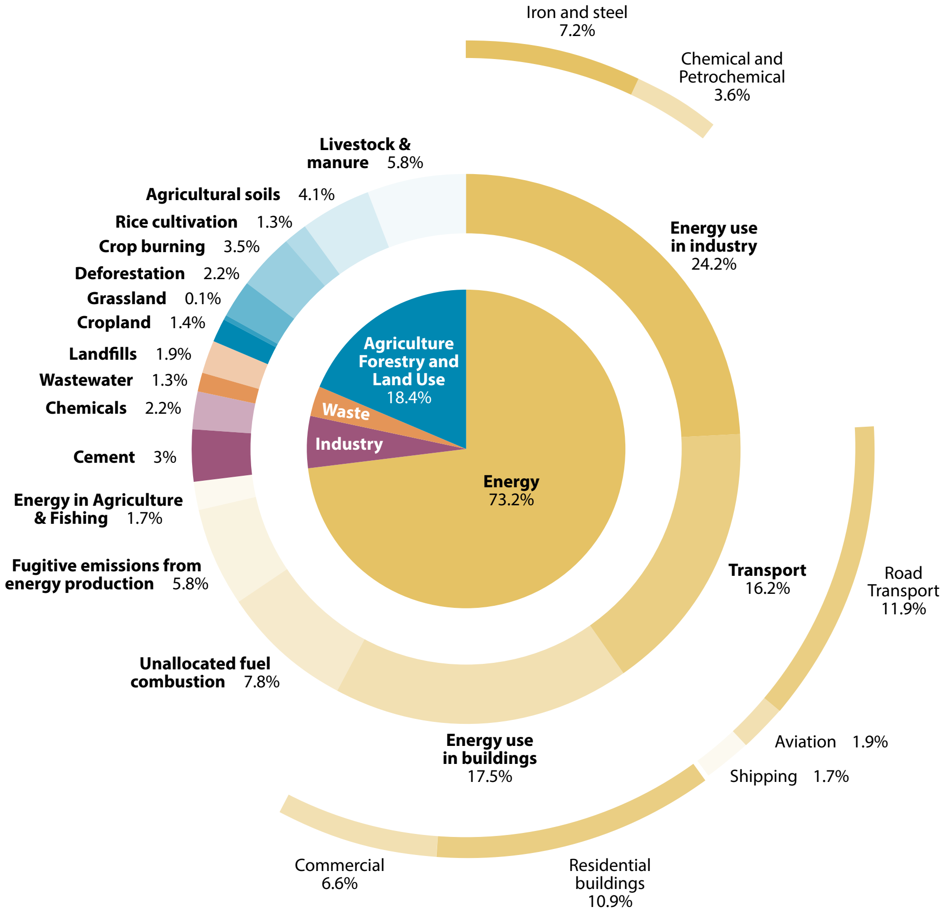

Figure 4. Global greenhouse gas emissions by sector in 2016 (total 49,4 billion tonnes CO_2 eq.).
Source: Adapted from Ritchie (2020). Licensed under CC BY 4.0.

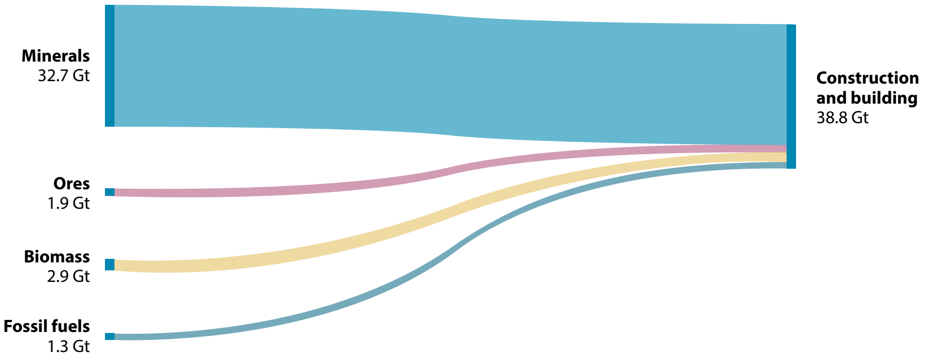

Figure 5. Raw material flow associated with the construction industry.
Source: Adapted from Valentini (2023). Licensed under CC BY 4.0.

Furthermore, the management of waste streams associated with this sector represents a priority, considering that construction and demolition account for nearly 40% of all waste generated in the EU (Moschen-Schimek et al., 2023).

Cement-based materials such as concrete represent the primary material used in construction. The current yearly production of cement amounts to more than four billion tonnes globally and is responsible for about 6% of the anthropogenic CO_2 emissions (Statista, 2025). To mitigate these effects, Europe should be focused on the development of long-lifespan and eco-friendly cement-based materials, with potentially self-healing properties, thermal efficiency, and earthquake resilience. These materials can have enhanced durability and corrosion resistance with new coatings and composites for harsh environments, smart coatings and surfaces for self-cleaning, anti-icing, and pollution-reducing materials for urban infrastructure. The use of nanotechnology to enhance targeted properties, such as the development of mechanical properties and impermeability, should also be considered (Valentini et al., 2018).

2.6.2.1. Alternative low-CO_2 cementitious binders

Portland cement has a formidably complex chemistry and is characterised by excellent engineering properties and durability. However, the significant CO_2 footprint associated with Portland cement production requires deploying alternative binders with advanced environmental performance. The simplest and most feasible alternative to Portland cement is blended cement, where a variable fraction of the former is replaced by powders with different degrees of reactivity in aqueous solution, among which are different types of industrial wastes. This approach does not require significant changes to the production process, while guaranteeing significant CO_2 emissions reductions. One point deserving attention is the long-term local availability of such stocks of industrial waste: for example, ground granulated blast-furnace slag is already incorporated in near totality within other sectors, whereas coal-combustion fly ash may face shortages due to phasing out of coal. To address this issue, blending with widely available raw materials, such as limestone and calcined clays, has been proposed as a viable solution to mitigate CO_2 emissions in the short term (Scrivener et al., 2018). Another possible approach is relying on alternative waste streams, which are not yet commonly used (and not envisaged in existing standards) in the production of alternative cements (Snellings et al., 2023). This will require that the EU stimulate basic research into the reactivity of such mineral waste streams in aqueous solution.

Though representing a concrete solution to cutting CO_2 emissions, blended cements still retain part of the carbon footprint embodied in Portland cement. Different types of Portland-free binders have been researched and tested in practical applications (Shi et al., 2019), among which alkali-activated materials (AAM) have received significant attention (Aiken et al., 2022). According to Aiken et al., alkali-activation entails the reaction of an aluminosilicate precursor with an alkaline solution, typically based on alkali silicates or hydroxides. A large variety of precursors can be used as an aluminosilicate source, including different types of waste, such as steel-making slags, coal combustion ashes, and other industrial side-streams (Aiken et al., 2022; Peys et al., 2025). One of the limits of AAM is that the alkaline activators often have a higher environmental impact than the aluminosilicate source materials, which has led to a search for lower-carbon alternatives, utilising waste streams, to further improve the environmental performance of AAM (Adesanya et al., 2021; Aiken et al., 2022). Alkali-activated materials have not yet gained widespread acceptance in the construction industry in comparison to Portland cement concrete due to several barriers and limitations. At the EU level, one of the main barriers is the lack of dedicated standards. Despite the solid knowledge developed in AAM, certain aspects require in-depth exploration from different perspectives to ensure their application in the construction industry. In this respect, AI and ML show great potential for revealing hidden relationships and optimisation design models for AAM (Y. Li et al., 2023; C. Völker et al., 2023), enabling more sophisticated links across materials' properties.

2.6.2.2. Cement-based materials and industrial symbiosis

The cement industry has a huge potential for upcycling waste streams from various industrial sectors (e.g., steel, non-ferrous metals, waste-to-energy, etc.). Whereas such wastes display reactivity in alkaline solutions, they can be utilised to partially or totally replace Portland cement, with the double advantage of cutting CO_2 emissions associated with limestone decarbonation during Portland cement production and reducing the pressure on landfill facilities. Moreover, CO_2 generated during Portland cement production can potentially be captured and upcycled to produce carbon nanotubes (Licht, 2017). Finally, construction and demolition waste can be utilised as a CO_2 sink to produce recycled carbonated aggregates, which can substitute natural aggregates—sand and gravel—in concrete (Villagran-Zaccardi et al., 2025).

One notable pioneering case of industrial symbiosis between the building and steel industries was the construction of multistorey buildings, using Portland-free cement, in Mariupol between 1960 and 1980 (Rossi et al., 2022). Large heaps of unused blast-furnace slag from the nearby Azovstal steel works could be tapped and used to produce a Portland-free binder by chemical activation of the glassy slag, using alkaline solutions. Likewise, several other waste streams can be used, especially if enriched in aluminium-silicon glass, to produce sustainable cementitious binders by blending with Portland cement or by chemical activation.

2.6.2.3. Low carbon steel

As per the European Steel Association (Eurofer, 2025), about 36% of steel was consumed by the building sector in 2024. At the same time, the iron and steel industry accounts for around 7% of global GHG emissions and 11% of global CO_2 emissions (Hasanbeigi, 2022). To decrease its environmental impact, the sector uses different strategies, such as promoting reuse at the end of life, increasing the recycling of scraps in electrical arc furnaces (EAF). New production routes are investigated, such as direct reduction of iron by hydrogen (so-called DRI), coupled to an EAF powered by renewable energy to drastically reduce CO_2 emissions (Benavides et al., 2024). Carbon capture technologies are also cited among the future decarbonisation pathways. This transition also fosters the development of new refractory materials able to resist in the presence of hydrogen. This topic is at the heart of the CESAREF[7] project, which has one objective dedicated to the anticipation of hydrogen steel making.

2.6.3. The AtLAST project: Incorporating life-cycle assessment in advanced materials for energy systems

The EU-funded AtLAST[8] project is a comprehensive feasibility study that seeks to alleviate technical, operational, and environmental challenges while building a telescope. Sustainability is at the core of this project, combining techno-economic models, holistic LCA, and energy justice considerations (with fair distribution of energy-related benefits and costs) in the selection of materials and components such as batteries, photovoltaics, and hydrogen technologies, from raw material extraction to component deployment and use.

The study particularly highlights the role of LCA in the choice of future energy systems components, focusing on important factors, such as cost-effectiveness and GHG emission reductions. It further evaluates additional important factors, including mineral resource depletion, water use in components production, consideration of where and how these components are produced along with environmental impacts of their transportation (Viole et al., 2024). Renewable and inclusive energy systems were also explored via multi-actor multi-criteria analysis that included different stakeholders (e.g., local residents, energy providers, scientists) in the energy design process, revealing prospects for future collaborative systems based on social engagement and acceptance, crucial for energy transitions and materials development (Valenzuela-Venegas et al., 2024).

A notable gap exists in up-to-date open-access life-cycle inventories reflecting new technologies, indicating opportunities for needed further research in energy system component databases.

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[7] https://www.cesaref.eu/project/

[8] https://www.atlast.uio.no/

2.6.4. The CLASCO Project: Sustainable and safe advanced manufacturing

The EU-funded CLASCO[9] project demonstrates how sustainable and safe advanced materials can be developed by applying nature-inspired micro- or nano-structures to surfaces, eliminating the need for critical raw materials or chemical post-processing. CLASCO uses a last-treatment approach, where functionality is introduced at the end of the manufacturing process by modifying the surface structure. Inspired by natural examples, such as the water-repellent properties of lotus leaves or the anti-reflective structures of insect eyes, the project enables material functions like hydrophobicity for corrosion resistance as well as reduced friction.

This strategy offers several advantages in accordance with SSbD principles. These include:

- Avoidance of critical raw materials like cobalt.
- Elimination of hazardous chemical processing to reduce environmental and health risks.
- Reduction of social risks throughout the material life cycle by substituting cobalt-chromium-based alloys with titanium alloys.

A dedicated pipeline in CLASCO evaluates all use cases against key SSbD criteria, including social responsibility, environmental footprint, supply security, and production safety. This ensures that material innovations are not only functional but also sustainable and responsibly designed.

CLASCO exemplifies a shift in materials development away from complex, resource-intensive formulations and towards smart, structure-driven design for circular, safe, and future-proof material solutions.

2.6.5. Next-generation EU projects: Championing safe and sustainable by design principles in advanced materials development

Among the ongoing efforts to incorporate SSbD principles, numerous EU flagship projects incorporate the SSbD approach in the creation of advanced materials. These projects focus on replacing harmful substances and reducing environmental and social impacts from the beginning:

- The MOZART[10] project develops special nickel-based coatings that function like harmful chromium coatings but without toxic chemicals.
- The NICKEFFECT[11] project works on nickel materials to replace expensive and scarce platinum metals in fuel cells and electronic devices.

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[9] http://www.clasco-project.eu/

[10] https://www.mozart-project.eu/safe-and-sustainable-by-design-ssbd/

[11] https://nickeffect.eu/

- The FreeMe[12] project aims to remove toxic chromium and palladium used in plastic coating processes.
- The NOUVEAU[13] project is creating a greener and cheaper technology for producing hydrogen fuel by improving key components and recycling parts.

Together, these projects demonstrate how SSbD principles—safer materials and processes, reducing hazards, and thinking about the entire life cycle—help design sustainable, resilient, and eco-friendly solutions that support the EU's goals for a circular economy and environmental protection.

In addition, large EU public–private partnerships play a major role: the Circular Bio-based Europe Joint Undertaking[14] (CBE JU) is a €2-billion partnership between the EU and the Bio-based Industries Consortium that funds projects advancing competitive circular bio-based industries in Europe. Its portfolio is largely focused on materials and demands high sustainability criteria.

2.7. Key messages

- Advanced materials and circular strategies can reduce raw material dependence, extend product lifetime, and improve energy and resource efficiency.
- Deploying advanced sustainable materials into the market requires the definition of policies based on quantitative and standardised approaches for the estimation of environmental, social, and economic implications. These estimations should also focus on human safety.
- Over-reliance on simple GHG metrics risks missing broader impacts; multi-criteria methods and transparency in performance claims are necessary to avoid greenwashing.
- Industrial symbiosis (cross-sector reuse of waste/resources) and design for disassembly can increase resource productivity and reduce waste, but require supportive infrastructure, regulation, and digital tools to address quality/consistency challenges.
- Strategic, circular sourcing (urban mining, component reuse, local loops) and indigenous recovery build supply chain resilience, especially regarding critical raw materials.

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[12] https://nsc-community.eu/nsc-overview/nsc-structure/ongoing-projects/freeme/

[13] https://www.nouveau-project.eu/?page_id=19

[14] https://www.cbe.europa.eu/organisation

Chapter 3: Emerging technologies in manufacturing, scaling, and infrastructure

3.1. Introduction and scope of the chapter

This chapter explores how advanced materials can strengthen Europe's strategic autonomy and drive innovation across sectors by highlighting the role of materials in sustainable industrial transformation. The chapter does not merely describe technologies, but links them to broader policy objectives, showing how materials research can support competitiveness, resilience, and environmental responsibility in positioning Europe as a global leader in this field.

The chapter directly addresses the two scoping questions. First, it identifies areas where Europe has strong capabilities, such as biotechnology, alloy design, and computational methods, emphasising gaps in scalability and circularity that need further investment. The chapter also addresses cross-cutting challenges, such as security, sustainability, and the lack of robust data infrastructure.

Second, it analyses how innovation can be better connected across applications in different sectors. It proposes practical mechanisms, such as innovative environments, learning factories, and biofoundries, that can help bridge the gap between research and industry. The chapter specifies the importance of feedback loops, interdisciplinary collaborations, and shared infrastructure to accelerate adoption and market readiness.

In this chapter, we aim to answer the following key questions:

- How are advanced materials manufactured?
- What production technologies should be used in manufacturing?
- Once these technologies have been defined, how can they be scaled up efficiently for market release?
- How can we leverage the advantages of interacting with all the agents in innovation ecosystems to accelerate innovation processes and subsequent commercialisation?

In addition to answering these questions, we emphasise key sectors for developing materials that expand the limits of their applications.

The new technologies and the industries that can support them are further examined from a cross-cutting viewpoint in this chapter. It analyses some of the main issues that need to be considered to maximise development, increase the production of materials, and take advantage of innovation and digital technologies without losing sight of the needs of society. The chapter concludes by emphasising the importance of developing innovation ecosystems that unite all stakeholders and networks to promote knowledge and competency sharing.

3.2. Emerging sectors and production technologies

Green and digital transitions have become one of the top priorities for the EU. Advanced materials that are lighter, stronger, smarter, and multifunctional are essential to achieve the EU's twin transitions towards sustainability and digital leadership. Cutting-edge technologies are essential for developing advanced materials, without losing sight of the fact that the real goal is to meet society's needs. This is especially true in EU priority areas, such as energy, construction, mobility, electronics, and health. In fact, new materials are already solving challenges such as making buildings more energy-efficient, improving battery performance, improving safety and recycling of medical devices, and many more.

This section highlights game-changing materials and technologies in five priority sectors. Moreover, it showcases how collaborations between research centres and businesses accelerate the material discovery process, from the laboratory to the factory and the market.

3.2.1. Types of emerging technologies

The emerging technologies in the development of advanced materials encompass two different types of technologies with specific and multifunctional capabilities:

1. The first type relates to advanced technologies required to find and develop new materials for various applications. Examples of distinctive technologies useful in wide-ranging applications (European Cluster Collaboration Platform, 2024) include: metallic nanoparticles that enhance energy conversion in solar panels; novel thermochromic microcapsules that absorb and reflect light in construction applications; thermoelectric materials for solid state cooling and energy harvesting; new materials "beyond silicon" for the next-generation chip manufacturing; elastomers and nanocrystals that enable flexible electronics for smart devices; bio-based materials with increased insulation and circularity capacity; recyclable carbon reinforced plastics for wind-mill blades, airplane wings, sports equipment; novel architectures for sodium-ion batteries for storing energy.
2. The second type of technologies relate to facilitating advanced materials synthesis, such as AI, biotechnology, 4D printing, robotics, etc.

Since emerging technologies and materials offer new functionalities in different sectors, here we define goals in each sector to enable both green and digital transitions. Table 4 provides a broad overview of key focus areas where emerging technologies and advanced materials will solve problems.

	Goals	Key focus areas	Collaborative opportunities
Energy	• Low-carbon and renewable energy generation, as well as the production, distribution, storage, and conversion of renewable fuels. • Joint efforts in solid-state batteries, energy-harvesting materials, and hydrogen storage infrastructures. • Cooperative studies on energy-harvesting materials, solid-state batteries, and infrastructure for hydrogen storage.	• Materials (e.g., containers, adhesives, and cryogenic-resistant alloys for high-capacity hydrogen storage). • Novel materials for batteries and photovoltaic systems (e.g., solid-state, and sodium-ion batteries). • Materials for CO_2 valorisation. • Advanced materials for wind and solar energy (e.g. high-performance composites for wind turbine blades and tandem and perovskite solar cells). • Materials for climate adjustment challenges in thermal engineering.	• In all these sectors, opportunities for collaboration can be explored in every way and direction: • Cross-collaborations between all actors involved in the sector. • Liaison and collaboration between authorities responsible for legislating and implementing regulations. • Collaborations between industry and academia, linking R&D and knowledge with the commercialisation of ideas and feasibility studies.
Electronics	• Ultra-low-power electronics: develop new materials and production techniques in addition to silicon. • Communication interfaces in electronics (including sensors, computing materials, digital communication, power electronics, optoelectronics, photonics, and quantum technologies) based on recycling and resource efficiency. • Flexible/wearable electronics, materials for AI and quantum computing (e.g., SiC, 2D materials), and the combination of 0D and 2D materials.	• -High-performance, environmentally friendly electronics materials (e.g. as metal oxides—nanorods, 0-2D materials). • Rare metal recycling and low-waste production. • Semiconductors can be replaced with high-purity silicon in AI and IoT applications. • Materials for substrates and packaging that are recyclable and biodegradable. • Effective strategies for rare metal resources especially for semiconductors and batteries. • Next-generation semiconductors (e.g., 1D/2D materials like Xenes for AI chips and digital applications). • Electronics that are printed and flexible (e.g. wearables, the IoT, and sophisticated displays made of stretchable materials). • Materials for neuromorphic and quantum computing. • High-performance metals, ceramics, and polymers for 3D printed electronics for additive manufacturing.	

Construction	⬢ Building energy and resource efficiency, reduction of CO_2 footprint, structural strength and durability, improved structural integrity monitoring, and occupant health. ⬢ New materials to increase performance, especially in harsh environments, reduce energy consumption, and give electronic components for smart buildings new capabilities.	⬢ R&D of materials for sensors with longer lifespan. ⬢ Green building supplies (e.g. thermal insulation, wood composites, and low-carbon cement). ⬢ Climate-resilient and self-healing materials (e.g. responsive building products and self-healing concrete). ⬢ Construction materials that are resistant to corrosion and earthquakes (e.g. deformable fibre-reinforced polymer composites and high-performance coatings for offshore wind, bridges, and tunnels). ⬢ Smart surface coatings (e.g. pollution-reducing, self-cleaning, and anti-icing urban surface materials). ⬢ Hydrophobic and self-cleaning materials that use nanotechnology and smart coating technology. ⬢ Properties of heating and cooling for climate adaptation. ⬢ Development of accelerated test methods to predict the service life and durability of alternative-cement-based materials. ⬢ Advanced manufacturing via 3D printing.	

Health	Encourage medical materials innovation to address the demands of an ageing population and quickly developing healthcare needs. Allow industry, hospitals, nurses, and surgeons to contribute to expedite material qualification, design next-generation devices, and shorten development times.	Medical device material qualification and lifespan prediction. Drug delivery, tissue engineering (e.g., organoids, cell therapy, multifunctional regenerative medicine, and sensing materials). Engineered materials (e.g. antibacterial coatings and ergonomic optimisation for medical implants and devices). Reusing biocompatible materials for implants and devices. Combining digital technologies (e.g. biosensing, bioimaging, bioimprinting, laser writing for graphene quantum dots in theranostics).	
Mobility	Innovative energy storage, unconventional fuels, and high-performance materials appropriate for harsh transportation conditions.	Lightweight components and materials. Cutting-edge technologies for recycling batteries. Automobile parts that can be recycled. Materials for hydrogen fuel cell cars. Development of shape memory alloys and application of generative AI to the design of materials for upcoming mobility solutions.	

Table 4. Key focus areas and collaborative opportunities in the EU in different sectors.[15]

3.2.2. Leveraging biology for material synthesis and manufacturing

In this report, we present numerous examples of bio-derived materials with exciting properties and describe all the benefits they offer (Chapter 4). Advancements in biotechnology are revolutionising how we manufacture and transform materials. Therefore, this section discusses biotechnology and synthetic biology that offer tremendous opportunities and a huge design space for improving organisms and creating better or novel material products.

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[15] This table provides some examples based on the working group's expertise and is not meant to be comprehensive.

3.2.2.1. Biotechnology

Biotechnology is uniquely positioned to create more sustainable processes than petrochemistry or other synthetic manufacturing processes (A. Kumar, 2023). Biotechnology leverages living organisms or their parts, such as catalytic enzymes, to develop new materials and products for a broad range of applications and industrial sectors.

In principle, any (bio)chemical compound or structural material found in biological systems can be manufactured using biotechnology. This is achieved by transferring the responsible genes to either microbes or mammalian cells grown in laboratories or bioreactors. In addition, microbes such as bacteria and yeast fundamentally use renewable resources (such as biomass and organic waste) as raw material, and the biochemical synthesis in bioreactors do not require toxic catalysts. The products are biodegradable, but this technology can also produce non-biodegradable products.

3.2.2.2. Synthetic biology

In recent decades, breakthroughs in genetic engineering and computational biology have created a new field of synthetic biology that envisions redesigning and engineering organisms to develop new abilities. While synthetic biology is a part of the broader field of biotechnology, it is unique in its pursuits. With synthetic biology, scientists imagine designing cells, metabolic reaction pathways, enzymes, and products that do not exist in nature. By engineering new cells and genomes combined with accelerated laboratory evolution, organisms with in-built synthesis pathways can be turned into production units or cell factories to obtain new products with higher yields.

Like engineering, synthetic biology uses the design-build-test-learn cycle, which operates in an iterative manner. Researchers use computational and experimental designing and building approaches to develop new predictable, tunable, and controllable systems. For example, AlphaFold, a Nobel prize winning AI system (The Nobel Prize, 2024), predicts a protein's 3D structure from its amino acid sequence, thereby allowing protein-based material structure designs (Jumper et al., 2021). Similarly, directed evolution of enzymes, a Nobel-prize-winning experimental strategy, enables changing substrate specificity robustness of enzymes, resulting in improved and/or novel functions for more environmentally friendly manufacturing or efficiently developing reactions that do not exist in biological systems, such as creation of carbon-silicon bonds (Kan et al., 2016; Moore & Arnold, 1996).

We currently have technology that produces synthetic DNA and genes designed by computational methods. Several companies do this cheaply and quickly. These genes can then be easily inserted into living cells. Researchers can routinely test hundreds of cells built using these principles for their performance in a high-throughput manner and select efficient ones to produce new materials and scale-up in bioreactors. In turn, employing AI tools to test the productivity of these cells and incorporating their behaviour into the next design-build-test-learn cycle will help develop better functional cells for material production.

In addition, the testing of synthesis reactions can also be carried out without living cells, by using just enzymes in a test tube. These cell-free systems do not yet allow commercial production and scale-up. However, they offer a rapid means to test feasibility of a great number of synthesis pathway reactions. Remarkably, testing a pathway to 3-hydroxybuturate (3-HB), which is a precursor to a biodegradable plastic polyhydroxybutyrate (PHB) (Karim et al., 2020), resulted in a 20-fold improvement when the best enzymes were expressed in a living organism for production.

Industrial-scale manufacturing of ethanol, beer, and antibiotics using biotechnology in closed bioreactors has been available for a long time. The process can be adopted to produce chemical building blocks and polymers. Here, we provide an example of a typical biotechnological process that uses synthetic biology to improve the process efficiency and product range (Figure 6). The renewable carbohydrate-rich raw materials, such as lignocellulose, are converted to sugars either by naturally occurring or designed enzymes produced by microbes. The sugars are then used as feedstock in a bioreactor by specific microbes to convert the feedstock to a product, such as chemicals, fuels, or polymers. In Chapter 4, we describe various biomaterial structures and products developed using these principles in greater detail.

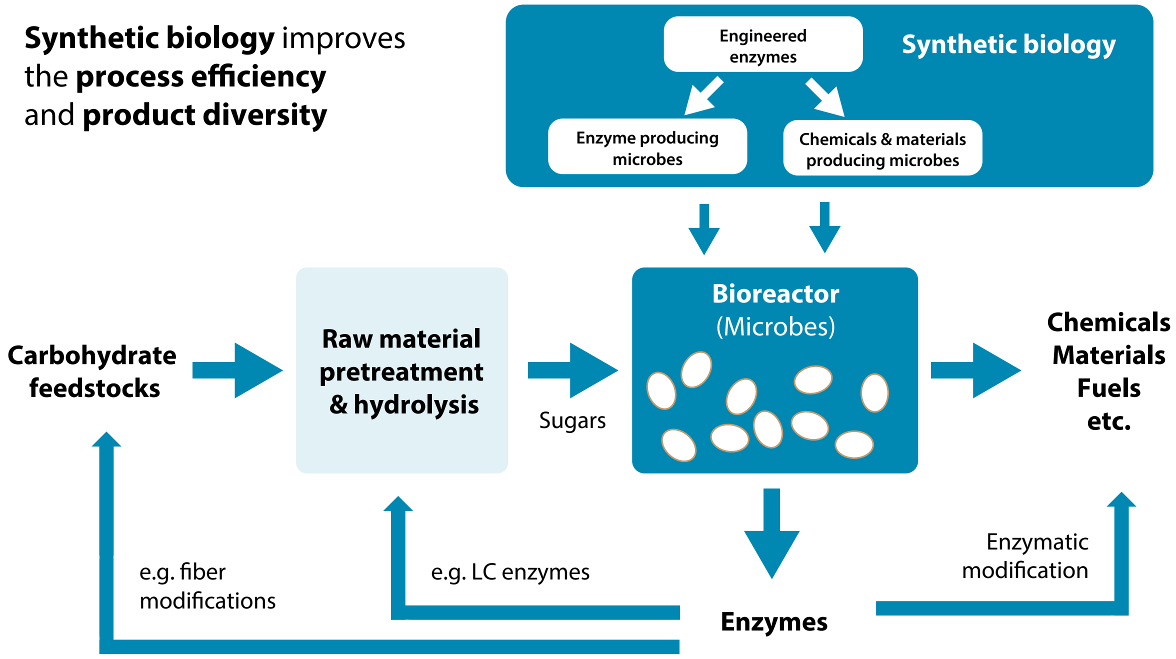

Figure 6. Combining synthetic biology and biotechnology processes to develop bio-based advanced materials. Source: unpublished source (credit: M. Penttilä).

3.2.2.3. Biofoundries

Future commercial biofoundries will offer an integrated infrastructure and AI tools to rapidly design, build, and test new microbial strains for production purposes. This field (currently mostly found at universities or university-private sector initiatives) is evolving towards standardised workflows operated by autonomous robotic systems. The small-scale operations that will generate optimal production strains will constitute the core of biofoundry. Selected production strains will be tested in bioreactors of varying scales to obtain data transferable to pilot-scale and industrial production plants. In turn, the process condition data are fed to the design of the production strains.

As biofoundries are rapidly established all over the world (with the support of a Global Biofoundry Alliance), they offer new frameworks to link modelling of the biosynthetic pathways and organisms into the production of new biosynthetic advanced materials.

3.2.3. Transversal aspects in emerging materials: Alloy design

3.2.3.1. Some lessons from the historical case study of the evolution of metals

Alloys have always contributed to the development of human society. Throughout history, they have been developed from a main base metal and one, two, or three minor alloying elements, which are added to improve some of the properties of the base metal. The 20th century saw alloys become more complex, with special steels, superalloys, and high-performance alloys being developed. The emergence of high-entropy or multi-component alloys requires many elements. More importantly, these new high-performance alloys require several alloying elements that have emerged throughout history, as shown in Figure 7. Therefore, the demand for more metals to make significant technological leaps in alloys is at odds with the critical metals' shortage. This means a major change in mindset is required to optimise resources and maximise performance.

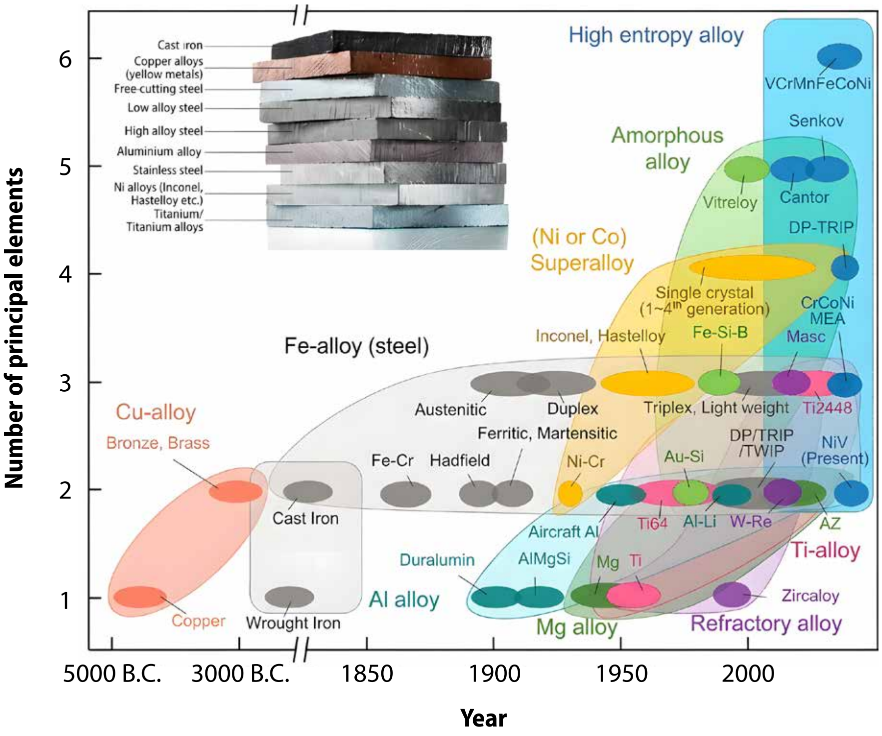

Figure 7. Evolution of the number of alloying elements required for the development of high-performance alloys throughout the human history. Source: Raabe (2023), based on Oh et al., (2019). Licensed under CC BY 4.0.

This is the major challenge facing the development of new advanced materials and technologies, especially alloys. While raw materials are critical, we must also develop and manufacture materials under the limited constraints of sustainability. This section raises a series of cross-cutting considerations and strategies to align with this premise, which can be extended to many families of materials and technologies. However, it is worth emphasising that certain sustainable technologies and solutions remain unviable if the scale of the processes required to meet the market demand is considered. In such instances, new considerations and alternative solutions are required to maintain the balance between sustainability and market needs.

3.2.3.2. Sustainability in materials design

The emergence of extremely complex compositions in most material families (especially in high-entropy alloys, intermetallics, and ceramics), the need for new material-selection criteria based on a deeper knowledge of materials, and restrictions on critical raw materials, all necessitate a shift in how we conceptualise and engineer materials.

As highlighted in Chapter 2, particularly in Section 2.4., sustainability needs to be embedded from the very beginning of materials design. These days, numerous materials are overdesigned, providing a far superior performance than required; they waste raw materials and increase processing complexity. Therefore, we must optimise composition and processing methods, considering resource limitations and the environmental impact of material production. A new design philosophy is essential—one that enables better performance with fewer resources (Raabe, 2023).

Traditionally, the development of a new material is focused on the initial chemical composition. However, this approach is being replaced by a paradigm that prioritises structure-driven design. This new approach is guided by two key principles: structure- and/or microstructure-based design rather than composition-based design; and alternative design concepts, such as configurational entropy of mixing, which act as dynamic elements in tailoring microstructures. The goal is to reduce dependency on specific raw materials, making the material development more sustainable. It also opens the door to incorporating elements from waste or scraps, thus enhancing circularity.

Overall, designing a new material under this framework requires considering four critical factors:

1. Raw material availability, including critical and strategic feedstocks, as well as scrap and waste.
2. Modelling and optimisation methods, including using AI.
3. Data integration between existing databases and newly generated data from high-throughput manufacturing and characterisation experiments.
4. Design parameters that define the target microstructure and guide processing techniques.

These factors are interdependent and directly influence both the material’s performance and the methods required for their processing(Torralba et al., 2025).

3.2.3.3. Modelling in materials science

Modern materials engineering relies on multi-scale simulation to predict properties (Geers & Yvonnet, 2016; Horstemeyer, 2009). We can establish, at least, three levels:

1. Atomic or nanoscale, where simulations based on quantum mechanics provide fundamental properties without empirical adjustments.
2. Micro- or meso-scale, where models like dislocation dynamics and crystal plasticity simulate grain-level mechanical behaviour.
3. Macroscale, where finite element methods simulate the mechanical performance of components.

Advanced characterisation data power these simulations, allowing for virtual manufacturing and testing, which saves significant money and time.

Phase structures during cooling and solidification can be calculated using thermodynamic modelling, specifically using the CALPHAD[16] approach. When integrated with data and programming tools, such as Python, thousands of multi-component phase diagrams can be generated rapidly. Together with CALPHAD, these tools enable precise solidification prediction in additive manufacturing, such as laser melting, and ingot casting.

In the case of metals, phase-field modelling further enhances our ability to predict microstructural evolution during solidification or phase transformations. Today, we can virtually simulate grain size and orientation (Segurado et al., 2018), twinning behaviour, tensile performance or fatigue life and fracture modes (Pilgar et al., 2022).

It is clear that the gap between modelling and actual results in certain industries can sometimes be large enough to raise doubts or suspicions about the reliability of modelling proposals. However, there is no doubt that this gap is narrowing considerably over time, with the help of improvements in processing speed, data storage capacity, and AI algorithms. Even in these latter cases, the current potential of modelling techniques is undoubtedly a tool of great importance in optimising the development of advanced materials.

3.2.3.4. Artificial intelligence and machine learning

The vast number of possible alloy compositions and microstructural variables makes traditional design approaches impractical. AI and ML offer powerful tools to navigate this complexity (Raabe et al., 2023).

To be effective, AI models need to: integrate all relevant design parameters and new concepts, such as topology; generate viable alloy compositions from virtual data; and be trained on extensive, standardised, and high-quality datasets that are taken from databases, literature, and high-throughput experimental methods.

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[16] Computer coupling of phase diagrams and thermochemistry – CALculation of PHAse Diagrams.

Predictive alloy design is made possible by this data-driven method, which speeds up innovation and lessens the need for trial-and-error tactics. This topic is discussed in greater depth in Chapter 5.4.

3.2.3.5. Robotics and automation

Rapid and efficient alloy development is now possible through robotic manufacturing and testing. Techniques like laser melting via direct powder deposition enable the creation of materials libraries at scale.

Testing systems can be fully automated, allowing for fast, consistent data acquisition. The goal is the realisation of fully robotic laboratories (Stack et al., 2025), where raw materials are prepared, specimens are manufactured, and tests are conducted with minimal human intervention.

3.3. Overcoming scalability challenges in materials production and advanced product development

This section discusses one of the biggest obstacles to materials innovation: scalability. It is not enough to develop a promising material in the laboratory; what really matters is being able to produce it reliably, affordably, and in large quantities.

Materials that perform well in small batches may behave very differently when production is scaled up. Processes that are efficient at the gram level may not be efficient at the kilogram or tonne level. In addition, there are challenges related to certification, safety, infrastructure, and integration into existing systems.

To address these issues, this section presents practical tools and approaches, such as innovation sandboxes. This will help researchers and companies to test and refine materials and processes in realistic environments before moving to full-scale production. The aim is to make the path from the laboratory to the market smoother, faster and more collaborative, bringing together science, industry, and policy from the outset.

3.3.1. Innovation sandboxes: Accelerating industrial transformation through safe experimentation

A persistent barrier to technological progress is the challenge of scaling high-performance, sustainable, and economically viable advanced materials for successful market entry. New materials must have a strong business backing to be commercially viable. However, a considerable number of new materials are economically unfeasible because they have complex processing routes, use disproportionate amounts of resources, are made from costly precursors or are derived from energy-intensive processes, and use infrastructure that is not readily available or scalable.

In addition, there are numerous challenges related to the limitations of the materials themselves, as well as the technologies used to develop them and improve their performance. These challenges may seem insurmountable today. That is why research in the development of advanced materials (Chapter 4) is a matter of paramount importance, since the limits of all technologies are directly linked to the limits of the properties of materials.

Few advanced materials make it from the lab to the market, despite the intense research that goes into creating them at the fundamental, applied, and industrial levels. A revolutionary, systemic approach that allows for quick trial, iteration, and adaptive development of innovations in real-world contexts is necessary to close this gap.

A variety of difficulties arise when a material is scaled from laboratory to mass production. When scaled to kilograms or tonnes, synthesis procedures that are often optimised for milligram- or gram-sized batches break down. For instance, endothermic reactions in thermal reactors behave differently at larger scales in terms of reaction kinetics, heat transfer, mixing, and interface control.

Translating research into application is further slowed by strict certification processes, regulatory barriers, and safety protocols. Additionally, advanced materials must be incorporated into current systems, which typically means co-designing suitable materials, production procedures, product designs, and supply chains.

Primarily, a new collaborative environment for innovation involving interdisciplinary researchers, startups, manufacturers, and end users is required to address these issues. Innovation sandboxes have the potential to significantly improve industrial technology. Businesses can test advanced manufacturing technologies and procedures in low-risk, enclosed settings that replicate real-world production conditions, frequently using the learning factory model. Sandboxes facilitate rapid development and industry collaboration by enabling manual experimentation without interfering with ongoing operations.

Together, academia, industry, and policymakers can upscale new materials in affordable, realistic settings by sharing infrastructure, experiments, and demonstrators. Research labs with co-located pilot infrastructure enable pilot-scale prototyping, and cyber-physical system[17] verify scaling models prior to expensive deployment. The early involvement of downstream integrators streamlines market adoption and certification, and involving researchers and industry in prototyping ensures that performance requirements are met from the start.

3.3.2. Scalability in manufacturing

Modern manufacturing systems must scale effectively to meet shifting consumer demand, embrace new technologies, and support growing sustainability goals. Scalability refers to a system's ability to adjust its capacity while maintaining efficiency and affordability. In this context, scalability refers to

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[17] A cyber-physical system is a broader, integrated framework including a digital twin that allows automated, closed-loop control and decision-making (see Czwick & Anderl, 2020).

the ability to transfer what is developed in a laboratory to an industrial process that can meet market demands, beyond raising questions of manufacturing quantities or volumes. Incidentally, there are industries in which scalability is closely linked to volumes or quantities, but this is highly dependent on the sector and business model.

Reconfigurable manufacturing systems enable scalability by allowing producers to modify system configurations and production capacity as needed. We can understand scalability in horizontal, vertical, elastic, economic, and geographic dimensions, each reflecting different aspects of manufacturing and information technology/operational technology integration.

Scalability influences system design and operation, management practices, and broader socioeconomic factors (Putnik et al., 2013). Two core principles drive scalable systems: (1) replicating identical components to increase efficiency, and (2) resizing individual components to adjust capacity. These principles shape the architecture of scalable manufacturing systems. Designers should embed scalability early in the system layout to enable cost-effective upgrades (Deif & ElMaraghy, 2007; Putnik et al., 2013; W. Wang & Koren, 2012).

Scalability also involves adding machines, rebalancing tasks, and adapting material handling systems. Reconfiguration costs, such as downtime, labour, and system disruption, play a key role in evaluating the economic feasibility of scaling. It is clear that scalability has a strong effect on energy consumption. In their study, Binderbauer et al. (2023) investigate the concept of 'energy of scale' in industrial energy systems, focusing on reducing specific energy consumption as production capacity increases.

When working with advanced materials, scalability becomes more challenging. Industrial large-scale production in kilograms or tonnes rarely adopts lab-scale processes, typically tailored for milligram or gram amounts, without modification. At larger scales, factors like heat transfer, mixing, reaction kinetics, and interface control behave differently, prompting engineers to develop new process strategies.

Supply chain logistics, infrastructure, and investment decisions also influence scalability (Fox, 2015). For example, distributed or mobile manufacturing systems allow companies to produce locally in unconventional locations. This approach reduces logistics challenges and training needs while improving access to raw materials and customers.

Despite its benefits, scalability presents trade-offs (Andersen et al., 2018). Flexible systems often demand more coordination, complexity, and funding. Context matters too. Manufacturers typically apply scalability in make-to-stock environments where they can predict demand and expand capacity accordingly. In contrast, make-to-order, or low-series production—common in early-stage advanced materials—struggles to implement scalable systems due to unpredictable demand and specialised processes.

Manufacturers should design systems that scale intelligently and incrementally to overcome these challenges. This approach prioritises long-term predictability over short-term responsiveness. Achieving this requires better design tools, focused research, and a deeper understanding of how scalability fits different manufacturing contexts.

3.3.3. Innovation in manufacturing

To scale-up novel materials, manufacturers need to innovate in the materials themselves and the systems and processes that produce them. They must prototype manufacturing technologies to bridge the gap between university-lab-scale innovation and industrialisation. This effort demands investment in manufacturing innovation skills alongside material development. Box 3 below illustrates the process by which laboratory-scale innovations in advanced materials can be translated into industrial-scale production.

Box 3: AAU Smart Lab – A demonstrator from Aalborg University in Denmark

The AAU (Aalborg University) Smart Production Lab (Madsen & Møller, 2017) and initiatives like The Circular Factory[18] are small factory industrial laboratories for circular and scalable production, providing valuable insights into how manufacturers can scale advanced materials from laboratories to industrial production.

Key considerations for scalable manufacturing of advanced materials:

1. Design for scalability from the start: Engineers should build manufacturing systems with scalability and sustainability as core principles. This includes modular layouts that support expansion, reconfigurable equipment that adapts to new processes and reserved infrastructure, primarily space, utilities, and digital systems, for future upgrades. Embedding scalability into the initial architecture increases cost-effective capacity and minimises disruptive redesigns (W. Wang & Koren, 2012).
2. Align production capabilities with market needs: Companies can use configuration models to evaluate their production capabilities in terms of process flexibility, raw material variability, and product complexity. This alignment ensures responsiveness to market demands and guides strategic investments in scalable technologies.
3. Use learning factories and sandbox environments: Learning factories and sandbox environments offer low-risk and cost-effective platforms for experimenting with new processes, materials, and technologies, and allow testing scale-up strategies and building internal competencies. These platforms are beneficial for companies that are unfamiliar with advanced materials or digital manufacturing.
4. Leverage digital tools for scalability planning: Use technologies, such as digital twins, simulation tools, or real-time analytics. These tools help model scalability scenarios, identify bottlenecks, and support proactive decision-making, reducing the risks and costs of scaling complex processes.
5. Enable incremental capacity expansion: Instead of duplicating entire production lines, manufacturers should support small-step scalability through parallel configurations or modular equipment additions. This approach allows flexible responses to demand fluctuations at a lower cost.

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[18] https://www.thecircularfactory.com

6. Integrate environmental considerations: Advanced materials production often involves resource- and energy-intensive processes. Scalability planning should include environmental impact assessments, waste and energy reduction strategies and circular production principles. These measures ensure that scale-up operations meet sustainability targets and comply with regulations.

Manufacturers can tackle the challenges of scaling advanced materials by combining digital technologies, modular system design, and collaborative experimentation environments like the AAU Smart Lab. These strategies accelerate the transition from innovation to production while minimising risk.

3.3.4. Scaling up bioproduction and infrastructure needs

The traditional and some current industrial bioprocesses outlined in Section 3.2.2. typically operate at a large scale. Especially for bulk chemicals such as bioethanol, industrial-scale bioreactors can have volumes of more than 1 000 cubic metres. Similar bioreactors of varying sizes are used for medium-volume products like organic acids (like lactic acid for bioplastic polylactic acid (PLA)) and industrial enzymes. Smaller volumes can be used for pharmaceutical high-value products and stricter standardised practices are mandatory (good manufacturing processes).

In contrast to other manufacturing processes, biotechnology can use more complex feedstock as raw material due to the intrinsic property of, for example, microbes, to use biological matter "for food" or due to our capabilities to engineer them to do so. Typically, the processes are carbohydrate (sugar)-based. The demand to use non-edible renewable feedstock in production of fuels to replace fossil oil raised significant interest in development of biotechnological processes that would enable the use of very complex lignocellulosic and waste fractions as feedstock in large-scale production of cheap products such as bioethanol. This process is probably techno-economically the most demanding but significant advancements have been achieved, with recent renewed interest (Kazmi et al., 2025). Likewise, similar process concepts could be used for other bioprocesses of varying sizes, including those for material products.

Even with complex feedstocks, the processes can be effective, despite the key role of a living organism in the manufacture of the product. Bioreactors are often designed to operate at ambient conditions with benefits such as low energy consumption, absence of toxic catalysts, minimal intermediate purifications, and biodegradable waste streams. Biomanufacturing takes place in closed bioreactor systems (without release of organisms into the environment), with the possibility of process control. Advanced tools such as process modelling, real-time in-line, and on-line sensors (e.g., Raman spectroscopy, microscopic analysis), and digital twins are becoming important for process understanding and control.

Biotechnological production of lactic acid for bioplastics PLA, PHB, and production of ethanol for bio-polyethylene are some of the large-scale examples of commercial products synthesised in bioreactors. These examples can have clear sustainability benefits and CO_2 impact (Ahmad et al., 2024; Mattlar &

Ekholm, 2025; Senila et al., 2025). While large-scale commercialisation of other products still remains challenging due to lack of process infrastructure, these cases are helping to re-imagine sustainable design for advanced materials.

The use of C1 compounds (CO_2, CO, methanol, formate) as feedstock, obtained from industrial flue gases or syngas, has been examined in production of materials and their building blocks. Gas fermentation of more than 50 products has been demonstrated. The company LanzaTech (US) has proven the technology at a full commercial scale (Köpke & Simpson, 2020). LanzaTech has demonstrated carbon-negative production of acetone and isopropanol at industrial scale (F. E. Liew et al., 2022).

New challenges in process development are brought about by the growing variety of genetically modified production organisms and product types. To address these, bioprocesses should be designed end-to-end, from feedstock preparation to product recovery. Solutions may come from process engineering or genetic tailoring of the production organism itself to overcome upstream or downstream bottlenecks.

3.3.4.1. Infrastructure gaps and opportunities

Europe currently faces a shortage of scaling-up facilities, which limits the development of sustainable industrial bioprocesses. Initiatives like the Bio-based Industries Consortium (BIC) and the Circular Bio-based Europe Joint Undertaking (CBE JU) have been instrumental in funding demo-scale operations, particularly in biotechnology and sustainable materials.

However, there is also a critical need for smaller-scale infrastructures that allow rapid screening of production strains, evaluation of feedstocks and cultivation modes (batch, fed-batch, continuous), and optimisation of nutrient and oxygen availability. These activities need to occur in controlled, small-scale bioreactors equipped with advanced measurement tools to generate data that can be reliably scaled up.

To accelerate development, data from biofoundries (e.g., organism modifications, enzyme engineering at technology readiness levels (TRL) 2–4 should be linked with small-scale bioreactor data (TRL 3–5) and pilot and industrial-scale data (TRL 5–8). This requires robust data collection, storage, and the application of AI-driven analytics to enable bi-directional feedback across development stages. Considerations of the material product—material design and product quality—adds another layer of complexity and opportunity. Despite progress, challenges remain in data standardisation, accessibility, and utilisation for informed decision-making.

3.3.4.2. European infrastructure initiatives

The EU supports several infrastructure projects that are critical for biotechnology and biomanufacturing:

- EU-IBISBA: A distributed ESFRI (European Strategy Forum on Research Infrastructures) infrastructure supporting synthetic biology developments and bioreactor cultivation up to pilot scale.[19]

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[19] https://ibisba.eu/

- Pilots4U: A platform mapping available bioeconomy pilot and demo-scale infrastructures, including bioreactors.[20]
- MIRRI**:** Provides access to microbial strain collections.[21]
- Euro-BioImaging: Offers advanced imaging technologies.[22]
- EBMRC: Supports access to marine organisms and biomaterials.[23]

Additional infrastructures for materials characterisation should also be integrated to support advanced material development.

At the European level, linking ESFRI research infrastructures with the technology infrastructures initiative will be essential. Incorporating strong materials science capabilities will help create distributed ecosystems for materials research and manufacturing.

3.4. Innovation ecosystems and networks in manufacturing

This section focuses on the people, places and partnerships that help turn advanced materials from ideas into real products. It is not just about technology, but about establishing strong links between researchers, businesses, governments, and investors.

Europe has worked hard to create innovation ecosystems that support collaboration between regions and sectors. These include digital innovation hubs, shared R&D labs, university science parks, and industry-driven incubators, among other environments. These provide researchers and companies with access to tools, expertise, and funding, helping them to test new ideas and bring them to market more quickly. The production of advanced materials benefits equally from technological advancement and robust, networked innovation ecosystems. To encourage innovation and commercialisation, the EU actively supports the development of cross-regional and cross-sectoral networks that link government, business, academia, and investors.

The following are some of the most important mechanisms governing this ecosystem:

1. **Physical and digital innovation hubs**: These are cooperative areas for research and development. For example, small- and medium-sized enterprises (SMEs) benefit greatly from the shared facilities, training, and matchmaking provided by European Digital Innovation Hubs (EDIHs).[24]
2. **Open innovation spaces and shared R&D infrastructure**: These promote interdisciplinary and intersectoral cooperation and provide inexpensive access to state-of-the-art facilities (BIOMAC, 2025; European Commission, 2025d).

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[20] https://biopilots4u.eu/

[21] https://www.mirri.org/

[22] https://www.eurobioimaging.eu/

[23] https://www.embrc.eu/

[24] https://digital-strategy.ec.europa.eu/en/policies/edihs

3. **Science parks and incubators at universities under the direction of industry**: By encouraging knowledge transfer between industry and academia, university-based science parks support early-stage innovation (Interreg Europe, 2022). Conversely, industry-led incubators concentrate on developing and bringing established technologies to market.
4. **Cross-sector innovation hubs**: Projects such as FULL-MAP combine materials science, robotics, and artificial intelligence to promote research and implementation.
5. **Programmes for mentoring and knowledge transfer**: These programmes have been promoted by organisations like EIT (European Institute of Innovation and Technology) Manufacturing and Steinbeis Europe and are an essential tool for helping startups and SMEs navigate the innovation cycle.
6. **Customised support systems**: Projects like LightCoce[25] show how customised support systems can bridge the gap between product innovation and materials development.
7. **Pre-commercial procurement**: By offering early market opportunities, public procurement agreements like public procurement programmes (PCPs) aid in the validation and de-risking of emerging technologies.[26]
8. **Defence-oriented innovation**: ROLIAC[27], AMALIA[28], and ASCALS[29] are examples of projects that show how defence requirements are propelling advancements in advanced materials related to adaptive camouflage and auxetic armour.

3.4.1. Academia–industry collaboration as a driving force in the transition from lab to market

Transferring innovation from a research lab to industrial scale is a complex but well-studied process (Behne et al., 2021; Rybnicek & Königsgruber, 2019; Thomas & Paul, 2019). Typically, it involves bridging the gap between academic research and market-ready solutions (Van Der Sijde et al., 2013).

This change is necessary to keep Europe competitive in both industry and innovation. Even in the early 2000s, Salter and Martin (2001) noted a broad agreement that academic research has a positive impact on industrial innovation. For example, various studies indicate that by the end of 1990s, roughly 10% of the new processes and products introduced by companies would either not have been created or would have emerged much later without input from academia (Bekkers & Bodas Freitas, 2008).

To maintain competitiveness in Europe, collaborative projects between academia and industry or transfer of innovation from lab to industry are essential. These models are complementary and include:

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[25] https://cordis.europa.eu/project/id/814632

[26] https://research-and-innovation.ec.europa.eu/strategy/support-policy-making/shaping-eu-research-and-innovation-policy/new-european-innovation-agenda/innovation-procurement/pre-commercial-procurement_en

[27] https://roliac.eu/

[28] https://eda.europa.eu/news-and-events/news/2022/10/21/eda-project-seeks-lighter-ballistic-armour

[29] https://defence-industry.eu/new-eda-project-to-identify-smart-and-adaptive-materials-to-enhance-camouflage-of-land-systems/

- Knowledge transfer offices (KTOs), incubators, and accelerator.
- Research and technology organisations (RTOs)
- Competitiveness clusters.

3.4.1.1. Knowledge transfer offices, incubators, and accelerators

Many universities offer KTOs, incubators or accelerators to support early-stage companies with mentoring, legal advice, and networking. An example is the LiEU[30] (Liaison Entreprises-Universités) network, which connects the KTOs of the five universities in the Fédération Wallonie-Bruxelles. Acting as a one-stop gateway to the full range of university expertise, LiEU has supported the creation of over 200 spin-offs.

However, these structures could be improved by focusing on four intertwined dimensions: people, culture, governance, and collaboration (Compagnucci & Spigarelli, 2024). For instance, to improve culture, the study suggests that fostering an entrepreneurial mindset among academic and non-academic staff should be promoted.

3.4.1.2. Research and technology organisations

Research and technology organisations (RTOs) serve as vital intermediaries between academia and industry. Through EU-funded programmes such as Horizon Europe, these organisations usually collaborate to promote cross-border innovation transfer. In a 2024 study[31], the European Association of Research and Technology Organisations (EARTO) assessed the economic footprint of 15 RTOs (Braito et al., 2024). Among the primary findings for 2022 were:

- Around 245,000 new jobs or 230,000 full-time equivalents (FTEs) were created in the European economy, corresponding to a total turnover of around €37.7 billion and a total value added of around €16.5 billion.
- For each job in RTOs, almost five jobs were created elsewhere in the European economy.
- For each €1 invested in operational grants, more than €2 flew back to the national governments.

3.4.1.3. Competitiveness clusters

In Wallonia, competitiveness clusters were established in 2005 to cover five sectors: biotechnology (BioWin), logistics (Logistics in Wallonia), aeronautics and space (Mecatech) and the food industry (Wagralim), with a sixth competitiveness cluster created in 2009, dedicated to green technologies (Greenwin) (Wilmotte & Halleux, 2018).

These clusters are structured entities, largely supported by public funding, and managed by operational units that coordinate member networks and support collaborative projects—for example, a regional

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[30] https://reseaulieu.be/en/

[31] https://www.earto.eu/wp-content/uploads/EARTO-Economic-footprint-final-report-2024.pdf

project including industrial partners, academia, and/or research institutes. Typically, the Walloon government issues calls for proposals roughly every six months (Wilmotte & Halleux, 2018).

Such initiatives are present throughout Europe: Axelera for chemistry and environment in France, BioRN for Biotechnology in Germany, SPRING green chemistry cluster—the national cluster for sustainable chemistry in Italy, and the Green Chemistry Campus in the Netherlands are some examples (Alfano et al., 2023). A review of existing clusters has been released in 2011 and would benefit from an update (Barsoumian et al., 2011). In parallel, the Cluster Collaboration[32] website also gathers, among others, information on these clusters.

Overall, innovation ecosystems depend on industry and academic cooperation. Whether through KTOs, RTOs, or regional clusters, these models provide essential avenues for translating research into useful applications. Enhancing these collaborations through better governance, cultural congruence, and shared infrastructure will be necessary to hasten Europe's transition from lab-scale innovation to global industrial leadership.

3.5. Success stories

This section presents some practical examples from the fields of healthcare, 3D printing, and high-performance computing, areas in which innovation is bringing about clear improvements. The cases focus on how materials are helping to solve everyday challenges: from improving medical devices and their sustainability, to developing bio-based materials for printing and designing smarter, more energy-efficient computing systems. These examples demonstrate that advanced materials are being tested, adapted, and applied in ways that really matter. By analysing what already works, this section helps us understand what is possible, what is still missing and where Europe can go from here.

3.5.1. Advanced manufacturing technologies for healthcare applications

The healthcare sector increasingly adopts advanced manufacturing technologies to create next-generation materials and devices. These range from biopolymers for tissue engineering, bioactive molecules, nanodevices for drug delivery to manufacturing of living organoids (small organ-like structures).

3.5.1.1. Biocomposites and biopolymers

Medical researchers and manufacturers are turning to biocomposites and biopolymers for tissue engineering, drug delivery, and wound healing applications. These materials often act as matrices for bioactive agents or nanoparticles that enhance therapeutic efficacy. Developers typically source them from natural compounds like alginate, collagen, nanocellulose, and chitosan.

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[32] https://www.clustercollaboration.eu/

3.5.1.2. Polymer-based electrodes

Polymer-based electrodes transform biomedical sensing by offering flexibility, comfort, and high signal fidelity. Engineers use materials such as PEDOT:PSS, carbon nanotube composites or silver nanowires embedded in PDMS, a silicone polymer, to fabricate dry, skin-conformal electrodes that outperform traditional Ag/AgCl wet electrodes. Researchers have successfully applied these electrodes in electrocardiography (ECG), electromyography (EMG), and brain-computer interfaces. Clinical trials have confirmed their biocompatibility and long-term stability (E. K. Lee et al., 2021).

3.5.1.3. Soft robotics in healthcare

Soft robotics are driving rapid innovation in medical technology by making devices less intrusive, more flexible, and safer. Engineers build these systems using biocompatible, deformable materials that mimic the mechanical properties of biological tissues. Key materials include silicone-based elastomers (e.g., Ecoflex, Dragon Skin), shape-memory alloys, dielectric elastomer actuators and ionic polymer-metal composites (Ashuri et al., 2020; Rodrigue & Kim, 2024).

Despite their promise, these technologies still face challenges in biocompatibility, durability, and regulatory approval. Nevertheless, the convergence of biomedical engineering, robotics, and materials science continues to push the boundaries of healthcare innovation.

3.5.2. 3D printing and Industry 4.0 in the context of bio-based materials

3D printing is central to Industry 4.0 by enabling decentralised, customised, and efficient manufacturing. Technologies like fused filament fabrication, stereolithography (SLA), and digital light processing (DLP) are increasingly integrated with cyber-physical systems, IoT, and AI to create smart, adaptive production environments.

However, the shift toward sustainable manufacturing faces a significant hurdle: the limited commercial availability of bio-based materials. Researchers have explored biodegradable thermoplastics such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and polybutylene succinate (Mehrpouya et al., 2021; Qahtani et al., 2019; Sabalina et al., 2023) for their renewable origins and compostability. Yet, these materials often lack the durability, mechanical strength, and thermal stability required for industrial use. They also perform poorly in high-throughput or precision 3D-printing systems (Begum et al., 2023).

These limitations become even more pronounced in UV-curable techniques like SLA and DLP, which manufacturers favour for speed and resolution—especially in biomedical, dental, and microfluidic applications (Billerbeck et al., 2024). Although researchers have extensively studied acrylate epoxidised soybean oil for these applications (Bruvere et al., 2024; Jurinovs et al., 2023; Rosa et al., 2023), other promising bio-based alternatives from grapeseed, linseed, rapeseed, and itaconates remain undeveloped for commercial use (Briede et al., 2022; Jurinovs et al., 2023; Papadopoulos, Malitowski, et al., 2023; Papadopoulos, Pezzana, et al., 2023; Qahtani et al., 2019; Yoe et al., 2025).

Though bio-based photopolymers have reached technological maturity, petrochemical-based acrylates still dominate the material ecosystem. Manufacturers rarely use bio-resins due to their low reactivity, short shelf life, high viscosity, and limited curing depth (Schittecatte et al., 2023). The need to tailor resin formulations to specific light wavelengths and intensities further complicates the development of sustainable, universally compatible materials (Billerbeck et al., 2024; Chaudhary et al., 2023; Schittecatte et al., 2023).

Systemic challenges go beyond technical issues and block the transition from lab-scale innovation to market adoption (Prashar et al., 2023; Sarkar et al., 2025). Weak supply chains, unclear regulations, and the absence of standardised testing methods contribute to the problem.

Economic barriers also play a significant role. Scaling up bio-based material production requires high investment, reliable feedstock, and complex logistics (Begum et al., 2023). Even though environmental awareness is growing, incorporating LCA into early-stage development adds cost and complexity (Ita-Nagy et al., 2020). The lack of standardised methods for evaluating land use change and other environmental impacts further complicates regulatory approval (Ita-Nagy et al., 2020).

In summary, despite increasing social and legislative pressure for greener technologies, manufacturers still struggle to commercialise sustainable, high-performance bio-based materials for 3D printing. Regulatory uncertainty, financial risk, and technical limitations contribute to this gap (Begum et al., 2023; Ita-Nagy et al., 2020).

Besides using bio-based materials, recycled metal powders can also be used as feedstocks for additive manufacturing techniques (Cacace et al., 2020). These include selective laser melting, electron beam melting, and cold spray for example. Recycled powders can be produced by atomisation of industrial scraps. This is currently developed in the REMADE Project, Recycled Metal Powders for Additive Manufacturing, funded by Next Generation Europe, in the context of the Reverse Metallurgy initiative[33]. At the same time this contributes to a circular economy and reduces our dependency on raw materials.

3.5.3. New design for high performance computing

To battle the continuously rising demand for computing power, high performance computing (HPC) needs to be more intelligently designed to allow scalable HPC solutions, in a combined effort between software and hardware development. This implies the intelligent use of emergent semiconductor and CMOS (complementary metal-oxide-semiconductor) technologies under the principles of circularity and sustainability in terms of material usage, manufacturing, and system operation. Figure 8 shows the evolution of the number of microprocessors over 50 years (between 1971 and 2021) as a function of their working frequency and energy consumption. Figure 9 analyses total R&D expenditures of companies (in billions of euros) in different countries in 2020: US, EU, Japan, South Korea, China, the UK, and the rest of the world.

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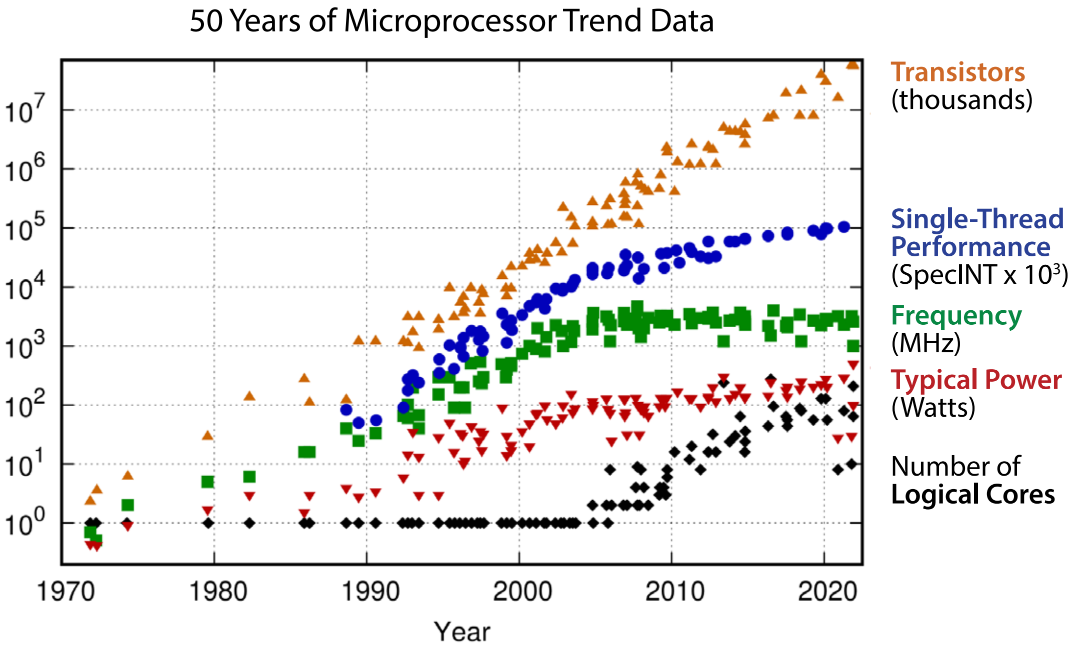
[33] https://reverse-metallurgy.net/rmplus/remade/



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2021 by K. Rupp

Figure 8. 50 years of microprocessor trend data (1971-2021).
Source: Adapted from Rupp et al. (2022). Licensed under CC BY 4.0.

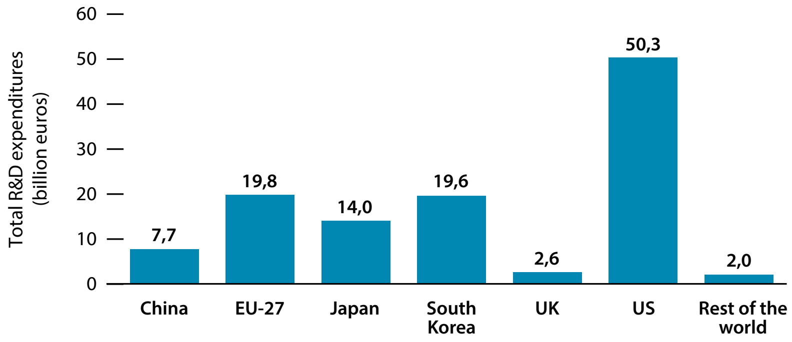


Figure 9. Total R&D expenditures by MIM and by country in 2020 (billion euros) – pharmaceutical companies excluded.
Source: Adapted from European Commission et al. (2024). Licensed under CC BY 4.0.

3.6. Key messages

- Advanced materials are at the forefront of driving the green and digital revolution, with applications in construction, energy, mobility, electronics, and health. They must be multifunctional, sustainable, and scalable.
- Advancing manufacturing technologies like additive manufacturing, AI-enhanced design, and biotechnology are essential to produce next-generation materials with new functionalities and circularity.
- Scalability ranks among the major issues to achieving lab-to-market materials. Process inefficiencies, certification barriers, and infrastructure constraints are some of the factors.
- Innovation sandboxes and learning factories are low-risk environments for piloting and scaling materials and processes. They encourage interaction between academia, regulators, and industry.
- Digital tools such as digital twins, simulations, and AI help predict scalability issues, optimise processes, and accelerate certification and market entry.
- Designers should shift from composition-based to microstructure-driven approaches when developing sustainable alloys and electroceramics, integrating AI, robotics, and circularity principles.
- Innovation ecosystems and networks—such as RTOs, KTOs, competitiveness clusters, and EU initiatives—are vital for bridging the lab-to-market gap and promoting cross-sector collaboration.

Chapter 4: Basic research directions for future transition

4.1. Introduction and scope of the chapter

This chapter aims to outline exciting research directions for materials-centred innovation that can also address the European manufacturing sector's dependence on raw and processed materials. The chapter establishes that an intimate connection exists between fundamental research (from flexible, curiosity-driven to goal-oriented projects) and applied research—from university projects to industrial manufacturing.

Fundamental research is pertinent to Europe's strategic autonomy and the cross-fertilisation of innovation because it offers a foundation for addressing today's global challenges, from the climate crisis to health emergencies. Therefore, this chapter highlights the importance of fundamental science in the discovery of new classes of advanced materials and new material functionalities for specific applications (Section 4.2.). The subsequent sections focus on areas where Europe is a strong player in fundamental science, facilitating the transition into innovation. Specifically, this chapter focuses on advanced materials from biological systems (Section 4.3.), advanced materials in green energy conversion and storage (Section 4.4.), advanced materials involving nanomaterials and 1D and 2D materials (Section 4.5.), and advanced materials with unique properties and functionalities (Section 4.6.).

4.2. The need for basic research in advanced materials

Basic research (also called fundamental or frontier research) aims to better understand scientific phenomena. Often, policymakers and the public find it difficult to understand the relevance of basic research projects or gauge their impact and value that benefits society. However, basic research in materials science and other disciplines has fuelled new materials and technological advancements for a long time; it is instrumental in developing new advanced materials. To reduce the gap between the new progress in understanding the mechanisms and design in advanced materials research and the information available to society, several activities have been created, such as infographics, accessible summaries, and dissemination efforts.

One of the most famous initiatives to bring not only advanced materials but also science in general to citizens is the European Researchers' Night and Researchers at Schools[34]. These initiatives have increased public awareness of the importance and benefits of research and innovation. the European

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[34] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-msca-2025-citizens-01-01

Commission and the signatories of the Materials 2030 Manifesto[35] also supported the Advanced Materials 2030 Initiative (AMI2030) with a commitment to co-create a common agenda for materials involving diverse stakeholders, including citizens, end-users, policymakers, and researchers. This initiative has since led to the establishment of the International Advanced Materials Initiative[36] (IAM-I).

The quest for reliable, efficient, and new materials with even more advanced properties requires new theories and new or deeper scientific understanding. Traditionally, materials are developed using trial-and-error approaches, with no or little input from deep scientific understanding. Since advanced materials are becoming more complex, consisting of multiple components with unique properties and functions, the trial-and-error method becomes less viable as the number of components in an advanced material increase.

Therefore, the only way to make progress in advanced materials research is to incorporate rational and systematic scientific approaches, a central focus of any kind of research. This pipeline will allow us to better understand the correlation between material design and the functionalities required to enhance the development of green and sustainable technologies by integrating these advanced materials. In addition, the multi-component nature of advanced materials also underpins the need to exploit AI and ML approaches to develop new knowledge and platforms for new synthesis and production protocols, allowing massive experimental screening of the materials' properties.

In this chapter, we highlight how new scientific theories and explorations led to a better understanding of materials, their properties, and new ways to modify them. In addition, we emphasise through numerous examples how basic and applied research go hand-in-hand to develop future advanced materials.

While it is difficult to describe all the exciting research directions in this chapter, we summarise the design strategies that can give extraordinary functionalities to the created advanced materials in Table 5. In Table 1, we listed examples of advanced materials and their applications that stemmed from new ideas, principles, and theories generated by basic research projects. These examples showcase a plethora of advanced materials with highly specific functionalities that are either already available or forthcoming. Systematic analysis of how each of these materials meets the EU's sustainability, safety, and raw material sourcing objectives will ultimately determine the EU's competitiveness in advanced materials.

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[35] https://beda.org/wp-content/uploads/2023/02/advanced-materials-2030-manifesto.pdf

[36] https://www.iam-i.eu/

Materials design	Example of functionality
Hierarchical assembly, modular structure	Building complex structures from simple building blocks, e.g., *metamaterials* from metals or oxides.
Biosynthesis, biomimicry, bioinspiration	Biosynthesise materials using living cells; mimic or take an inspiration from behaviour in biology and apply it to non-biological materials.
Nanoscaling, dimensionality	Control surface to volume ratio (catalysis, air/water purification); quantum confinement (design optical, electrical, and/or chemical sensing properties).
High-entropy	High mechanical and thermal stability; tune electronic, optical, and/or catalytic properties.
Responsive materials	Stimulus to response conversion, stimulated shape memory, and self-healing.
Multi-component	Synergy of combined individual component's properties to improve function and/or yield emergence of new function.

Table 5. Examples of materials design and functionalities.

4.3. Advanced materials from biological systems

The European Commission launched a new strategy in July 2025 to make Europe the world leader in life sciences by 2030 (European Commission, 2025b; European Council & The Council of the European Union, 2025). Europe has been a strong player and leader in the knowledge base and scientific excellence in life sciences. Still, in turning this fundamental science into real-world solutions, Europe's leadership is diluted by the other global players. The Strategy for European Life Sciences aims to reduce the gap between fundamental science and the real world. Consequently, it proposes two key points:

1. Optimise the research and innovation ecosystem with an EU investment plan to facilitate funding for clinical trials across countries. This will also promote a One Health approach[37] to research and innovation.
2. Recognise the importance of advanced materials and their implementation within the EU Bioeconomy Strategy (European Commission, 2025a) . Enable rapid market access for life science innovations by proposing action in the EU Biotech Act.

Under these goals, the EU aims to boost trust, uptake, and use of innovation to stimulate the procurement of life science solutions in areas such as climate change adaptation and next-generation vaccines. This section aims to give an overview of the immense variety of biological materials, which will allow the creation of innovative, advanced materials with vital functionalities that may overcome the challenges in different applications and fulfil the life science strategy.

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[37] https://health.ec.europa.eu/one-health/overview_en

4.3.1. Special features of biological materials

Nature consists of materials with superb functionalities created through evolution. A large variety of biochemical and polymeric structures exist in living organisms, offering new types of materials with different functionalities. Given the large number of living organisms present on the planet, materials science researchers have an enormous discovery space in biology. Scientists are just touching the surface of knowledge of biological materials and their engineering capabilities.

The functionalities of biosynthetic materials are broad. They can be hydrophobic or hydrophilic, tough, and strong with good mechanical strength or elastic, conductive, antimicrobial, chiral, sensing, and forming nanoparticles. Functionality can be obtained with various molecular means. For example, hydrophobicity is obtained by special protein structures or on plant leaves by polyesters. Self-repair or responsiveness often comes through environmental changes, triggering responses intracellularly in an organism to modify gene expression for resynthesis in order to heal or modify the material. Even though biotechnology can be used to produce replacement materials for the non-degradable ones made by petrochemistry, biological materials in general are intrinsically recyclable and biodegradable to various extents. As in nature, the material can serve as feedstock for the resynthesis of new structures.

The biological materials found in nature can be extracted in their functional form from biological organisms—such as cellulose and lignin from wood or chitin from shrimp—and modified further to suit applications. Increasingly, biological materials are produced by living cells using biotechnology and synthetic biology, thereby enabling the engineering of materials structures for new advanced properties.

The functionality of biological materials has inspired material scientists to mimic nature in the design of novel materials, i.e. following the concept of biomimicry (bio-inspiration). In this approach, the materials are non-biological and can be made using chemical technologies only.

4.3.2. Biotechnology and synthetic biology in the design and production of biological materials

Biotechnology allows the synthesis of individual components by transferring genes responsible for material structures to specialised microbes and cultivating them in closed bioreactors for large-scale production (see Chapter 3). Furthermore, it is possible to design and engineer new material building blocks and polymers, as well as functionalities, using synthetic biology tools (see Chapter 3, Section 3.2.2.). While biological processes in organisms are complex and elaborate, biotechnology and synthetic biology aim to manufacture materials and microbes using simplified processes (Q. Gao et al., 2022; Karataş & Ayaz, 2025).

In biology, material properties are encoded in an organism's DNA, which determines cellular pathways to produce a material. Leveraging the enormous variability that exists in DNA and biological material structures makes it possible to design many possible materials. Incorporating computational methods such as AI and ML algorithms is vital to designing new materials and efficient production organisms.

Researchers can use AI and ML to extract and analyse features from genome and protein databases of various organisms and design new material structures with interesting material properties. In addition, ML algorithms and simulations facilitate guiding the complex design process to overcome challenges in mechanical robustness, biocompatibility, and production scalability, thereby unlocking the transformative potential of these materials.

4.3.3. Research on biomolecules as advanced materials

Biological materials are composed of a variety of different chemistries and polymer types that create material functionality. For this reason, research and engineering efforts in biology have produced a broad range of promising materials, many of which are already commercially produced, either as smaller-scale speciality products or larger-volume materials (Chong et al., 2023; J. W. Lee et al., 2011).

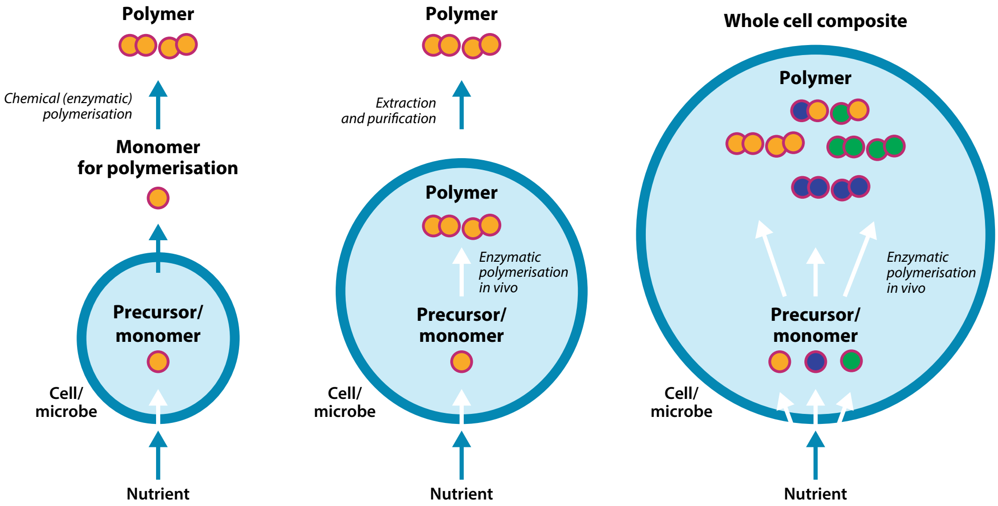

Figure 10. Biotechnological production of biosynthetic polymers where polymers synthesised from various biochemical building blocks encoded by the specific DNA (genes) introduced into the organism.
Source: unpublished source (credit: M. Penttilä).

4.3.3.1. Bioplastic building blocks and polyesters

There is a need to replace fossil resources; many recyclable or biodegradable bioplastics can be produced using monomer building blocks in microbes that use renewable resources as feedstock. For example, bio-PET monomers to replace PET and organic acids for bioplastics using microbes have already been achieved. PLA, another common plastic used in packaging, textiles, and medical implants, is commercially produced via a large-scale microbial production of lactic acid, which is then polymerised to PLA. This production process is more sustainable than making PLA from fossil raw materials. Similarly, polyhydroxy alkanoates (PHAs) such as PHB can be made in cells (Q. Gao et al., 2022). PHAs can be synthesised from well over 100 different monomer building blocks (Q. Gao et al., 2022). Collectively, there is a vast design space to predict and create bioplastic homomers, co-polymers, or co-block polymers with unique barrier properties, crystallinity, elasticity, melting temperature, processability and as responsive materials. It is also possible to aim for polyamide production or polymers with aromatic monomers that are difficult to produce by chemistry.

4.3.3.2. Carbohydrates

Cellulose is the most abundant carbohydrate polymer in nature (Marinho, 2025). It has become an obvious choice to develop new materials that replace fossil-based plastics and packaging materials. For example, new processes have created excellent textile fibres from cellulose fibres that can replace unsustainable cotton production.

Microbes naturally produce cellulose as a highly crystalline, ultra-fine nanofibrillar network. Bacterial cellulose is more flexible and porous than plant cellulose and has higher tensile strength and stiffness. It is also less brittle than plant cellulose (Girard et al., 2024; X. Wang et al., 2025). Cellulose can also be processed to be transparent and conductive with good thermal and chemical stability, making it a good alternative in medical applications and flexible electronics. Despite all these functionalities, the production of bacterial cellulose remains costly.

Cellulose and other carbohydrates, such as beta-glucan and starch can also be synthesised in a test tube in-vitro, with single robust enzymes that form polymers of glucose (Pylkkänen et al., 2022; Ubiparip et al., 2021). These novel carbohydrates can find applications in packaging, adhesives, whitening agents, and drug delivery applications.

4.3.3.3. Lipids

Lipids such as medium-chain triglycerides and fatty acids are increasingly used in polymers due to their unique physicochemical properties (Reddy et al., 2022). They increase flexibility, thermal stability, and solubility. Incorporating them in PHA polymers improves their industrial biodegradability. Castor oil, a key medium-chain-length triglyceride, provides a hydroxyl group for chemical reactions and can be used to produce polyurethane foams, coatings, and adhesives. It can also be used to produce Nylon-11—a durable, high-strength material used in cold-resistant plastics, paints, and coatings—from renewable resources. The natural lipid synthesis pathways in microbes can be modified to produce medium-chain dicarboxylic and hydroxy acids suitable for polymerisation. This is beneficial because longer monomers require less energy in polymerisation per chain length.

4.3.3.4. Proteins

Nature is full of proteins with specialised functions: spider silk fibres are light and extremely strong (Gomes & Salgueiro, 2022); elastins are strong and elastic; muscle proteins titin and resilin have rubber-like properties; mussel foot proteins act as a strong glue under water; viruses and bacterial microcompartments form specific 3D structures with cavities (Stewart et al., 2021); and lustrin, an insoluble protein found in nacre, has self-healing properties and high elasticity (Shen et al., 1997). These proteins offer new possibilities to design or derive advanced materials like them for specific applications. In addition, light-capturing rhodopsin and electron-transporting cytochromes can be arranged for better conductivity to act as nano-bioelectronics and biocompatible circuits (Bostick et al., 2018; Chryssikos et al., 2024).

4.3.3.5. Nucleotide polymers

DNA nucleotide strands can be designed and assembled to form specific nanoscale loop structures and 3D scaffolds, also called DNA origami. RNA can also be used similarly. They are revolutionising the manufacturing of nanoscale materials and devices, with applications in drug delivery, biosensing, nanophotonics, and molecular machines (Dey et al., 2021). In addition, researchers have recently created triple helical structures, added functional groups to the nucleotides, used artificial nucleotides, and changed the chirality of nucleotides to include them in various applications.

4.3.3.6. Composites

There are various examples of composite structures with distinctive properties in nature. For example, lignocellulose found in plants consists of three components of varying structures and chemistries: cellulose that forms strong fibres, heterogeneous branched hemicellulose, and aromatic lignin polymers. It can be an excellent construction material. Mineralised composite structures, such as bones, consist of protein collagen and a naturally occurring mineral, hydroxyapatite. Magnetotactic bacteria build up magnetic structures within the cells (Strbak et al., 2022). Mantis shrimps' club, a specialised part used by the shrimp to deliver powerful strikes, is a highly organised nanoparticle structure composed of fibres formed of chitin, proteins, and carbohydrates. This layered structure has extraordinary strength, toughness, and resistance and its design can be used in several potential applications, such as impact-resistant materials, protective gear, seismic-resistant architecture, sound filtering materials, and packaging. In particular, this concept has been used to create a tooth implant composite (Mohammadi et al., 2021).

4.3.3.7. Whole cell systems and engineered living materials

Whole cells can also be used as material, providing unprecedented possibilities to engineer new composites by tweaking the genetic code and synthesising and assembling them in a functional form inside cells in a single step. One current example is the production of fungal leather, which has properties similar to animal-derived leather materials (Amobonye et al., 2023, 2023). It is obtained by cultivating filamentous fungi, the mycelium, in bioreactors and feeding them with renewable bio-based feedstock. While living cells are used for the material synthesis in controlled bioreactor cultivations, the cells are killed before final material manufacture. The process can be fully sustainable.

There is also an emerging field of engineered living materials (ELMs), which uses living organisms within the materials (Lu et al., 2024). The goal of the ELMs is to incorporate the main attributes of living things, mainly self-healing, response, and sensing, to develop new materials. Special care needs to be taken to address the possible toxicity and safety aspects of the engineered living materials (ELM).

In addition, organoids, which are small organ and tissue prototypes, offer a scalable and robust technology to study the efficacy and side effects of tissue support materials and environmental factors. They facilitate the development of safe nanomaterials (Baek et al., 2024; Caipa Garcia et al., 2021).

4.3.4. Case studies

It should be noted that much of the know-how and possibilities of advanced materials illustrated in Sections 4.2., 4.3., and 4.4. may remain underutilised. Scientists and companies tend to concentrate, although for good reasons, mainly on the most obvious materials like cellulose, or new trendy ones, such as silk, viral structures, and biosynthetic materials.

However, biosynthetic materials and biological systems can find uses in almost all application areas, ranging from construction, bioplastics, and electrochemistry to environmental remediation materials, as emphasised before. While the new and emerging processes to incorporate these ideas have a long way to go, the following two case studies to illustrate how much progress has been made in successfully implementing these ideas into applications.

Case study 1: Silica-based materials from diatoms

Mesoporous silica is a highly demanded material, produced synthetically since the 1950s (Y. Wang et al., 2016), and suitable for various applications due to its material properties: high surface area, high porosity, chemical inertness, biocompatibility, and excellent thermal and chemical stability. These make it highly suitable for various applications, including drug delivery, biosensing, water treatment, optics, electronics, and energy transfer. When combined with active components, functionalised structures can be fabricated, inducing catalytic and/or photonic activity with excellent stability.

Current industrial production of mesoporous silica commonly relies on supply chains and expensive and environmentally hazardous compounds, such as tetramethyl orthosilicate and tetraethyl orthosilicate (B. Li et al., 2023). Therefore, cost-effective and more sustainable alternatives are needed, and natural sources of mesoporous silica have been studied with increasing interest. Diatoms, single-cell microalgae, have attracted significant attention as a promising natural source of silica materials for numerous applications (Mourya et al., 2022). For instance, diatom powder composed of *Chaetoceros, Navicula*, and *Nitzschia genera* was combined with carbon to fabricate silicon-based anodes and integrate them in lithium-ion batteries, showing promising results in battery performance (Z. Wang et al., 2021). Moreover, the discovery of natural slab photonic crystals in diatoms opens new applications since it enables precise light manipulation, which is essential in sensing, quantum computing, and photonics (Ashworth et al., 2025; Goessling et al., 2025).

Case study 2: Biomaterial implants

Traditional implant materials like titanium or stainless steel often require secondary surgeries due to wear, corrosion, or rejection by the body. Advanced biomaterials that are bioresorbable, self-healing, or capable of integrating with living tissue can eliminate these issues (Silva-López & Alcántara-Quintana, 2023). One such example is a device consisting of a semi-permeable pouch, made from chitosan (a biopolymer from shellfish) with a tunable reservoir and molecularly engineered interface. The molecularly-modified chitosan limits cell adhesion and foreign body response, while barrier properties for cell encapsulation are retained (Perikamana et al., 2022). As noted by Perikamana et al., in addition to being permeable to nutrients, oxygen, and different cell-secreted biomolecules, this device provides local immune-protection, thereby decreasing tissue rejection risk. The device was found to work in cell transplantation experiments in mice (Perikamana et al., 2022). Developing such materials that are also cost-effective and scalable remains a major challenge.

4.4. Advanced materials for green energy conversion and storage

In a society with a sustainable economy and infrastructure, materials, as a finite earth resource, will be central; sustainable energy needs sustainable materials as much as the converse. The need for novel materials arises from society's need for more efficient, functional, flexible, and less time-consuming things, as well as less toxic and less polluting ones, in response to our increasing demands on Earth's resources. Scientific progress is expected to provide such material targets. To that end, a rough sketch of research and development directions should include data creation, as well as data collection. The latter refers to data collection of the known materials (cf. Chapter 5) and the former to new material, from design via high-throughput synthesis and automated characterisation to data creation.

4.4.1. Future materials for conservation of resources

Building materials represent, by volume and weight, the largest burden on our resources. The material impacted most is sand (and gravel) (UNEP, 2023), more specifically sand that can be used to make concrete and asphalt, glass and silicon. To counter the trend of dwindling building material resources, methods for recycling—especially of concrete—need to be developed, and sand alternatives (Jensen et al., 2025) explored wherever possible.

Other examples include lighting (buildings and outdoor) and building climate control. These two features consume enormous resources. Thus, HVAC and water heating in buildings (residential and commercial/government) are estimated to use up to 50% of their total energy consumption (up to 80% for residential energy use in the EU) (U.S. Energy Information Administration, 2023, and European Commission, 2022, as cited in World Bank, 2025). Lighting has been revolutionised with the advent of the LED (Palacios-Intriago et al., 2024), especially the LED luminaire and the rise of OLEDs (organic LEDs). If they can be manufactured for recycling, they may make the LED revolution complete.

Another promising approach is waste heat harvesting. If waste heat is purposed from warming our homes and offices (district heating) more frequently (Knudsen et al., 2025) and to generate electrical power at a competitive cost, there is the potential to reduce residential energy consumption significantly. Waste heat could also power low voltage devices, using thermoelectric converters. Cost-competitive, efficient, on-demand space heating may well need new materials/material combinations for thermal storage. For thermoelectric co-generation, advanced materials are needed.

4.4.2. Future materials for mobility/transport

We are already well inside the revolution created by composite materials for transport, for instance, in automobiles, trucks and plane bodies. It comes, though, with a price of end-of-life material management, and we will need to reduce their waste. The composite materials (mostly with C-based fibres) should be designed for recycling (Sharma et al., 2025), something that is often not the case with today's industrial products. A promising example of development is that of the Siemens company's recyclable wind blades (see Section 4.4.3.3., below).

Apart from new materials for batteries, discussed in Section 4.4.4., other materials for propulsion include, beyond the magnets (see also below), the conductors (mostly copper) and insulation materials, including resins, which together enable today's highly efficient electric motors (Drexler et al., 2025). Minimising materials used is an important drive to higher electric propulsion/mobility efficiency. The magnets for direct-drive, Direct Current (DC) electric motors are rare-earth-based. To bypass the expected long time lag in establishing a viable rare-earth mining and processing infrastructure in the EU, new advanced magnetic materials that use more readily available, earth-abundant materials are needed (in addition to other electric motor types, such as the Brushless DC, the induction, and the switched reluctance motors, each with their own material demands). While some candidates have gained attention (S. Song & He, 2025), much more needs to be done, building on our increasing understanding of magnetism in materials.

4.4.3 Future materials for energy conversion

4.4.3.1. Direct solar (PV, CSP)

While photovoltaic (PV) direct solar to electrical energy conversion is today's dominant direct solar energy conversion technology[38], the evolution of heat storage that has reached 15 hours represents a potential game changer for concentrated solar (to thermal) power (CSP) in Southern-European areas with rich direct insolation. This is because of the steep increase in cost for battery storage of more than ~4 hours, the time span needed to cover most night and cloudy consecutive periods. Even so, today the levelised cost of energy from CSP and storage is at times higher than it would be for a hypothetical PV+ battery storage for 12-15 hours (Bošnjaković, 2025). If significant cost reductions can be achieved in building and maintaining CSP systems, including their thermal storage materials, its near base-load character (with exceptions for dark and cloudy periods of more than 15 hours), could lead to its resurgence for specific locations. This will require significant breakthroughs in reducing both capital and operating expenses (Hernández et al., 2020).

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[38] For a simple, short explanation of PV cells, see Box 1 in (Kirchartz et al., 2025).

4.4.3.2. Photovoltaics

4.4.3.2.a. Crystalline silicon and tandem approach

For silicon (Si)-based electronics, and for c-Si (Crystalline Silicon) solar PV, the technology appears to be able to reinvent itself time and again. Already, we know that in the future there will be options of double-sided ("bifacial") and Si-on-Si cells for improved performance, with the former already in use on some commercial cells, while the jury is still out on the latter (Kim et al., 2023).

Much more publicly visible is the concept of halide perovskite-c-Si tandem cells. This is because c-Si solar cells cannot efficiently convert to electricity the higher energy (green-blue) part of the sun's radiation that reaches Earth. As c-Si cells make up >95% of all the solar cells in use, using a tandem configuration is currently the only practical approach to addressing this problem. Certain lead-halide perovskites (HaPs, cf. Sections 2.3.3., 4.6., and the table in Annex 1) are the first-ever efficient *and* low-cost option, based on earth-abundant, readily available materials, to do so. Tandem PV cells, based on HaPs on top of c-Si PV cells, are being developed intensively and widely these days, but face a "stability gap": the c-Si cells have an expected useful lifespan of 25-30 years, while the HaP ones may last five years, based on optimistic extrapolations today. Major developments are needed to enable the latter to match the c-Si PV cell stability. Alternatively, materials need to be discovered or developed to improve the stability of the HaP PV cells, or to enable, for example, stick-on/peel-off cells to replace them (with their electrical connections) on the same c-Si cell, when the c-Si cell still functions efficiently, while the HaP PV cell's efficiency has decreased so much so that replacement is needed.

4.4.3.2.b. Beyond halide perovskites

A "dark horse" is the organic PV cell, which has improved enormously in the past decade. While it still lags significantly behind HaP PV cells, it may become an option for the 2nd cell in tandem with c-Si ones. The issue of how easily top-performing organic materials can be produced on a large scale (a PV cell is a macro-electronic device) will be central, even if desired efficiencies of sufficiently large area cells have been reached. In addition, the rediscovery of HaPs, finding that they are useful for PV, as well as the change of one of the components of organic cells, away from what in hindsight appears like a "stuck" mindset, point to the need for continuing basic materials research here.

4.4.3.3. Wind energy: Composite and structural materials

Mostly, wind turbines are viewed as a mature technology with little need for more *basic* research. While overall this is basically correct, it may miss some important aspects that need to be addressed for SSbD.

4.4.3.3.a. The dilemma of composite material blades of wind-turbines

Modern wind turbine blades are made from lightweight, fibre-reinforced (glass or carbon) polymer composite materials (Riley et al., 2025), with an organic resin holding the fibres around a polymeric foam (Cheng et al., 2025). This composition was chosen because of its strength and (light) weight but poses a recycling problem that is becoming more serious as more turbines are installed. The materials can be difficult to recycle, involving high-energy processes which both destroy fibre integrity and are unsustainable. A major challenge for advanced materials research is to find replacements that fit into a circular economy (cf. Sharma, Shukla et al., *loc. cit.*), because otherwise this waste undermines the environmental case for wind energy (Spini & Bettini, 2024). A promising European development is the RecyclableBlade[39] effort of Siemens.

As wind turbines grow larger, the demands on the mechanical properties for blade materials increase, for instance, material fatigue resistance. Furthermore, offshore wind turbines must withstand corrosive environments, making coating materials, protective layers, and corrosion-resistant composites critical.

Promising options for recycling include mechanical shredding with fibre recovery, thermal or chemical (pyrolysis, solvolysis) treatments, and repurposing shredded material into building composites or cement additives, enhancing the circularity potential of wind blade materials. Adoption of thermoplastic composites from the outset (instead of thermosets) may further simplify recycling, as thermoplastics can be remelted and reprocessed, offering a future pathway to circular materials use in wind energy (Carnicero et al., 2025; Cheng et al., 2025).

4.4.3.3.b. Magnets for the wind turbine generators

Modern wind turbines mostly have direct drives, which require permanent magnets. Today, that means rare earth-based magnets. As discussed in Section 4.4.2. above, the EU requires an alternative for those magnets and/or those drives, which will be another one of the great challenges for future advanced materials.

4.4.3.4. Other options: Realistic ideas or wishful thinking?

The vision of combining high, minimal loss efficiency of conversion and storage of energy and of materials use sparks the imagination of many and thus leads to a plethora of ideas, as well as realisation of what is missing. The latter includes materials for a self-sustaining nuclear fusion reactor in which the materials surrounding the cavity with the plasma will need to be able to withstand heavy neutron bombardments. In addition, so-called Generation IV nuclear fission reactors are promised to be more economical, much safer with less high- and intermediate- radioactive waste, and proliferation resistant. The challenges to achieve these goals were summarised in a 2016/7 book (Yvon, 2017). While some of these challenges are now tested in the small high-temperature pebble-bed (pebbles instead of rods as fuel) reactor that started up some two years ago in China and a research reactor in Japan, meeting all four conditions to qualify as a Generation IV type remains a major materials challenge.

Less conventional ideas abound, such as cooling in summer by saving large ice cubes from winter, storing excess kinetic energy in potential energy (lifting weights), and liquifying air to store excess energy, to name a few. Companies have started based on such ideas. For any of these to significantly fulfil the need for storage to allow optimal use of intermittent solar (PV, CSP) and wind energy conversion remains a challenge that has a substantial materials component.

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[39] https://www.siemensgamesa.com/global/en/home/explore/journal/recyclable-blade.html

4.4.4. Next generation batteries

The surge in battery demand, primarily from vehicular mobility, poses a current threat since Europe relies on raw materials such as lithium, cobalt, nickel and graphite for battery compositions, all mined and mostly also processed in non-EU countries (Edström et al., 2022).

Future battery technology must reduce reliance on critical raw materials and enable recyclability, which calls for new chemistries, new engineered electrode-electrolyte interface architectures (Joshi et al., 2025), and leveraging excellence in architecture design and innovation within the EU. These batteries should be high-performance, safe, durable, and inexpensive, and support circularity across their life cycle. Materials and design choices should be guided by scalable manufacturing and facilitate reuse/recyclability. Promising avenues for battery design are batteries with built-in diagnostics (e.g. with embedded nano-sensors), and self-healing materials that are able, for instance, to repair micro-damages and stabilise interfaces (Edström et al., 2022).

Acceleration of materials development through the combination of computational modelling, data screening, and synthesis/testing, discussed in Chapter 5, could enhance a systematic understanding on how interfaces (solid/liquid, electrolyte/electrode, solid/solid) influence the durability and safety of batteries (Edström et al., 2022).

Chemistry beyond Li is explored worldwide to address limitations imposed by resource scarcity. Research explores sodium-ion and multi-valent ion batteries (Mg, Ca, Al), which offer cheaper and abundant materials. Various flow batteries are also investigated for stationary applications.

While lithium-ion batteries have been used for decades and are a vital technology with many applications, they still present safety concerns due to their liquid electrolyte. At the same time, their current energy density may be insufficient for next-generation mobility or grid storage needs. The use of solid electrolytes in the emerging field of all solid-state batteries (ASSBs) promises simultaneous increase in energy density, safety, and stability (Ma et al., 2023). In ASSBs, innovation on the cathode side includes high-voltage materials and cobalt- or nickel-reduced compositions (e.g., spinels or modified layered oxides), to balance energy density with resource security (Ma et al., 2023). On the anode front, of all-solid-state Li batteries (ASSLBs), silicon-rich composites or lithium metal promise significantly higher gravimetric capacity than graphite, but their volume changes and interface instability demand sophisticated interphase design to avoid capacity fade or failure (Jia et al., 2024).

Solid electrolytes, including sulfides, oxides, halides and polymers, are the enabling materials for ASSBs. Sulfide-based electrolytes stand out for high ionic conductivity and compatibility with Li metal (Man et al., 2025). However, the largest obstacle is at the solid/electrolyte interface, which now is a solid electrolyte/solid one, with likely a poor contact, as well as a stable interphase (a separate phase), which can cause cycle life degradation. Solutions may come from appropriate interface engineering, for instance with thin interlayers and use of dopants (X. Gao et al., 2024).

4.4.5. Hydrogen systems: Materials for fuel cells, electrolysers, and storage systems

4.4.5.1. Materials for water electrolysis

Green hydrogen production via electrolysis depends critically on catalyst and membrane materials in alkaline, anion-exchange membrane and proton exchange membrane electrolysers (Sebbahi et al., 2024). Traditional catalysts (iridium for the oxygen evolution reaction, platinum for hydrogen evolution) are costly and scarce (Eikeng et al., 2024).

Recent studies highlight strategies including atomically dispersed catalysts, or earth-abundant alternatives to lower noble-metal content without sacrificing activity or durability (G. R. Lee et al., 2023).

An alternative electrolysis technology uses solid oxide electrolysis (SOE) systems (C.-G. Chen et al., 2025), which leverage ceramic electrolytes, requiring materials with high oxygen-ion (oxide) conductivity, redox stability, and thermally robust ceramics (because of the higher temperatures needed for oxide conductivity). SOE cells (SOECs) are interesting energy conversion devices that can transform thermal and electrical energy into chemical energy. At present, however, their high cost limits their scale to laboratory prototypes. Transitioning to industrial-scale systems will be fundamental for the realisation of the full potential of solar energy-based conversion using SOECs.

4.4.5.2 Fuel cell materials (PEM and SOFC)

Fuel cells are devices that convert hydrogen back to electricity, and are classified as low-, intermediate-, and high-temperature fuel cells. Their long-term viability depends on materials stability, catalysts' support, membrane robustness, and cost-effective manufacturing (Shao & Ni, 2024).

For low temperature proton-exchange membrane fuel cells (PEMFCs), research explores improved polymer membranes with broader temperature/humidity tolerance, along with better catalyst-support materials and reduction of precious-metal usage, to reduce degradation and extend operating windows—critical for automotive and stationary applications (Shao & Ni, 2024).

Beyond PEMFCs, solid oxide fuel cells (SOFCs) and intermediate-temperature variants offer advantages in fuel flexibility, potential integration with hydrogen or syngas, and robustness, but require ceramic electrolytes and electrodes optimised for chemical stability under redox cycling, and long-term mechanical reliability.

4.4.5.3 Hydrogen storage

Efficient, safe, and practical hydrogen storage remains one of the greatest materials challenges for the hydrogen economy, across transport, industry, and electricity systems. Storage is identified as one of the central barriers to large-scale hydrogen adoption. Improved materials—rather than incremental engineering alone—will be required to meet practical performance and cost targets for vehicles, stationary systems and seasonal energy buffering (Bellosta von Colbe et al., 2019; Egeland-Eriksen et al., 2021; U.S. Department of Energy, n.d.-a, n.d.-b).

Policy and industrial decisions need to consider that a one-size-fits-all storage solution is unlikely, and strategic choices should match material-technology combinations to use cases (on-vehicle versus stationary and seasonal buffering), while investments should prioritise materials that can be produced and recycled on a commercial scale. A portfolio of solutions (e.g. compressed gas, hydrides, liquid carriers) could de-risk the scaling-up (Egeland-Eriksen et al., 2021).

Hydrogen storage typically is divided into (a) compressed or liquefied gas in engineered tanks, (b) physisorption in high-surface-area porous adsorbents (MOFs, porous carbons), (c) chemisorption in metal and complex light-metal hydrides (e.g., alanates, borohydrides), and (d) carrier-based chemistries or liquid organic hydrogen carriers (LOHCs) (Dornheim et al., 2022).

Gaseous storage remains the most practical option in the short term. Here advanced composite tanks (Type-IV with carbon fibre reinforcement, resin, and polymer liners) are essential to achieve required strengths and low weight; materials research must address permeability, hydrogen embrittlement of liners and lifetime behaviour under pressure cycling. Materials choices for tank liners, adhesives and barrier layers therefore directly affect the operational safety and operating cost of the hydrogen supply chain (Feki et al., 2025). Furthermore, because of the difficulty of recycling the current tank design, the development of alternative matrices (for instance thermoplastic) can enable recovery while maintaining comparable mechanical performances (Feki et al., 2025; Gul et al., 2023; KU Leuven, n.d.).

Metal hydrides are among the most mature materials-based options because they incorporate hydrogen directly into their crystal structure, offering exceptional volumetric density at moderate pressures. Alloy design, nanoscale catalysts and controlled defect chemistry can substantially accelerate hydrogen uptake and release, while also lowering the temperatures needed for desorption (Bellosta von Colbe et al., 2019). Even with these improvements, hydrides still face two strong practical constraints: releasing hydrogen requires significant heat management, and the supporting hardware—reactor shell, heat exchangers, insulation—adds mass that erodes system-level gravimetric performance. These trade-offs explain why hydrides are promising for stationary storage but remain challenging for weight-sensitive mobile systems.

Emerging materials that are still at an early research stage are high-entropy alloys (HEA) systems, described in some detail in Box 4. Machine-learning guided design of HEAs with favourable hydride formation enthalpies suggests a potential route to room-temperature or near-ambient hydrogen storage, offering reversible storage without high pressure or temperature (Dangwal et al., 2024).

Box 4: Emerging materials – High entropy alloys for sustainable energy sources

HEAs are emerging as a promising solution for the use of sustainable energy sources with advanced storage systems, aiming to meet future energy demands while minimising CO2 emissions (Srinivaas et al., 2025). HEAs consist of four or more elements in a near-equimolar ratio. HEAs are gaining increasing interest in the energy storage industry due to their strength, structural and thermal stability, and resistance to oxidation and corrosion (Niketh et al., 2024). An emerging application of HEAs is for solid-state hydrogen storage, where the configurational entropy plays a crucial role in the material's unique characteristics and phase stability. Recent research focuses on hydrogen absorption properties of HEAs under ambient temperature and pressure, and their potential use in environmentally safe and efficient hydrogen storage systems (Qureshi et al., 2024).

The exclusive properties that HEAs possess are essential in improving hydrogen transport and storage efficiencies, which could replace traditional hydrogen transport methods. Authorities and experts are raising concerns about the development and manufacturing of new HEAs, as hydrogen storage necessitates careful consideration of stability, durability, and hydrogen embrittlement susceptibility. Estimating environmental influence, ensuring commercial viability, establishing regulatory standards, and fostering public acceptance are crucial for successful integration into sustainable energy systems. The widespread implementation of HEAs in hydrogen storage and transport involves a multidisciplinary discussion of knowledge on materials science, safety standards, economic viability, and environmental impact.

The EU prioritises developing hydrogen that is generated using renewable energy (European Commission, n.d.-c), which aligns with its long-term climate neutrality and zero pollution goals. The incorporation of HEAs in hydrogen storage applications necessitates eco-innovative solutions that promote decarbonisation, the hydrogen economy, ecosystem services, and the circular economy. HEAs-based storage is an efficient and stable solution for hydrogen transportation. However, traditional design standards may hinder their complete potential exploration.

The research direction for HEAs for storage applications focuses on developing HEA composition, which will provide hydrogen absorption at room temperature and with good cyclability. Since the number of possible compositions accounts for millions, the chemical variations that can be exported are limited compared to the possible number of compositions. Recent directions (Witman et al., 2020) allowed high-throughput screening of HEA properties with machine-learning and data-driven approaches. Advancements of machine-learning/data-science tools toward more complex multiscale problems (such as kinetics across scales, which include mass and heat transport) and real-world operation (for instance, lifetime) will enhance the design of HEAs.

4.5. Nanomaterials and 1D and 2D materials

Nanomaterials represent a key class of advanced materials, as noted earlier in this report (Table 5). In this section, we provide additional remarks to emphasise specific aspects. Zero-dimensional (0D) nanomaterials are spherical entities with dimensions in the nanometre range, i.e., they present three-dimensional quantum confinement. They have been explored for a long time and widely incorporated into technologies, with examples such as nanodots, nanoparticles, nanoclusters, and fullerenes. Notably, their physical properties, biological properties, and safety can strongly depend on the particle size in addition to compositions. A classic example involves gold nanoparticles and gold nanoclusters. In biomedical applications, gold nanoclusters smaller than 1-2nm can avoid harmful accumulation in biological tissues through renal clearance and exhibit completely different medically relevant properties compared to larger gold nanoparticles (Mussa Farkhani et al., 2024). This creates challenges for legislation, which should not unduly restrict new application potential based on scientifically unjustified material classifications.

One-dimensional (1D) nanomaterials are nanofibrillar entities wherein the fibre diameter is at the nanoscale while their length is significantly larger. They may appear as curled nanofibers or straight nanorods, exhibiting markedly different properties and safety profiles. Recently, they have attracted considerable attention as advanced materials, with examples including bio-derived high-strength nanofibers and nanorods of cellulose or chitosan, as well as amyloid fibrils. Their technological potential in composites, colorants, absorbents, and biological scaffolds is being extensively explored (Gericke et al., 2024; Heise et al., 2021; Ke et al., 2020).

Two-dimensional (2D) materials attract attention due to their different properties, outperforming conventional materials used in various applications. In this context, strategies to produce materials that incorporate nanoscale building blocks can lead to materials with improved or novel properties. Among one of the most attractive groups of materials, 2D materials allow the possibility of creating, for example, thin or multi-layered structures where van der Waals or electrostatic forces hold the layers together. The isolation of single *graphene* sheets in 2004, and especially the demonstration of its extraordinary quantum properties, were a significant jump for the field of 2D materials, which has been studied for the past 60+ years (Murphy & Hull, 1975). The discovery of these manifestations of quantum mechanics in these materials marks the beginning of the era of new materials based on building blocks with a wide variety of physical and chemical properties. As transistors in microchips become smaller and smaller, down to the nanometre scale, the traditionally used silicon-based materials face two problems. First, the quantum tunnelling effects become more common, and second, heat dissipation becomes more difficult. Materials such as graphene and transition-metal dichalcogenides (TMDs) boast superior electrical properties but integrating them into existing manufacturing processes poses a challenge. Increasing data transmission speed without signal loss or overheating is a growing bottleneck in chip performance.

Box 5: Emerging 2D materials

Sheet-like materials that have ultrathin nanometric thicknesses are denoted as 2D materials. Classically, 2D materials can be separated mechanically from specific crystals having internal layered structures or, more recently, upon direct chemical synthesis of the nanometric sheets. Related to layered crystals, naturally emerging clay minerals have been used in pottery for a long time (Faustini et al., 2018). In recent decades, their internal layered crystalline structure has allowed their separation to 2D materials to allow structural reinforcing in polymer nanocomposites, e.g., in the car industry (Okada & Usuki, 2006). A breakthrough took place, when it was observed that graphite allowed peeling single sheets, denoted as graphene, wherein the Nobel Prize 2010 was granted to Andre Geim and Konstantin Novoselov (The Nobel Prize, 2025). Graphene is a prototypical 2D material, showing fascinating properties, such as high electrical and thermal conductivity, as well as high strength, thus facilitating a plethora of applications in devices and light-weight construction.

More recently, the generic potential of 2D materials has been realised, and presently the number of 2D materials is strongly growing, each having their specific properties. A recently archived manuscript gives an authoritative description of the different types of 2D materials and the available applications (Ren et al., 2025; Uddin et al., 2023). Among other examples of 2D materials beyond graphene, one could first mention molybdenum disulfide, which belongs to the group of layered TMDs. It is a semiconductor 2D material suggesting technological potential due to the ability to produce wafer-scale single crystalline monolayers allowing downscaling of transistor dimensions (L. Li et al., 2024).

MXenes are other example of 2D materials consisting of transition-metal carbides and nitrides (Gogotsi, 2023). They have high metallic electrical conductivity, are dispersible in water allowing easy and sustainable processing, are strong and stiff, optically transparent as thin films, and provide a large electrochemically active surface. Their electronic and optical properties make them promising candidates for sensors (Cai & Kim, 2025), actuators, electromagnetic interference shielding, wireless communication, and antennas (Iqbal et al., 2024). In energy storage, they might be used in batteries or supercapacitors as electrode materials, solid-state electrolytes, anode protectors, or functional additives (Khan et al., 2024). Their high electrocatalytic activity, especially for the hydrogen evolution reaction, supports their application in energy conversion. MXenes have also been proposed for water desalination and purification membranes (Meskher et al., 2025) due to a high resistance to biofouling, a phenomenon where plants, algae, microbes, and animals accumulate on wet surfaces. Some MXene compositions have also been proposed in biomedical applications, such as cancer theranostics, drug delivery, and implant devices (Avinashi et al., 2024).

4.6. Advanced materials with unique properties and functionalities

In addition to novel material families as described above, designing new properties and functionalities in known material families also has the potential to create new advanced materials by employing processes such as mixing, alloying, and advanced synthesis. For example, lead-halide perovskites have been known since the late 19th century (Mitzi, 2019). But in recent decades, new advancements in their strong lattice dynamics and disorder led to minimal static defect densities (Rakita et al., 2019). This imparted amazing optoelectronic properties, as well as self-healing of damage to the material.

A fascinating class is that of so-called topological materials, specifically topological insulators (Choi, 2021). Those materials are electrically insulating, but because of their electronic structure, they need to have a conducting outer shell when in contact with another insulator, such as air. A logical follow-up from nanomaterials, high temperature, and other new superconducting materials is what can be called quantum materials (Pogue, 2022), which display a clear quantum mechanical property, such as superconductivity, coherent transport, and entanglement.

The need to preserve curiosity-driven explorations of new materials or new properties of existing ones is illustrated by considering the much sought after material property of superconductivity: it allows transmission of electrical power without any losses (of the 0.32 TW electrical power generated in in 2023, 1-4% is lost in high voltage, long-distance transmission). Until 1986, we did not have materials that became superconducting at temperatures above ~23K (-250ºC). In 1971 the world expert on superconducting materials wrote that the highest temperature at which a material can superconduct is -243ºC and that no organic material can do so (Matthias, 1971). In 1986 four-element cuprate materials were discovered to superconduct at -237ºC at the IBM Rueschlikon (CH) laboratory; today's record for a related, five-element material is -135ºC. In 1980 superconductivity was found (in France) in an organic material (Jérome et al., 1980) and today's record is -135ºC. While enormous materials processing problems needed to be solved, today we have practical magnets with cuprate superconductors. The take-home message is clear.

The significance of high-entropy materials, previously discussed in this report, extends t beyond their original property of mechanical strength. The design concepts based on high configurational entropy have been extended to many other materials such as different families of alloys (steels, light alloys, superalloys), and intermetallics or ceramics. The design concept has been moved from "high-entropy materials" to "materials with high-entropy" (Torralba et al., 2025). There is great logic to the approach, which was used successfully in Europe in the past (Philips labs) to tailor-make magnetic oxides (spinels). It is also explored for heterogeneous catalysis, and further directions are likely to open up. One possible issue with these materials can be their recyclability, because at least some of the components will need to be separated from each other for reuse. The higher the number of different elements in a material, the more problematic that process will become.

4.7. Key messages

- Fundamental science has a critical role in advancing materials science, emphasising that this is not merely a tool for applications but the bedrock of innovation. Significant efforts are being made to translate scientific insights to the public and policymakers through infographics, accessible summaries, and dissemination activities such as open days. These efforts aim to ensure that discoveries in advanced materials reach the broader public.
- It is crucial to maintain solid, predictable investment (e.g., ERC grants) in fundamental science without expecting immediate returns, as many developments take decades to materialise. Understanding fundamental mechanisms and questions provides the knowledge necessary to transform society.
- Materials set the limits of any technology or product.

Chapter 5: Digitalisation: Data, simulations, and AI

5.1. Introduction and scope of the chapter

One of the main bottlenecks in advanced materials discovery is the expensive and error-prone trial-and-error approach. The emergence of predictive capabilities with advancements in data, simulation, and AI can drastically accelerate advanced materials discovery. As part of its digital vision, the EU seeks to integrate AI across key industrial ecosystems to achieve strategic autonomy. In addition, AI and digitalisation of industrial processes are key to cross-sector innovation that can further reinforce new technologies to benefit advanced materials discovery.

In this chapter, we describe the potential of computational (numerical implementation of physical and chemical quantitative models) and data-driven (AI/ML models for explaining experimental data or surrogate models of computational models) approaches in guiding advanced materials discovery, experimentation, and synthesis. We first present challenges associated with developing robust data ecosystems and offer suggestions to alleviate them (Section 5.2.). We further discuss key simulation resources from European providers available for advanced materials discovery (Section 5.3.) and how these, combined with AI/ML tools, may enable safe and sustainable materials discovery for a wide range of applications (Sections 5.4.).

5.2. Advanced materials data: Problems and solutions

A generation ago, the *Handbook of Chemistry and Physics* (also called the *Merck Index*), the Landolt-Börnstein tables, and the Beilstein series for organic materials (Beilstein Handbook, currently, Reaxys, Elsevier) were found in many offices and laboratories. These resources contained curated, time-proven data for a wide variety of chemicals and their properties, including solid materials. While excellent in terms of quality, these datasets are insufficient in terms of the quantity of data by today's standards (especially for ML). On the other hand, modern materials science and research have led to the development of databases that have many more entries, but often with poor curation and reliability. In many cases, most of the data on material properties are computed, where we lack or have very little experimental data.

Moreover, there are field-specific challenges to data curation. For example, solid materials come in different forms, such as single crystals of differing quality and dimensions, polycrystalline powder that can also be pressed into dense pellets, and thin polycrystalline films. High-quality measurements on different forms of materials can lead to different results because surfaces and interfaces can affect the measurement results strongly for a given property. While our knowledge of atoms' and molecules' arrangements is ordered and solid, and there has been a consensus among the scientists on how to report raw data in a universally used format, challenges related to extracting this data from extant literature still persist.

Data are the basic foundation for the use of AI in science and technology. There is a data need for a range of materials and their properties to pursue deep learning and AI in materials science. In addition, data are needed to develop a digital twin for a specific material or application or a combination of materials and their production processes. We currently face two problems related to data: i) how accurate the computed data needs to be to tackle the huge computational problems and ii) what needs to be done in the absence of accurate and comprehensive computational data?

5.2.1. Modern data infrastructures and their drawbacks

Databases described below collect experimental data, with some form of reviewing and a varying degree of curation. There exist several important databases for materials science research based on experimental data. They are:

- Pauling File[40], the world's largest database for inorganic compounds, which recently was merged into the more general Materials Platform for Data Science[41].
- Inorganic Crystal Structure Database (ICSD), the world's largest database for completely identified inorganic crystal structures.[42]
- Springer Materials, a database for identifying material properties, including the Landolt-Börnstein tables (2000s).[43]
- Crystallography Open Database (COD) for all types of ordered solids.[44]
- Cambridge Structural Database (CSD) for organic and metal-organic solids.[45]
- Protein Data Bank (PDB) for 3D structure data of proteins and nucleic acids.[46]

Among these, the structural databases—mainly COD, CSD, and PDB—are the most comprehensive and of the highest quality. More recently, several large databases of computational materials data have been established, including:

- AFLOW (Automatic-FLOW for Materials Discovery)[47]
- Alexandria[48]

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[40] https://paulingfile.com/

[41] https://mpds.io/

[42] https://icsd.products.fiz-karlsruhe.de/

[43] https://materials.springer.com/

[44] https://www.crystallography.net/cod/

[45] https://serc.carleton.edu/research_education/crystallography/xldatabases.html

[46] https://www.rcsb.org/

[47] https://aflowlib.org/

[48] https://alexandria.icams.rub.de/

- JARVIS (Joint Automated Repository for Various Integrated Simulations)[49]
- Materials Cloud[50]
- Materials Project[51]
- NOMAD (NOvel MAterials Discovery).[52]

These databases, in general, accept contributions from several research groups worldwide, and they can also be accessed by a single API (application programming interface) developed by the OPTIMADE[53] (Open Databases Integration for Materials Design) consortium. There are also databases focused on specific material types, such as nanomaterials or layered materials. Despite the large amounts of data related to the characterisation of nanomaterials and their synthetic approaches that have been generated in recent years, there is a lack of harmonisation in metadata format and type of information.

These databases, each counting at least hundreds of thousands of entries spanning the periodic table of elements, also including defective materials, are composed of datasets which are internally coherent in terms of numerical precision, but often do not contain enough metadata to allow for an *a posteriori* assessment of data quality.

In addition, assessing the reliability of *computed data* is not easy. For example, different databases use different computational approaches, and their results do not always match. This makes it challenging to determine whether the computed data are consistent with the experimental ones.

5.2.2. Databases generated to feed tools for fostering the implementation of the safe and sustainable by design framework

The SSbD framework (Commission Recommendation (EU) 2022/2510, 2022) has been introduced by the European Commission to promote the substitution of substances of very high concern (ECHA, n.d.; Regulation (EC) No 1907/2006, 2006). However, the lack of data across value chains (Apel et al., 2024) poses significant challenges to implementing the SSbD framework within the EU industry.

Horizon 2020 and Horizon Europe (ongoing and soon starting) projects such as HARMLESS, SbD4Nano, SUNSHINE, SSbD4Chem, SUNRISE, Bio-SUSHY, SUBBIMATT, and SiToLub[54] have focused their efforts on generating reliable data and tools for supporting stakeholders in the selection of promising alternatives.

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[49] https://jarvis.nist.gov/

[50] https://www.materialscloud.org/

[51] https://next-gen.materialsproject.org/

[52] https://nomad-lab.eu/nomad-lab/

[53] https://www.optimade.org/

[54] https://cordis.europa.eu/project/id/953183, https://cordis.europa.eu/project/id/862195, https://cordis.europa.eu/project/id/952924, https://cordis.europa.eu/project/id/101138475, https://cordis.europa.eu/project/id/101069573, https://cordis.europa.eu/project/id/101091464, https://subbimatt.eu, https://cordis.europa.eu/project/id/101138807

Initiatives such as the PARC[55] and the IRISS[56] project are accelerating the transition to SSbD chemicals, materials, products, and processes. In addition, the OECD Safe(r) Innovation Approach (SIA) Project developed an inventory of tools for SSbD implementation (OECD, 2020). Despite these initiatives and projects, there are still several gaps in data availability, especially in advanced materials due to their complexity (Ildefonso et al., 2024; Schmid et al., 2023). Thus, there is an urgent need to update existing data that follow FAIR (findable, accessible, interoperable, and reusable) principles to develop new AI-assisted tools to support the industry's implementation of the SSbD framework, including circularity and socio-economic criteria.

The availability of FAIR data may increase by developing an "AI-assisted FAIR Data Hub" and developing robust APIs, such as INSIGHT (Serra et al., 2025), to allow efficient data import and export between relevant data platforms. This AI-assisted Hub could also be designed as a knowledge-sharing platform to foster dialogue between actors in the supply chain. It would allow the estimation of the environmental and social profiles and socio-economic impacts of new products and early prototypes that contain advanced materials, and the optimisation process.

As noted above, several data gaps exist in the intrinsic properties of the chemical, advanced materials, and products targeted. One strategy to overcome them is Quantitative Structure–Activity Relationship (QSAR) modelling (Caldeira et al., 2023) to define *in vitro* approaches and generate robust data, covering human, environmental, and physical hazards, as well as information on the mode of use with a life cycle perspective.

5.2.3. Solutions

How can the issue of insufficient or insufficiently documented (in terms of metadata) data in materials science be solved? One possibility is to use newly available tools to search the existing peer-reviewed scientific and technical literature for data that may have been overlooked until now. An even more fruitful approach could be to search for experimental data from which the desired property can be derived. Such data may not have been reported explicitly if the original study had a different focus, but the property can often be deduced from plots or tables. For example, dielectric permittivity from impedance data, thermal expansion from temperature-dependent structural data, optical bandgap from optical absorption and reflection data, and diffusion coefficients from ionic conductivity data can be obtained.

For experimental data, it is essential to identify reproducible and reliable data. In many cases, this requires manual inspections of reports to understand potential causes for variations (e.g., powder, thin film, single crystal; annealed or not, types of contacts, pressure, temperature range, purity, etc.). Results from pure material are preferred as this is primarily used by the computation. One strategy is to search for correlations for a given property of materials with both experimental and computed data. If the experimental data are reliable and align with results from one or more computational approaches, then

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[55] https://www.eu-parc.eu/

[56] https://iriss-ssbd.eu/

computations can be employed to estimate the same property for other materials lacking experimental data. In addition, methods of interpolation may provide data for materials with missing entries.

As highlighted by Torralba et al. (2025), accurate data are essential for supporting learning-based design systems. This need can be met through two complementary approaches, which are aligned closely with the concept of 'autonomous materials research and development':

1. Establishing a strong data management system, which includes systematically acquiring data from open sources - a practice actively promoted by the European Union.
2. Generating large data sets through high-throughput fabrication and characterisation techniques.

A fundamental requirement in academic research institutes and industries for generating high-quality data is that each laboratory has high demands for rigorous metadata collection and adherence to best practices to ensure comparable datasets for different materials, including standardised methods where appropriate.

Research data management (RDM) refers to the processes used to collect, organise, store, and document research data throughout and after a research project. Effective RDM supports researchers in making their data available according to the FAIR principles. Increasingly, research institutions ask their researchers to produce a data management plan so that these considerations are addressed from the outset of any research activity (Science Europe, 2024).

5.2.4. Using large-language models to harvest data from existing literature

In addition to generating new data in accordance with the FAIR and SSbD guidelines, harvesting the extensive body of materials science literature data published over the past century is highly recommended. Large-language models (LLMs) are becoming increasingly reliable in extracting information from existing texts into tabular formats suitable for AI further analysis. LLM-driven information extraction from multi-modal sources such as tables, plots, figures (e.g., microscopy images), and movies is still in its early stages. In the foreseeable future, provided the published literature contains the necessary metadata (i.e., a human expert would understand it by reading the text), LLMs may be capable of converting original publications into FAIR, particularly AI-ready, data. Such digitalisation of the literature would also help identify consistent versus potentially unreliable data by leveraging modern unsupervised and semi-supervised learning techniques.

5.3. Materials simulations

Materials simulations have become a dominant force in materials science in the past decades. In fact, when the journal *Nature*—first in 2014, and then again in 2025—looked at the most cited papers in the entire scientific, engineering, medical, and biological literature field over the past two centuries to analyse the top 100 most cited papers, it discovered that the most represented field was quantum simulations of molecules and materials, with 12 papers in the top 100 and three papers in the top 10 in 2025 (Van Noorden, 2025; Van Noorden et al., 2014).

Electronic-structure codes developed in Europe have been fundamental to the rise of advanced materials science over the last three decades. Packages such as VASP (Vienna Ab initio Simulation Package), Quantum ESPRESSO (Quantum Open-Source Package for Research in Electronic Structure, Simulation, and Optimisation), and a broader ecosystem of European-led codes (ABINIT, Wien2k, SIESTA, CP2K, FHI-AIMS, FLEUR, ELK, Yambo, etc.) have effectively turned quantum mechanics into an everyday engineering tool, used from basic research to industrial design. In particular, VASP (commercial) and Quantum ESPRESSO (open source) are the two most used codes in the world for materials simulations.

First, these codes made density-functional theory (DFT) and beyond-DFT methods practically usable. European groups were among the earliest to push systematically for plane-wave/pseudopotential and augmented-wave formulations that are robust, transferable, and automatable. They implemented the foundational algorithms into software that non-specialists could use reliably. This dramatically lowered the barrier between sophisticated quantum theory and mainstream materials research.

Second, they created a common language and shared infrastructure for the international community. Because many of these codes were developed in academic consortia and released under open or academic licenses, they became *de facto* standards for methodology, formats, and benchmarks. A PhD student in Zurich, an R&D engineer in Munich, and a beamline scientist at a synchrotron can all exchange input files, workflows, and results because they rely on the same European-origin codes. This interoperability has been crucial for building curated databases of materials properties, for high-throughput screening, and for connecting simulations to experimental facilities.

Third, they enabled quantitative, predictive design of advanced materials across essentially all technologically relevant domains. European electronic-structure codes are now routinely used to design and understand:

- Energy materials (battery electrodes, solid electrolytes, photovoltaics, thermoelectrics, catalysts and electrocatalysts)
- Quantum and topological materials (2D magnets, topological material, quantum spin liquids, superconductors)
- Functional oxides and ferroelectrics, piezoelectrics, multiferroics
- Semiconductors and wide-band-gap materials for power electronics and optoelectronics
- Surfaces, interfaces, and heterogeneous catalysts.

In many of these fields, design cycles now begin with parameter-free simulations that screen thousands of candidate compounds, narrow down the most promising ones, and guide targeted synthesis and characterisation. This shift from trial-and-error to computation-guided discovery rests heavily on the scalability, robustness, and accuracy of the European codes.

Fourth, these codes have been central in training generations of scientists and in shaping the culture of open, reproducible research. Summer schools, hands-on tutorials, and online documentation built around these packages have educated tens of thousands of students and researchers worldwide in electronic-structure theory and practice. The open or community-driven development model has fostered a culture where new methods are very quickly disseminated, tested, and adopted globally.

Finally, European electronic-structure codes are now a cornerstone of emerging digital infrastructures and AI-driven materials discovery. Because they are modular, automatable, and well-documented, they integrate naturally with workflow managers, materials databases, and machine-learning frameworks. This makes them the engines behind large-scale screening campaigns, training sets for interatomic potentials, and closed-loop discovery platforms that combine quantum mechanics, data, and artificial intelligence.

In short, electronic-structure codes have not only provided the core algorithms and software that power modern computational materials science; they have also shaped the global ecosystem, culture, and methodology of the field. Without them, the current landscape of advanced materials—where predictive simulations are tightly coupled to experiment and industry—would simply not exist in its present form (Leopold Talirz et al., 2025; Talirz et al., 2021).

5.4. AI in materials and materials design

AI is revolutionising how organisations and industries operate. Organisations are already envisioning and implementing automation and data management to enhance efficiency and productivity. The scope of AI is expanding towards paradigm shift ideas such as generating new knowledge and materials using digital tools and integrating them into autonomous infrastructure to propel advanced materials discovery (Bauer et al., 2024; Liu et al., 2023; Morgan & Jacobs, 2020; Wei et al., 2019). In addition, digital tools are aiding advanced materials' designing and manufacturing (Jin et al., 2020; Penumuru et al., 2020) while solving challenges related to sustainability (Yao et al., 2023).

5.4.1. AI-driven materials discovery and design: Active learning for digital twins and self-driven labs

AI/ML models can become active agents in materials discovery and design (Zivic et al., 2025). In particular, two interconnected fields of research can be distinguished: digital twins and robotic (self-driven) labs.

The term digital twin encompasses a wide variety of related efforts, where the common leading idea being to generate an *in silico* model of a material (or a device) and the production and synthesis process so that its complete properties and functions can be simulated without actually synthesising and manufacturing or characterising the material and device. Besides testing and maintaining the real-world counterparts or educating the personnel (de Jong et al., 2013), the digital twin can be used to explore the parameter space and optimise the performance of the material or device. More recently, surrogate, simplified versions of (expensive) theoretical models have been named digital twins as well. With the unifying idea that the digital twin is faster and less resource-intensive, it enables feedback and control of the process and, therefore, is more sustainable than the real twin. This could be an actual material or device, or a sophisticated model.

Robotic labs use AI/ML predictive models that are continuously trained and refined with new data for determining which new materials or chemicals should be actually synthesised. The new data could serve to refine the model and/or optimise the desired performance. Ideally, the full *active-learning* workflow—involving synthesis and manufacturing, characterisation, model refinement, identification of new data points, and new synthesis—can be completely automatised (Tom et al., 2024). A milder version of the synthesis, characterisation, and simulation workflow is AI-driven.

Both related concepts, digital twins and robotic labs (self-driven labs) (Adesiji et al., 2025; Barber, 2023), are based on both the quantitative prediction of AI/ML models trained on the available data as well as on the uncertainty quantification (UQ) of such models. The UQ aspect is vital to promote the exploration of yet poorly known regions of the parameter space. Both quantitative prediction and UQ are used to design the active-learning workflow that drives the robotic/self-driven labs and updates the digital twins.

As of 2025, the evidence on the impact of (even partially) autonomous laboratories is already profound in materials science and in the industry. However, the discussion on whether such technology is going to revolutionise the field is still ongoing in the community (Leeman et al., 2024). Many of these initiatives have been developed under the umbrella of the so-called "Materials Project[57]" and the concept of the "Materials Genome Initiative" (Abolhasani, 2025).

It is possible to design active-learning workflows where not only the performance of the material and device but also its sustainability (suitably measured) is in some sense optimised.

Databases highlighted in Section 5.2**.** already serve as starting points for active-learning workflows. However, improved (more strictly FAIR) databases could grow in such a way that fewer and fewer iterations are needed in the active-learning workflow, considering that every new data point can and should be uploaded to FAIR databases. Robotic labs should also improve on the reproducibility challenge, as the protocols used should be transferable to other labs (if not in the same lab at a later time), and the completeness of the metadata can be empirically tested, with error bars, etc.

5.4.2. AI in resilient circular material systems and advanced materials

As outlined in Chapter 2, achieving scalable circularity requires material systems that support a broad range of R-strategies—including reuse, repair, refurbishment, remanufacturing, repurposing,

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[57] https://next-gen.materialsproject.org/

and recycling. AI is a key enabler in managing complex and variable waste streams, opening new possibilities for circular material flows.

The EU already holds significant quantities of critical materials within its waste streams (including batteries, photovoltaic modules, construction materials, industrial residues, and consumer goods). These streams can serve as a valuable source for the development of new advanced materials that meet modern performance and sustainability requirements.

AI can support this transformation in several ways: by identifying suitable secondary inputs with desired properties, predicting material behaviour, and generating new formulations or "recipes" for combining recovered substances into high-performance materials and optimising recovery processes.

In parallel, AI also enables the design of advanced materials with engineered surface structures that deliver desired functionalities—such as hydrophobicity or corrosion resistance—without requiring additional coatings or multi-material layering. While these structures may not rely on waste inputs, they support circularity by reducing material complexity and improving recyclability.

Altogether, these strategies show how AI can bridge materials science, digital technologies, new manufacturing technologies, and circular economy thinking—turning waste into innovation, fostering the development of advanced materials, and supporting the EU's goals for resilient, low-carbon, and resource-efficient industrial systems.

5.5. Key messages

- Data-driven approaches and AI are becoming instrumental in designing new advanced materials.
- High-quality databases built on FAIR principles are critical to employing AI and simulations in materials discovery. In addition, these databases should incorporate digital profiles of materials for specific applications and industrial use.
- There is a need for improved data mining and curation to create and strengthen reliable data pipelines.
- AI can enable next-generation digital twins and self-driven labs that will scale advanced materials discovery and manufacture at previously unattainable levels and identify new sustainable materials.

Chapter 6: Policy, legislation, and governance of innovation ecosystems

6.1. Introduction and scope of the chapter

This chapter aims to introduce and discuss EU policy and legislation relevant to advanced materials. The focus is especially on the scientific and technical challenges related to regulatory practices. We particularly focus on lessons from the regulatory developments the EU has undertaken for nanomaterials since the 2000s. The broader point we make in this chapter is that challenges in nanomaterials and advanced materials are not limited to studying and addressing scientific and technical challenges, but also focused on challenges related to risk governance and governance of innovative ecosystems.

Policy and regulations are cornerstones of the EU's strategic autonomy and the cross-fertilisation of innovation. The development, design, and implementation of regulation and policy can be applied strategically to spark innovation while ensuring the protection of public health and the environment.

The EU is generally recognised as a frontrunner when it comes to the protection of public health and the environment. There are several examples of the EU effectively exporting its regulatory standards to large markets because of setting stringent internal standards. For instance, the EU's chemical legislation, known as REACH[58] (Registration, Evaluation, Authorisation and Restriction of Chemicals) (Regulation (EC) No 1907/2006, 2006), has had an impact on the design and development of chemical laws in Korea, Turkey, and India (Van Heerden, 2012).

Furthermore, the EU is unique in its effort to systemically integrate environmental goals on chemicals, clean air, water and soil, waste, biodiversity, and circular economy across all policy areas, including trade, agriculture, energy, and industry. Finally, the EU has been a global leader in the application of the precautionary principle, and it's embedded in international law; the adoption of the One Health framework[59] that aims to integrate human, animal, and ecosystem health through multidisciplinary collaboration; and finally, the development and operationalisation of the SSbD framework.

With this in mind, this chapter begins by situating current advanced materials policy within the wider historical and political context (Section 6.1.) and changing regulatory landscape (Section 6.2.). The latter reviews relevant policy and legislation and discusses recent updates on nanomaterials and advanced polymers. In Section 6.3. focuses on challenges related to defining and categorising advanced

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[58] https://echa.europa.eu/regulations/reach/understanding-reach

[59] https://op.europa.eu/en/publication-detail/-/publication/56b65e58-a309-11ef-85f0-01aa75ed71a1/language-en

materials from a regulatory perspective, whereas Sections 6.4. and 6.5. discusses the generation of environmental, health, and safety data, fulfilling risk assessment requirements, and monitoring and regulatory enforcement. Section 6.6. introduces a roadmap towards safe and sustainable advanced and innovative materials (Outlook for 2024–2030) from the NanoSafetyCluster that provides the foundation for a discussion about different regulatory measures that could potentially be taken to ensure advanced materials that fulfil the SSbD criteria. Section 6.7. then examines possible regulatory measures for ensuring safe and sustainable-by-design advanced materials, comparing options such as adapting existing frameworks or creating a dedicated regulation. Lastly, Section 6.8. discusses governance issues, including risk governance of nanomaterials and governance on innovation and innovation of governmental institutions.

6.2. Historical policy paradigms shaping research and development

The term "advanced materials" has been around since the 1950s (Curlee et al., 1990). Starting in the 1950s, broadly two paradigms have informed thinking in research and development policy in general, both of which have influenced the development of advanced materials. One paradigm, which was dominant in the 1950s-70s, emphasised the value of generous natural scientific funding programmes and large public and private laboratories, for example, AT&T Bell Labs and Oak Ridge National Laboratory in the US, and the European Organization for Nuclear Research (CERN) in Europe. This was a paradigm that provided the basis, among other things, for nuclear power, high-performance aerospace, and an ongoing expansion of the use of petrochemicals. Advanced materials developed during this period include high-performance polymers (Teflon, Kevlar), composites (glass fibre, carbon fibre), semiconductors (silicon, gallium arsenide, integrated circuits), superalloys and high-temperature ceramics, optical fibres, and liquid crystals that offer properties far superior to conventional metals, woods, and simple plastics. At the time, these advanced materials provided the foundation for whole industries, producing jet engines, space exploration, fibre-optic telecoms, and modern electronics.

A second paradigm, which gained increasing prominence from the 1980s onwards, emphasised the role of users in the innovation process, the need for public participation, and even transdisciplinary research involving natural and social scientists, and citizens (Callon et al., 2001; Nowotny et al., 2001). The failures of earlier high-tech programmes to foster competitiveness were increasingly criticised, and the unintended environmental consequences of the earlier paradigm became evident (European Environment Agency, 2001, 2013). It became clear that the voices of both consumers and citizens in the innovation process needed to be recognised, and some even considered it appropriate to consider a precautionary approach to innovation. This period witnessed vigorous debates in some European countries about both pharmaceuticals in the environment, genetically-modified organisms (GMOs), and nanotechnologies, resulting into the need for a systematic review of the evidence that assessed successes and failures of past attempts to regulate new materials and technologies (Laurent, 2017; Nielsen et al., 2023).

Current policy on advanced materials needs to be understood in this wider historical and political context. To some extent, there has been a return to the emphasis on large science-driven programmes. In the wake of the COVID-19 pandemic, economists have argued for a "mission-driven economy" (Mazzucato, 2017), which explicitly draws comparisons with the state-funded R&D programmes of the 1950s and 60s. The renewed emphasis on critical materials (Laurent et al., 2025), climate change, AI, and energy security has occurred in a period of heightened geopolitical competition and a shift from the neo-liberal economic model that dominated economic policy in Europe and the US from the 1980s to the late 2000s. The idea of 'advanced materials' reflects a range of recent scientific developments, but the term also reflects the effort by the EU and its member states to embody strategic priorities in material design. As discussed in earlier chapters, the priorities focus on dealing with the challenges related to heightened geoeconomic competition from the US and China, access to resources, the development and regulation of AI, as well as environmental concerns relating to climate change, chemical pollution, and public health. This chapter focuses on policy and legislation that relate specifically to advanced materials; however, it is important to recognise that the development of advanced materials in Europe is powerfully affected by a wide range of policy areas, including, for example, foreign, trade and energy policy, as well as broader and shifting political economic conditions.

Considering the evidence and learning from the successes and failures of the paradigm involving consumers and citizens that dominated R&D policy from the 1980s to 2010s, this paradigm needs to inform EU policy on advanced materials and sustainability as well. Antagonistic conflict about the development of new technologies has occurred in past decades, and there is a need to continue to support constructive and inclusive debate about innovation in materials. More broadly, socio-economic research on R&D policy and innovation should become part of advanced materials research.

6.3. Changing regulatory landscape

Advanced materials consist of many different categories of materials, where some of them, such as nanomaterials, have been subject to regulatory scrutiny for decades, whereas others have not. The regulation of advanced materials as an overall category has so far not been subject to an in-depth analysis. In 2016, the European Commission published a consultancy report in "Support for 3rd regulatory review on nanomaterials – environmental legislation" (European Commission et al., 2016) that included a prospective view on future developments in advanced materials and challenges for environmental legislation. This section will first introduce the main findings of the prospective view from 2016 regarding the implementation of advanced materials, and subsequently will discuss the regulatory developments with relevance to advanced materials since 2016 .

6.3.1. Prospective view from 2016 regarding the implementation of advanced materials

In their consultancy report for the European Commission, Broomfield et al. (European Commission et al., 2016) investigated a range of legislative questions, such as:

> *Are advanced materials covered in the general objectives [of EU environmental legislation]? (…) What are the tools used to control? EQS [Environmental Quality Standards], ELVs [Environmental Limit Values]? Are they also effective for advanced materials? Are monitoring requirements (criteria, measurements, thresholds, regularity, monitoring—e.g. by an authority of self-monitoring) applicable to advanced materials in terms of volume and associated risks? (…) Enforcement – is there a need for specific elements covering advanced materials?* (European Commission et al., 2016).

The authors of the report concluded that no legal issues were to be expected for most categories of advanced materials, such as active materials, advanced composites, advanced manufacturing, advanced textiles and fibres, coatings, gels and foams and light alloys (see Table 6). These are typically governed by a general product safety framework and applicable sector-specific regulations, and there are no specific EU laws solely for these. For example, active implantable medical devices (like a drug-release implant) would be regulated by the Medical Devices Regulation and 'active' building materials like self-healing concrete must comply with existing construction standards. Relying on existing regulations and testing protocols could be an issue as many of these were developed for traditional chemicals and materials, such as steel, aluminium, and others, and may not directly apply to advanced composites.

Category	**Classification and coverage under EU legislation**	**Potential legal issues**
Active materials	Articles under REACH Regulation. RoHS Directive and WEEE Directive (Directive 2012/19/EU, 2012) if used in Electronic and Electric Equipment. Active food contact material under Regulation (EC) No 450/2009 (2009) on active and intelligent materials intended to be in contact with food.	None.
Advanced composites	Mixtures under REACH Regulation.	None.
Advanced manufacturing	Electronic and Electric equipment subject to the RoHS Directive and the WEEE Directive. Article under REACH. Products under the product safety regulation.	None.
Advanced textiles and fibres	Regulation (EU) No 1007/2011 (2011) on textile fibre names and related labelling and marking of the fibre composition of textile products.	None.

Coatings	Substance and mixtures under REACH. Biocidal product under Regulation (EU) No 528/2012. Coating falling under Directive 2004/42/EC (2004) on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain paints and varnishes.	None.
Nanotechnology	Substance under REACH and CLP Regulation.	REACH and CLP Regulations do not effectively identify and generate information on nanomaterials, and downstream environmental laws (e.g., waste, water, air emissions) rely on these two instruments to trigger their risk management measures for hazardous chemical substances. Scientific knowledge gaps on nanomaterials toxicity and behaviour in environmental media remain, which impedes an effective implementation of the EU environmental acquis for such chemical substances.
Gels and foams	Substances and mixtures under REACH. Construction products under the Regulation on Construction Products. Products under the product safety regulation.	None.
High-performance polymers	Substances under REACH with specific derogations to the REACH obligations. According to Article 2 of REACH polymers do not have to be registered, but according to Article 6(3), the monomer substance(s) and other substances of the polymers that have not already been registered by an actor up the supply chain are to be registered if both the following conditions are met: The polymer consists of 2% weight by weight (w/w) or more of such monomer substance(s) or other substance(s) in the form of monomeric units and chemically bound substance(s) (i.e. free or unbound monomers shall not be considered when checking this condition). The total quantity of such monomer substance(s) or other substance(s) makes up 1 tonne or more per year (the total quantity in this context is the total quantity of monomer or other substance ending up in the final polymer unbound or chemically bound to the polymer).	According to Article 138(2) of the REACH Regulation, the European Commission may present legislative proposals with requirements for the registration of polymers once a practicable and cost-effective way of selecting polymers for registration on the basis of sound technical and valid scientific criteria can be established. Such criteria have not yet been established. Furthermore, the definition of polymers under REACH may not be adequate for high-performance polymers.

Light alloys	Alloys are considered special mixtures under REACH (Annexe I (0.11)); they are not subject to registration as such, but the alloying elements are. Components not important for the properties of alloys can be considered as impurities and do not need a separate registration dossier.	None.

Table 6. The types of advanced material identified in the DAMADEI EU project, classification of advanced materials, and the potential legal issues identified in the preliminary regulatory analysis reported by Broomfield et al. Sources: European Commission et al., (2016); European Union, (2013).

For high-performance polymers, Broomfield et al. (European Commission et al., 2016) noted that the definition of polymers and registration requirements under Europe's chemical legislation (REACH) might not be adequate, whereas a range of issues were highlighted for nanotechnology. These include that the nanoscale properties of nanomaterials, and any potential hazards that could be associated with these nanoscale properties were not adequately addressed in most of the pieces of EU legislation analysed. One of the main reasons for this was identified to be that the REACH and CLP (Classification, Labelling and Packaging) (Regulation (EC) No 1272/2008, 2008) regulations do not effectively identify and generate information on nanomaterials, whereas a great deal of downstream environmental legislation (e.g., waste, water, air emissions) relies on these two instruments to trigger their risk management measures for hazardous chemical substances (European Commission et al., 2016).

It was also noted by Broomfield et al. (European Commission et al., 2016) that there are still scientific knowledge gaps on nanomaterial toxicity and behaviour in environmental media, which impedes an effective implementation of the EU environmental requirement for such chemical substances. Back in 2016, some pieces of EU legislation had just been amended to address potential risks from nanomaterials, such as the RoHS Directive (Restriction of Hazardous Substances in Electrical and Electronic Equipment, Directive 2011/65/EU, 2016), EU ecolabel criteria decisions, Biocidal Products Regulation (Regulation (EU) No 528/2012, 2012), several EU food laws, the Cosmetics Regulation (Commission Regulation (EU) 2016/1143, 2016). However, the lack of an apparent consistent approach across all EU acquis on the regulation of nanomaterials was highlighted in their conclusions as a final issue.

6.3.2. Regulatory developments since 2016 with relevance to advanced materials

6.3.2.1. Nanomaterials

Since 2016, major regulatory updates have been implemented for nanomaterials in the EU (Nielsen et al., 2023). These efforts are important as nanotechnology is considered by many as one of many categories of advanced materials and because some see the EU's approach to governing nanotechnology as a model for how the EU might also consider addressing advanced materials overall (Groenewold et al., 2024).

First of all, since 2020, nanoform ingredients must be registered with the European Chemicals Agency (ECHA) under REACH by producers and/or importers with nano-specific data. Specifically, the Commission adopted Regulation (EU) 2018/1881 (Commission Regulation (EU) 2018/1881, 2018; Clausen & Hansen, 2018) amending multiple REACH Annexes (I, III, VI-XII) to introduce nano-specific information requirements. These changes mean that any substance with nanoforms must be explicitly registered with data on particle size, morphology, and surface chemistry (Clausen & Hansen, 2018). REACH Annex II (safety data sheet requirements) has also been updated via Regulation (EU) 2020/878 (Commission Regulation (EU) 2020/878, 2020) to ensure safety data sheets include nanoform information consistent with the new registration rules.

In 2022, the EU updated its formal definition of nanomaterials (Commission Recommendation of 10 June 2022, 2022) intended to be used across regulations, and the revision will be progressively integrated into EU laws (REACH, biocides, medical, etc.) to harmonise what is considered a nanomaterial. The updated 2022 definition includes any solid particle with at least one dimension <1 nanometre (nm) and retains the core 100 nm threshold and particle number concentration threshold, with some clarifications (e.g., how to measure size distribution). The revised definition explicitly excludes soluble or degradable materials that do not persist as particulate at the nanoscale (Hansen et al., 2022).

Besides REACH, the EU Medical Devices Regulation (MDR) (Regulation (EU) 2017/745, 2017), fully effective since May 2021, requires that manufacturers demonstrate biocompatibility and chemical safety for any gels/foams in devices in a pre-market evaluation. Certain substances are restricted (e.g., MDR Annex I forbids carcinogenicity, mutagenicity, and reproductive toxicity (CMR) or endocrine-disrupting chemicals above 0.1% in implantable or long-term exposure devices without justification). Rule 19 of the MDR classifies devices that incorporate or administer nanomaterials into higher risk classes (IIb or III) depending on exposure level, which could apply to nano-hydrogels or nanostructured foams used in drug delivery or tissue engineering (Medical Device Coordination Group, 2021).

6.3.2.2. Polymers

Since the adoption of REACH in 2007, polymers have been exempted from registration, and this has also applied to high-performance polymers (Risk & Policy Analysts Limited, 2012). The European Commission initiated a process in 2020 to end this general exemption by having companies marketing polymers in the EU in quantities above 1 tonne per year adhere to new notification and registration requirements. According to a proposal by the European Commission, all polymers produced or imported in the EU in quantities exceeding 1 tonne per year will need to be notified so that so-called Polymers Requiring Registration (PRR) can be identified (European Commission et al., 2020). It is estimated that around 200,000 polymers available in the EU market will need to be notified. Criteria for PRR have also been developed through industry consultation and are based on issues of potential concern, low molecular weight oligomers, the presence of reactive or hazardous functional groups, solubility and bioavailability, and ecological and toxicological concerns. It is expected that between 11,000 and 30,000 polymers may need to be PRR registered. The European Commission's public consultation period ended in April 2025, and final adoption is anticipated by the end of 2025 (BIO by Deloitte, 2015; Bougas et al., 2020).

It is anticipated that the planned revisions to REACH for polymers are very likely to affect manufacturers of advanced polymers as they will need to notify and potentially register and submit data on polymers' physical and chemical properties, manufacturing volumes, environmental fate, and health and environmental hazard information.

The EU also adopted a restriction on synthetic polymer microparticles in 2023 (Commission Regulation (EU) 2023/2055, 2023), which is important to consider when discussing advanced polymers. Synthetic polymer microparticles are defined in the restriction as polymers that are solid and that fulfil both of the following conditions:

1. Are contained in particles and constitute at least 1% by weight of those particles or build a continuous surface coating on particles.
2. At least 1% by weight of the particles referred to the condition above (point i) fulfil either of the following conditions, including all dimensions of the particles are equal to or less than 5 mm, or the length of the particles is equal to or less than 15 mm and their length to diameter ratio is greater than three.

Polymers that are excluded according to the definition include those that are degradable, have a solubility greater than 2g/L and do not contain carbon atoms in their chemical structure (Commission Regulation (EU) 2023/2055, 2023). The restriction directly impacts high-performance polymers if marketed in microscopic form (for example, polymer-based microcapsules or nanocapsules containing active ingredients used in smart materials, controlled-release systems, or coatings).

6.3.2.3. Standardisation and certification effort

Standardisation of advanced materials has been the subject of international effort for almost half a century. In 1982, the Versailles Project on Advanced Materials and Standards (VAMAS) was launched at the G7 Economic Summit in Versailles as an international initiative to develop standards and promote characterisation methods specifically for advanced materials (Dickson, 1983).

A range of efforts has been undertaken by the OECD and European Committee for Standardization (CEN) supporting the development of regulation relating to nanomaterials, microplastics, and advanced materials. For instance, the European Committee for Standardization's Technical Committee (CEN/TC250) on Structural Eurocode has published CEN Technical Standard (CEN/TS) 19101: Design of Fibre-Polymer Composite Structures (2022) to put composite materials on the same level as conventional construction materials. The European Committee for Standardization's Technical Committee on Nanotechnologies (CEN/TC352) has developed guidelines for waste management of nanomaterials and testing standards for detecting nano-objects in complex matrices and nanoparticle release from coatings. This is crucial for understanding if sanding or weathering of a nano-coating could release nanoparticles and assessing exposure. In addition, the EU-funded "Malta Initiative" (Cassee et al., 2024) has driven the OECD to develop or update over 10 test guidelines relevant to nanomaterials.

For polymers, the European Committee for Standardization's Technical Committee on Nanotechnologies on Plastics (CEN/TC 249) is working on standards to define and test biodegradability in various environments. This is important for validating that polymers are truly biodegradable, as this is one of the exemption criteria for polymer particles under the EU restriction on synthetic polymer microparticles.

6.3.2.4. Adoption of European strategies and action plans

A range of different European strategies and action plans could potentially influence advanced materials in the future. First of all, the European Commission has published the Communication "Advanced Materials for Industrial Leadership" in 2024 (European Commission, 2024b). The Communication emphasises that sustainability and circularity of advanced materials and resilience of value chains must be factored into Europe's efforts to ensure it has the necessary capacities and resources to lead innovation and deployment in advanced materials.

The Communication proposes actions along five pillars:

1. European research and innovation on advanced materials: a launchpad for the twin transition, EU resilience, and open strategic autonomy.
2. Fast track from lab to fab.
3. Increasing capital investment and access to finance.
4. Fostering the production and use of advanced materials.
5. Overall governance framework.

It is unclear how sustainability and circularity of advanced materials can be ensured, and the European Commission has been criticised by different European Member State agencies, such as the German Environment Agency (UBA) and Dutch National Institute for Public Health and the Environment (RIVM) for not considering how conflicting goals can be addressed. For example, advanced materials essential for renewable energy technologies might also have harmful environmental or health impacts. According to UBA,

> *it is important to develop approaches that allow balancing between the use of advanced materials to combat the major crises of our time and their possibly limited chemical safety or sustainability over the life cycle. This also includes to identify conflicting goals at an early stage, and to derive and implement measures in a timely manner* (D. Völker et al., 2023).

RIVM (2024, 2025) argues that regulatory preparedness and SSbD are two key strategies that need to go hand-in-hand. Through regulatory preparedness, governments should identify and address knowledge gaps regarding safety, sustainability, and regulations. RIVM argues that advanced materials often display complex behaviours that make risk assessment challenging and therefore it is essential to update regulatory frameworks and OECD testing guidelines to ensure safety and legal clarity for industries. Through SSbD, innovators should integrate safety and sustainability early in material development rather than focusing solely on functionality.

Other strategies and action also should be noted:

- The European Commission’s Chemicals Strategy for Sustainability (CSS)[60] (European Commission, n.d.-b, 2020b). explicitly mentions incorporating lessons from nanomaterials regulation to improve the broader chemicals framework. The CSS also notes that the goal is to address knowledge gaps about polymers and ensure the development, commercialisation, deployment, and uptake of SSbD substances, materials, and products.
- One output of the CSS is the SSbD framework released in 2022 (Commission Recommendation (EU) 2022/2510, 2022), a voluntary guidance for industry to design chemicals and materials (including nanomaterials) that are safer and greener from inception. The European Commission’s Joint Research Centre (JRC) led the development of SSbD criteria and a five-step assessment process (Caldeira et al., 2022), and a Commission Recommendation in 2022 (Commission Recommendation (EU) 2022/2510, 2022) launched a two-year pilot phase for SSbD adoption. While not legally binding, SSbD is poised to influence future approvals and funding (Horizon Europe calls now often require aligning with SSbD principles).
- The Critical Raw Materials Act (Regulation (EU) 2024/1252, 2024) is relevant, for example, to those advanced light alloys that rely on specific minerals (e.g., *lithium* in aluminium-lithium alloy for aerospace, *rare earth metals* in magnesium alloys for improving strength).
- The Circular Economy Action Plan (European Commission, 2020a) identified composite waste (e.g., wind turbine blades, aircraft parts) as a challenge. While not yet expressed in regulation, the EU has funded projects on recycling carbon fibre and glass fibre composites, and some Member States have pilot rules for producer responsibility on large composite waste.
- The Circular Economy for Plastics proposed a Packaging and Packaging Waste Regulation (PPWR) effective as of 2025 (Regulation (EU) 2025/40, 2024) that requires all packaging (including plastic) to be recyclable or reusable by 2030, and to set recycled content targets for plastics. This means that advanced polymer packaging (multi-layer films, engineering plastic containers) has to be (re-) designed both for recyclability and in order to incorporate secondary raw material.

6.4. Challenges related to definitions and classes of advanced materials from a regulatory perspective

A range of regulatory challenges can be identified when it comes to advanced materials, and these must be addressed to ensure the development of safe and sustainable advanced materials for the circular economy and to establish appropriate mechanisms to tap the potential of new innovative functionalities across sectors and applications. Several of these are very similar to the challenges that the EU has faced when it comes to nanomaterials, whereas others are unique.

Advanced materials can and have been defined in many ways, and do not yet have a formal definition like the one proposed by the European Commission for nanomaterials. Regulatory definitions are crucial, as they provide the legal and technical foundation for how laws are interpreted, enforced,

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[60] https://environment.ec.europa.eu/strategy/chemicals-strategy_en

and complied with, and therefore it is important to define what falls under "advanced materials" in a regulatory sense. Unlike traditional chemicals defined by specific molecular identity, advanced materials are often defined by their novel properties or structures. In its Communication on Advanced Materials for Industrial Leadership, the European Commission (referring to the working description of the OECD from 2023) states that:

> *Advanced materials are understood as materials that are rationally designed to have (i) new or enhanced properties, and/or (ii) targeted or enhanced structural features with the objective to achieve specific or improved functional performance. This includes both new emerging manufactured materials (high tech materials), and materials that are manufactured from traditional materials (low tech materials).* (European Commission, 2024b, footnote 1).

As with the many different working definitions of nanotechnology and nanomaterials in the 2000s, this definition of advanced materials raises a number of questions about what it means to be rationally designed, to have new or enhanced properties, what constitutes targeted or enhanced structural features, and how to determine the objective to achieve specific or improved functional performance. Until such aspects are clarified and methods to determine them become available, the advanced materials definition for regulatory purposes remains fluid. This lack of clarity complicates regulatory efforts as regulators and companies may be unsure whether a given novel material will have to undergo additional scrutiny and specific guidelines.

Nanomaterials were among the first advanced materials to test the limits of EU regulation. In the early 2000s, nanotechnology was identified as a key enabling technology, prompting waves of EU-funded safety research and eventually new regulatory measures. One of the fundamental hurdles regulators faced was the lack of agreed definition of nanomaterial, making it unclear whether the bulk and nanoform of a given material should be considered different from a regulatory and risk perspective and whether nano-specific oversight was needed. In 2011, the European Commission eventually proposed a regulatory definition of nanomaterials (Hansen et al., 2022) that ignored the novel properties that were typically associated with the nanoscale until then. The 2011 definition was further updated in 2022 (Commission Recommendation of 10 June 2022, 2022) to improve clarity. The lack of a clear definition hindered consistent regulation early on and led to divergences in the ways in which nanomaterials were handled in legislation, creating inconsistencies.

Nanomaterials are an important class of advanced materials. The EU faced many regulatory and socio-technological challenges in the last 20 years related to nanomaterial regulation. Now, the same challenges are playing out for advanced materials in general. Although nanotechnology is a term that encompasses multiple techniques, methods and materials, the scope of advanced materials is even broader. To begin with, virtually all nanomaterials are advanced materials, but not all advanced materials are in the nanoform. In addition, nanomaterials are just one of at least ten categories of advanced materials. Along with nanomaterials, each of these categories of advanced materials have to be determined and methods must be available to determine whether a given material falls under the definition or not.

Back in 2016, Broomfield et al. noted that a range of classification schemes had been suggested for advanced materials (European Commission et al., 2016; European Union, 2013; Technology Strategy Board, 2008). Most of these provide a clear description of distinct advanced material categories; however, these categories are often not well-defined. Some schemes feature undefined advanced material categories not explained in detail, whereas others include unique categories of materials not widely recognised as advanced materials. Regulatory definitions must evolve to reflect these complexities, ensuring regulators have the capacity to protect human health and the environment, provide clear compliance and enforcement rules, and, at the same time, foster innovation.

6.5. Current data, information, and risk assessment requirements

As with nanomaterials, it is the novel properties of the other categories of advanced materials that pose significant questions about how to best ensure proper data collection; generate of environmental, health and safety information; and carry out hazard, exposure, and risk assessment under EU's regulatory frameworks such as REACH. A significant hurdle with nanomaterials was the lack of standard characterisation, test methods, and detection techniques that could be used on the materials themselves, whether they existed in complex matrices and products, or in environmental media such as water and soil. Without the information derived from such tests, it is not possible to assess hazards and exposure or complete any kind of risk assessment, life-cycle assessment, or SSbD assessment, without making unsubstantiated assumptions. Furthermore, for a decade or more it was not clear whether existing standardised eco-toxicological tests that most EU regulatory frameworks rely upon were applicable to nanomaterials. These tests were originally developed for soluble chemical substances and had to be revised to provide meaningful information on nanomaterials. The EU and many EU Member State agencies with OECD coordination have put substantial effort into developing nano-specific test guidelines in the last 15 years (Nielsen et al., 2023).

Several areas of EU policy and legislation require that the risks posed by substances and materials are assessed to answer the fundamental question: "What are the risks for humans and the environment?". For example, Europe's chemical regulation, REACH, mandates the assessment of human exposure and the derivation of a Derived No-Effect Level (DNEL) for substances registered at volumes of 10 tonnes or more per year. The ratio between the estimated exposure level and the DNEL is expressed as the risk characterisation ratio (RCR). An RCR ≤ 1 indicates that exposure remains at or below a threshold considered safe, while an RCR >1 signifies potential health risks and the need for additional risk management measures. To conduct a robust risk assessment, a broad range of information is required, including: physicochemical properties of the material, toxicokinetic data in humans, acute and chronic toxicity data, evidence of systemic and local effects, and studies on CMR. Additionally, data on exposure levels in dietary and environmental contexts, degradation, transformation, and fate are essential, alongside analytical methods for sampling and measurement, along with the derivation of DNEL(s) or Derived Minimal Effect Levels (DMELs).

For advanced materials—including engineered nanomaterials, stimuli-responsive systems, and multifunctional composites—these data are often incomplete or unavailable. This is due to the novel, hybrid, or adaptive characteristics of such materials, which may not align with existing test methods or regulatory thresholds. Consequently, hazard characterisation, exposure assessment and risk characterisation of advanced materials remains a challenge, particularly when it comes to understanding how functionality, life cycle transformations, and material complexity affect exposure, bioavailability, and toxicity. We furthermore have no overview of the production and use of advanced materials with regard to what, where, how much is produced, commercialised, and product concentrations, which are prerequisites for exposure assessment. Addressing these data gaps and setting up continuous monitoring of production and commercialisation is essential to ensure that innovation in advanced materials proceeds without compromising human health and safety.

6.6. Roadmap towards safe and sustainable advanced and innovative materials (Outlook for 2024–2030)

The question of how to address these challenges has been subject to academic and regulatory scrutiny within the OECD Working Party on Manufactured Nanomaterials (WP on NM) as well as within the EU NanoSafety Cluster[61]. In 2024, experts from the EU NanoSafety Cluster and associated European research institutes and agencies, including RIVM, Germany's Federal Institute for Occupational Safety and Health (BAuA), BNN, and the JRC proposed a "Roadmap towards safe and sustainable advanced and innovative materials (outlook for 2024–2030)" (Cassee et al., 2024). Building on two decades of nanosafety research and EU-funded initiatives such as NANoREG, Gov4Nano, and NanoHarmony, the authors emphasise that the future competitiveness and societal acceptance of advanced materials depend on early integration of safety, sustainability, and regulatory preparedness. Cassee et al. (2024) identifies major challenges that currently hamper the development of advanced materials within an SSbD framework, including fragmented data on environmental health and safety and production and commercialisation; lack of harmonised testing methods; and insufficient regulatory readiness (see Figure 11).

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[61] https://nsc-community.eu/

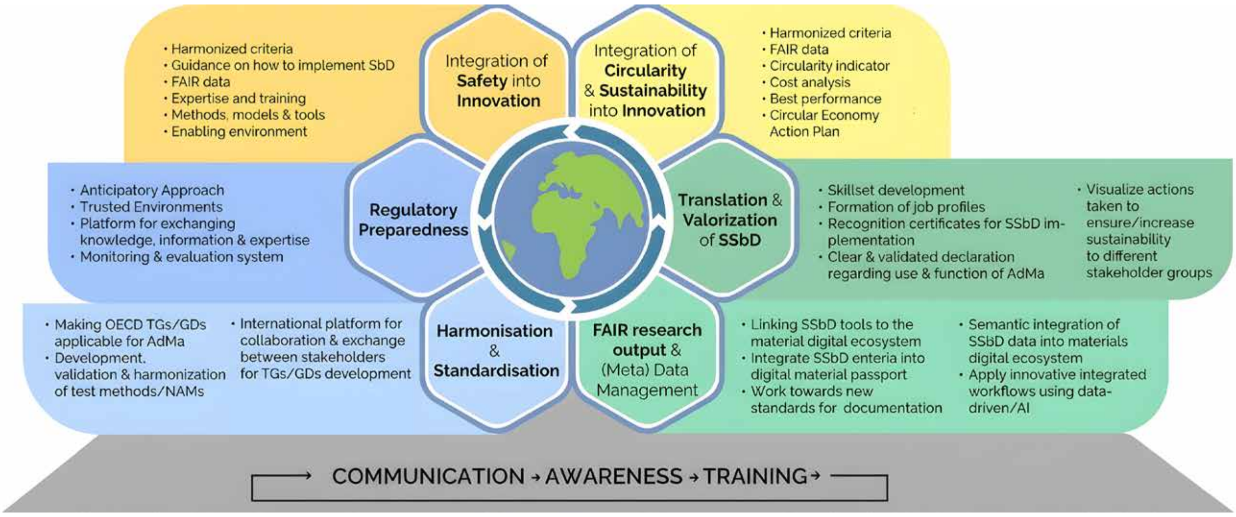

Figure 11. Overview of the actions needed in several areas of governance to ensure their safety and sustainability.
Source: Cassee et al. (2024). Licensed under CC BY-NC-ND 4.0. No changes made.

To overcome these challenges, Cassee et al. (2024) proposes a set of cross-cutting enablers that link scientific, industrial, and policy efforts:

1. The first is collaboration and infrastructure, calling for stronger EU-wide cooperation through the upcoming IAM4EU partnership[62] to align research and innovation with regulatory and industrial needs.
2. The second is the creation of a digital ecosystem based on interoperable and AI-ready data systems that enable predictive safety assessment and sustainability evaluations across the material life cycle.
3. The third enabler, regulatory alignment, stresses the need for continuous dialogue between researchers, innovators, and regulators to ensure that scientific progress translates into market- and policy-ready practices.
4. Finally, capacity building is highlighted as a cornerstone—encompassing targeted training, stakeholder awareness, and improved cross-sector governance (see Table 7).

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[62] https://www.iam-i.eu/our-work/

6.7. Regulatory measures for ensuring safe and sustainable by design advanced materials

To address advanced materials, EU regulators can choose to modify or build upon the existing chemical and product safety frameworks or create new instruments. Each of these suggested regulatory measures has strengths and weaknesses that must be considered before deciding in favour of one or the other.

One possibility is enacting a dedicated advanced materials regulation (AdMa Regulation) that specifically governs these materials (analogous to how the EU has sectoral laws for GMOs, medical devices, or AI). Having a dedicated AdMa Regulation might be the only way to ensure a comprehensive framework that is specifically tailored for advanced materials. Such a regulation might set clear requirements for safety, sustainability, and traceability of advanced materials across their life cycle, ensuring no gaps in oversight. A weakness of an AdMa Regulation might be that it could be difficult to define the scope of the regulation and develop clear legal definitions. A new law could also overlap with existing regulations (like REACH) or create duplication and administrative burden. Finally, developing a new regulation could be time-consuming and would require consensus on what materials are covered and how to evaluate their risks (Reihlen et al., 2019).

Another option is to rely on and adapt existing regulatory frameworks and non-legislative measures (strategy documents, guidance, etc.). This could be, for instance, to amend existing chemical legislation (REACH, CLP, etc.). For example, REACH and CLP could be revised or given new annexes as in the case of nanomaterials. Choosing such an approach would have the advantage of building on well-established mechanisms, infrastructure, and institutions to evaluate and control risks of substances, extending them to advanced materials (e.g., ECHA's processes for registration and risk assessment). This would provide a sense of efficiency and familiarity to stakeholders. Regulators, however, must be willing to expand the REACH substance definition or annexes to clarify that advanced materials (including multi-component or novel-form substances) are covered. Similarly, CLP could introduce new hazard categories or criteria if advanced materials present unique hazards. The EU has adopted new hazard classes under CLP (e.g., for endocrine disruptors in 2023) and updated REACH annexes for nanomaterials (in 2018) and this process provides a template for individual categories of advanced materials. Adjusting existing laws is generally faster than new legislation, but technical challenges arise in developing appropriate test methods and data requirements. For nanomaterials, this process has taken more than 20 years, so the effort needed should not be underestimated.

Finally, the EU has adopted a range of non-regulatory measures to promote responsible innovation of advanced materials including funding programmes, partnerships, and voluntary guidelines on, for instance, SSbD. These initiatives do not impose legal requirements on any stakeholders but can be used as ways to influence the advanced materials' innovative ecosystem. This approach includes organising structured dialogues, observatories, and international cooperation fora that aim to help frame the environment in which advanced materials policy is made. For instance, the structured industry dialogues in 2024 gathered stakeholder input for the advanced materials strategy (European

Commission, n.d.-a). The EU is also engaging internationally through the OECD and other bodies to share best practices on advanced materials governance (the OECD's expansion from nanomaterials to advanced materials safety is a direct result of EU and others' input) (OECD, n.d.). Such cooperation can lead to harmonised standards and avoid trade barriers down the line.

Independently of the measures chosen, a substantial effort should be made without delay to establish clear definitions or criteria for advanced materials for policy purposes. This will help avoid lengthy discussions related to risks and regulation that stalled nanomaterials regulation process between 2004-2011. In that spirit, a formal definition of advanced material—such as the one provided in Chapter 1—could help regulators identify which materials require special oversight or data and would enable specific provisions to be developed in sectorial laws. For instance, labelling requirements or reporting duties for advanced materials meeting the criteria.

There is a risk of having an overly broad definition that may capture too many substances, creating unnecessary regulation, while a narrow one might exclude future innovations. And there will also always be a risk that some advanced material "systems" (complex combinations or embedded materials) are not within the scope of any adopted definitions of advanced materials. The 2024 European Commission Communication on Advanced Materials for Industrial Leadership (European Commission, 2024b) uses broad descriptors but stops short of a strict definition. The process of learning about advanced materials through the formal adoption of a definition needs to be initiated.

6.8. Governance of advanced materials

In many ways, the current discussions about advanced materials mirror previous discussions about nanotechnology and materials (K. Grieger et al., 2025). This includes how advanced materials should be defined, what are the likely, unknown (and speculative) hazards and risks, how these hazards and risks might be tested, measured, and documented, and whether existing test methods are adequate.

Recognising the similarity of many of these issues and challenges could facilitate our collective effort in addressing them more swiftly than with nanotechnology and nanomaterials. Doing so will help ensure that the emerging governance structures for advanced materials evolve in ways that are both efficient and effective, while also building on Europe's existing leadership in responsible innovation and risk regulation.

Revisiting the original ideas and principles of risk governance is advisable as these were meant to ensure that risks are addressed in a systematic, transparent, and socially robust manner. These principles include a commitment to act before harm occurs, especially under conditions of uncertainty (prevention and precaution) on the one hand while ensuring that the response matches the seriousness of the risk (proportionality). It furthermore includes ensuring open sharing of information, acknowledging uncertainties, and openly discussing trade-offs, while avoiding hidden agendas or selective disclosure (transparency and communication). Effective risk governance is also not limited to experts or regulators and requires the involvement of multiple actors, including scientists, industry,

Table 7. Roadmap towards safe and sustainable advanced and innovative materials organised according to thematic area, key actions, responsible actors, and indicative timelines (2024–2030). Sources: Based on Cassee et al. (2024).

Thematic area	Key actions/recommendations	Main responsible actors	Indicative timeline
1. FAIR data and digitalisation	- Implement FAIR data principles. - Develop harmonised ontologies and metadata standards linking safety, sustainability, and materials data. - Integrate SSbD data into Digital Product Passports. - Create FAIR implementation network (AdvancedNano IN).	EU JRC, RIVM, OntoCommons, NanoCommons, PARC, Industry Commons, OECD Working Party on Manufactured Nanomaterials (WPMN)	2024–2027 (infrastructure build-up)
2. Integration of safety in innovation (SSbD)	- Harmonise SSbD criteria and tools across innovation stages. - Encourage regulatory acceptance of new approach methodologies. - Develop guidance on responsibilities and data needs per stage. - Train SMEs and contract research organisations (CRO) in SSbD application. - Create an enabling environment for next-generation safety assessment.	NanoSafety Cluster (NSC), RIVM, BAuA, Bundesinstitut für Risikobewertung (BfR), OECD, European Commission, CROs, industry	2024–2028
3. Integration of sustainability and circularity (SSbD)	- Develop harmonised SSbD sustainability criteria (environmental, social, economic). - Combine LCA, S-LCA, and life cycle costing. - Introduce SSbD label or certification scheme. - Embed circularity indicators (durability, recyclability). - Complement Product Environmental Footprint with biodiversity metrics.	JRC, Horizon Europe projects (SUNSHINE, PARC, IRISS), industry, ISO/CEN	2024–2029
4. Harmonisation and standardisation	- Update OECD Test Guidelines and ISO/CEN standards for advanced materials and 2D materials. - Establish EU steering group for prioritisation and validation. - Fund validation and harmonisation projects (beyond scientific R&I). - Coordinate efforts under the Malta Initiative.	OECD WPMN, CEN/TC 352, ISO/TC 229,NanoHarmony, Gov4Nano, EC Directorate-General for Research and Innovation (DG RTD)	2024–2030
5. Regulatory preparedness and governance	- Establish trusted environments (regulatory sandboxes). - Operationalise Early4AdMa anticipatory system[1]. - Develop open-access exchange platform for regulators and innovators. - Implement monitoring and evaluation systems for SSbD progress.	OECD WPMN, EU Member State authorities, EC DG ENV/DG GROW[2], NSC	2024–2028
6. Stakeholder engagement and governance	- Create multi-stakeholder SSbD governance hub (e.g., "SSbD House"). - Integrate social and ethical aspects (Step five of JRC framework). - Use Explainable AI (XAI) and Knowledge Readiness Levels. - Embed SSbD into corporate ESG strategies.	NSC, EC, industry associations, NGOs, academia	2025–2030
7. Translation and valorisation	- Bridge research–industry interface (testing, data, services). - Establish SSbD consultancy and "translator" roles. - Define clear SSbD compliance criteria. - Develop recognition certificates and product labels. - Support SSbD business models for SMEs.	Industry, NSC, BNN, IRISS, Horizon Europe partnerships, IAM4EU	2025–2030
8. Communication, awareness and training	- Embed SSbD and sustainability into university and vocational curricula. - Develop continuous professional training for SMEs and CROs. - Create a central communication hub (EU Nanosafety backbone). - Run public awareness campaigns on safe and sustainable innovation.	NSC, EU education networks, universities, NGOs, EC DG EAC	2024–2030
9. General research needs	- Study biological interactions and long-term effects. - Improve exposure and fate modelling for advanced materials. - Conduct LCA covering health and environmental dimensions. - Advance interdisciplinary collaboration. - Develop adaptive regulatory frameworks.	Academia, JRC, OECD, European Food Safety Authority (EFSA), ECHA, Horizon Europe projects	Ongoing (2024–2030)

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[1] Early4AdMa is the early screening frameworks developed within the OECD nanomaterials working group to flag potential safety or sustainability issues of new materials before they reach mass market.

[2] Directorate-General for Environment / Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, European Commission.

civil society, and the public, underlining the importance of connecting disciplines, sectors, and scales. Cross-sectorial and multi-national environmental, social, economic, and technical perspectives should be integrated to avoid fragmented or contradictory approaches (integration and coherence). Finally, decision-makers must be answerable to stakeholders, and governance structures should be designed to be transparent, fair, and credible (accountability and legitimacy) (IRGC, 2017, 2018; Klinke & Renn, 2002; OECD, 2010, 2016; Renn, 2008, 2015; Renn & Walker, 2008).

6.9. Key messages

- Determining policies and regulations for advanced materials is a messy and complex task due to how heterogenous advanced materials are. This is further complicated by regulators and consumers who solely focus on the composition and properties of individual materials. However, materials or their components have broader socio-economical aspects that remain poorly understood due to the lack of robust studies and evidence.
- Definitions are crucial in regulatory practices. Typically, creating definitions for specific policy and regulation is a long process requiring multi-stakeholder inputs to identify specifics of numerous parameters. Since advanced materials are very heterogenous and complex, it is challenging to create a definition encompassing all advanced materials for a regulatory purpose.
- The regulatory discussions about advanced materials mirror earlier debates on nanomaterials. Learning from these parallels—particularly lessons related to the lack of a clear definition, standard characterisation and test methods, and detection techniques—can accelerate progress and avoid past delays, ensuring that emerging governance structures for advanced materials evolve efficiently and effectively while building on Europe's leadership in responsible innovation and risk regulation.
- Regulatory approaches may involve new dedicated frameworks or adaptation of existing laws: options include enacting an advanced materials regulation or revising established frameworks like REACH and CLP. Non-legislative measures, such as voluntary guidelines and structured dialogues, also shape the innovation ecosystem.
- For selling and usage, materials are associated with information about their properties, including their performance and toxicity, whether they can be recycled, their sustainability, their legal regulation and its enforcement, etc. (Nielsen et al., 2023). In these circumstances, much of the politics and economics of materials revolves not around materials themselves, but in relation to the ways in which they have been 'packaged' and standardised, informationally and legally, and have come to figure in wider economies of recycling and waste (Fisher, 2008; Laurent, 2017, 2022).

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Chapter 7: Conclusions and policy options for European leadership in advanced materials

7.1. Conclusion

Advanced materials are designed to have new or enhanced properties resulting in specific or improved performance. Because of their targeted or enhanced features, advanced materials are ubiquitous in all industrial sectors. They help replace critical raw materials, reduce waste and pollution, and empower new industrial sectors and applications that benefit society. For these reasons, advanced materials are central to Europe's strategic autonomy and twin green and digital transition. The EU aims to develop an advanced materials strategy to support industrial transformation and competitiveness in sectors such as energy, construction, mobility, electronics, and health.

In this report, we think about advanced materials along these five axes: sustainability, emerging technologies, basic research, digitalisation and AI, and policy and governance. We evaluate how each of them relates to and impacts advanced materials and provide evidence on how advanced materials can improve efficiency and innovation in critical sectors, reduce pollution, and have minimal impact on health and the environment.

We emphasise the need for sustainability in all aspects of advanced materials design, development, manufacturing, and end-of-life disposal. Under this directive, there is a strong emphasis on reducing emissions and removing toxic components right from the beginning at the design step. A key focus is on circular economy principles that ensure the production and consumption of materials involve reusing, repairing, and recycling to extend product lifespan and reduce reliance on raw material sourcing. While this is always difficult to achieve, emerging bio-inspired and biodegradable materials as part of the circular economy can certainly help mitigate the ill effects on health and the environment. In addition, we showcase how incorporating holistic life cycle assessments is critical to achieve sustainability along social, economic, and environmental dimensions.

Innovation in advanced materials requires new technologies and robust infrastructure for their manufacturing and scaling up. In addition to summarising production technologies specific to critical sectors and their potential for transforming other sectors, we also emphasise the need for innovation ecosystems and networking across different sectors to manifest cross-fertilisation in manufacturing and scaling up.

We highlight that basic research is a cornerstone of innovation, providing numerous examples and case studies of exciting research avenues that will one day materialise into products solving challenges in energy, construction, mobility, electronics, and health sectors. While the report provides an extensive list of basic research directions that will yield new materials, it is important to note that determining when those discoveries will be ready for market use and what their short- and long-term impacts will be remains challenging to evaluate.

In each aspect of sustainability, manufacturing technologies, and basic research, we identify processes and ideas that can massively benefit from computational and data approaches. Leveraging AI and ML to design sustainable materials, automating manufacturing and production pipelines, and generating new basic research directions is a common theme we discuss throughout the report. However, digitalisation is not easy and systematic efforts to develop curated materials data libraries and synergistic alignment with the large industry networks within the EU for automation remain a challenge.

Lastly, we centre our discussion towards policy and regulatory practices. Even though Europe achieves new capabilities in advanced materials, it cannot maintain competitiveness without sound policies. We share how the regulatory landscape changed over time for nanomaterials—an important class of advanced materials—to highlight challenges associated with making new regulations for complex material classes.

7.2. Europe’s current landscape in advanced materials: Strengths and weaknesses

Before presenting ideas that may help policymakers take new steps towards achieving autonomy in advanced materials, Europe’s strengths and weaknesses are summarised.

7.2.1. Strengths

Europe possesses strategic strengths that it should leverage to build a resilient, low-carbon industrial base:

- **Research excellence**: European universities and research programmes produce high-quality, innovative research output, such as scientific publications and patents. In many areas of advanced materials, European researchers outcompete their peers in North America and Southeast Asia. In addition, robust funding mechanisms like the ERC and European Innovation Council (EIC) offer continued support to basic and applied research projects.
- **Research infrastructure**: Europe has world-class facilities for frontier research, characterisation, and pilot testing. Institutes such as CERN, European Synchrotron Radiation Facility (ESRF), European Molecular Biology Laboratory, Institut Laue–Langevin (ILL), European Spallation Source, European X-Ray Free-Electron Laser Facility (XFEL), ESFRI, JRC, EIT and many others attract researchers from all over the world for their unique and high-profile research infrastructure.

- **Databases and digital tools**: Europe boasts some of the most comprehensive and sophisticated databases on materials properties and predictive testing systems. This wealth of data enhances research capabilities, allowing scientists to conduct more accurate simulations, accelerate discovery, and develop innovative materials tailored to industrial needs, supported by AI and supercomputer tools.
- **Industrial ecosystem**: The EU has a strong industrial base in aerospace, automotive, energy, electronics, and healthcare sectors, supported by large producers such as Volkswagen, Mercedes-Benz, BMW, FIAT, Statkraft, BASF, ArcelorMittal, Solvay, and SMEs. In addition, Europe recently launched the **IAM-I**, a new non-profit association tasked with bringing together stakeholders across research, industry, and public sectors to accelerate innovation, reduce time-to-market for advanced materials, and strengthen Europe's strategic autonomy in materials R&D.
- **Policy frameworks**: Europe benefits from robust innovation framework programmes, such as Horizon Europe, EIT Raw Materials, and Important Projects of Common European Interest (IPCEI) programmes, along with national funding synergies. Moreover, it benefits from the establishment of innovation-driven PPP clusters. These frameworks facilitate the transition of research innovations into market-ready solutions.
- **Leadership in selected areas of sustainability**: Europe plays a pioneering role in circular economy, eco-design, responsible sourcing, and deployment of advanced process technologies.

Collectively, scientific excellence, cutting-edge infrastructure, comprehensive data resources, and well-established funding and collaboration frameworks provide a resilient foundation for pioneering research in materials science. This integrated ecosystem helps sustain Europe's leadership in selected critical domains of material research and ensures that Europe is at the forefront of technological advancement to address global challenges.

7.2.2. Weaknesses

Europe faces several structural challenges that hinder its ability to scale production quickly and stay competitive with global leaders, particularly China. To enhance industrial resilience and secure a competitive edge on the global stage, Europe can focus on removing these roadblocks:

- **Fragmented ecosystem**: Regional disparities among research and development ecosystems and insufficient cross-border coordination delay market adoption and hinder scale-up efforts.
- **Scaling challenges**: Translating pilot research projects into large-scale, high-volume manufacturing remains a challenge. Most ventures fail to cross the valley of death due to the lack of long-term funding specifically needed to move forward in scale-up and commercialisation.
- **Raw material dependency and geopolitical vulnerabilities**: Europe largely imports critical raw materials, mainly rare earths, lithium, cobalt, etc. and domestic mining and recycling capacities remain underdeveloped.
- **Need of central large-scale facilities to explore structure/kinetics/function interplay and automated labs:** There are several barriers that Europe must overcome to establish these kinds of

facilities and labs. These barriers come from the fragmentation of national strategies and funding models, and the lack of coordinated investment. This also creates insufficient access or significant obstacles for users to the existing facilities network in Europe.

- **Need for small-scale, high-quality devices:** The complexity in the composition of the advanced materials generates the need for developing new methodologies for their characterisation by adapting existing facilities or installing new components in the large-scale central characterisation facilities within Europe (e.g., ESRF and various other synchrotron, neutron and free electron ones), as well as in dedicated advanced local ones (e.g., the Ernst Ruska Centre in Juelich, Germany). A recent example is the low-dose beam line at BESSY 3 in Berlin for (electron) beam-sensitive samples. Such facilities require investment in high-risk research, but will keep Europe at the forefront of materials characterisation and constitute a magnet for attracting talent from outside Europe.
- **Infrastructure and skilled worker gaps**: There is a lack of dedicated platforms for rapid testing, validation, and industrialisation of emerging materials and ideas. In addition, there is a dearth of qualified engineers, materials scientists, and digital and manufacturing specialists. Specifically, a lack of skilled personnel in high-speed production technologies, such as in battery, solar cell, and wind turbine manufacturing, limits the EU's ability to scale production rapidly and remain competitive. There is also a shortage of blue-collar factory workers who are skilled in equipment manufacturing and running emerging gigafactories, slowing down Europe's adoption and industrialisation of advanced materials.
- **AI and robotics adoption**: There is a limited use of autonomous, AI-driven robotic labs in the advanced materials discovery process.
- **Policy gaps:** Europe's policy and regulatory landscape is complex and differs between member states and sectors. Differences in bureaucratic measures compared to the US and China may impact the EU's overall competitiveness.

The following two examples depict how different policy choices and institutional frameworks can change market realities in the EU:

- **Example 1**: PV panels production - A Horizon Europe PILATUS[63] project aimed at producing photovoltaics in Europe by using digitalised pilot lines for silicon heterojunction tunnel interdigitated back contact solar cells and modules. However, the project stalled due to the financial difficulties faced by the main industrial partner, Meyer Burger. Meyer Burger struggled to make production profitable despite higher efficiencies and lower environmental impact assessed by LCA because of cheap PV panels coming from Asia. In the end, the only company producing solar cells in Europe filed for bankruptcy (Reuters, 2025).
- **Example 2**: First-buyer effect - In the US and China, defence procurement serves as the first large-scale buyer of emerging technologies, providing a guaranteed demand market and accelerating scale-up. With massive investment from the defence budget in basic research, emerging advanced materials from the defence sector transform critical sectors, such as health, energy, construction,

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[63] https://pilatus-project.eu/

and others. Europe lacks this mechanism, which restricts its ability to rapidly industrialise materials innovation.

7.2.3. Strategic pathways and sector enablement

In terms of technological capabilities, Europe has excellent activities across several high-impact areas, such as composites—used extensively in aerospace, automotive, and construction to achieve high strength-to-weight ratios; metallurgy, involving lightweight alloys, especially aluminium and magnesium-based materials, which are critical to reducing the weight of vehicles and aircraft while maintaining safety standards; functional ceramics—such as piezoelectric, ferroelectric, and thermoelectric materials—driving innovations in sensors, energy harvesting, and healthcare applications. Moreover, Europe is strong in the development of nanomaterials, which enable breakthroughs in electronics, coatings, and medicine, as well as in eco-friendly materials designed to reduce environmental impact, promote recyclability, and support circular economy initiatives.

Europe's future economic resilience hinges on integrating advanced materials into critical sectors that can promote our prosperity. The following applications present a vision for autonomy in critical sectors through advanced materials Europe:

- **Energy**: Innovations that underpin the transition toward a sustainable, low-carbon energy economy, and industrial decarbonisation include: harnessing renewable sources, such as wind, solar, bioenergy, geothermal, ocean energy, and emerging fusion technologies; scaling up production of environmentally friendly high-efficiency photovoltaics, wind turbine composites, mechanoresponsive materials, and (nano)materials for energy storage; CO_2 capture and utilisation; targeting a reduction of greenhouse gas emissions; and materials to improve the efficiency of engines and reduce fuel consumption and CO_2 emission.
- **Construction**: Several technologies are at the forefront of tailoring material functionalities, reducing maintenance costs, and improving overall durability. These include the development of durable, eco-friendly, self-healing concrete; smart coatings; eco-designed windows with tunable properties; resource-efficient structures; hybrid ink-coating processes to significantly extend the lifespan of infrastructure elements and enhance their functional performance; steels with extreme tensile features combined with high ductility; innovations in corrosion repair techniques for offshore structures, such as kinetic spray methods; and cutting-edge nanotechnology and smart coatings, such as self-cleaning, hydrophobic, or anti-corrosion surfaces.
- **Mobility**: Important materials in aviation and engine systems include: recyclable alloys with high specific mechanical properties; bio-based polymer composites, to significantly reduce the weight of vehicles for terrestrial or aerospace applications; recyclable batteries, such as Na-ion and flow batteries; hydrogen-compatible components, including containment systems, adhesives, and seals; materials for advanced energy storage; corrosion-resistant coatings for magnesium and aluminium alloys vital for extending the service life of components subjected to harsh environments; high temperature alloys, thermal barrier coatings, advanced ceramics critical for high-temperature applications,.

- **Electronics**: To ensure the availability of sustainable, high-performance electronics that minimise waste and recycle the rare elements that are critical to communication and optical applications, the electronics sector should focus on: sustainable high-performance materials; next-generation semiconductors for AI, quantum computing, and radiation hardened components and devices, ultralow-power electronics, quantum computers, embedded sensors, transducers, and actuators for industrial automation; smart sensors for packaging and supply chain monitoring, integrated chip, and packaging solutions; printed sensors for environmental monitoring; oxide semiconductor technologies, such as metal oxide thin-film transistors with high switching frequencies (~5 GHz), low operating voltages (<1 V), and ultra-fast response times (<0.01 microseconds); radiation-hardened electronics for communications and positioning satellites; alternative materials for next-generation semiconductors, such as energy efficient knowledge-based defect control in high-purity silicon and emerging compound semiconductors.
- **Health**: Advanced materials that will revolutionise personalised medicine and improve patient outcomes include: biosynthetic, biodegradable, and biocompatible materials for diagnostics, implants, regenerative medicine, and targeted drug delivery; functional materials compatible with additive manufacturing; and biomaterials with integrated biological functionalities and smart surfaces capable of detecting infections or delivering targeted treatments.
- **Agriculture and environment**: Sustainable and fully recyclable sensors for soil, water, and climate; biodegradable polymers for resource-efficient farming, CO_2 storage, advanced filtration; and implementing climate-smart, farming practices will improve global food production and contribute to sustainable food security.

Overall, these integrated, cross-sectoral approaches to develop advanced materials for specific applications are vital for driving innovation in critical sectors. Further, these solutions create a sustainable, resilient, and technologically advanced future for Europe.

Box 6: An example of cross-fertilisation

The European Space Agency (ESA) represents a unique strategic enabler for cross-fertilisation across sectors. ESA has privileged access to space-related standards and has consistently supported advanced materials development across diverse projects. Because space technologies cut across multiple industrial domains, ESA provides a powerful platform for aligning standards, validating new materials in extreme environments, and diffusing innovations across industries. Leveraging ESA's role more systematically could strengthen Europe's autonomy while creating high-value case studies for materials deployment in critical sectors.

7.3. Evidence-based policy options

We finally finish this report by providing a range of options that will allow policymakers to move forward towards EU's autonomy and resilience in advanced materials. These evidence-based policy options cover important research areas and critical sectors.

7.3.1. Policy options related to sustainability

- **Policy option one: Create a long-term vision for raw material resilience and circularity.**

What: A coherent strategy combining sustainable domestic mining, expanded recycling/refinery capacity, and harmonised standards for recycled materials.

Why: Reduce geopolitical and supply-chain risks, build secondary raw-material markets, and address low public acceptance and limited capacity/standards.

How: Set long-term targets and roadmaps; invest in recycling/refinery capacity and R&D; harmonise recycled-content and quality standards; promote transparent mass-media public engagement.

Advantages and disadvantages/risks:

- Advantages: greater supply resilience; new jobs and value chains; stronger secondary markets.
- Disadvantages/risks: public opposition to mining; environmental/social harms if safeguards fail; high costs.

Impact: Improved material security and circular markets, lower life cycle impacts, and potential public trust.

- **Policy option two: Prioritise holistic sustainability assessments, including S-LCA, -LCA, LCC, and multicriteria LCA for all advanced material innovations, ensuring integration across environmental, economic, and social axes throughout the product life cycle.**

What: Holistic sustainability assessment.

Why: Some types of impact (e.g., on local communities) are often neglected in standard approaches.

How: Integrating environmental, economic, and social impact assessments.

Advantages and disadvantages/risks:

- Advantages: avoid externalities and unwanted negative impacts.
- Disadvantages/risks: possible need for new standards may delay the process.

Impact: Harmonisation of policies and creation of awareness in holistic assessment among policy makers; cross-sectoral collaborations (STEM – Science, technology, engineering, and mathematics, economics, social sciences).

- **Policy option three: Promote and regulate regional circular strategies, and secondary raw material recovery through legislative frameworks such as Critical Raw Materials Act and Product Environmental Footprint methods.**

What: Incentives for local commodity sourcing and circular strategies.

Why: Primary sourcing of raw materials is strongly dependent on non-EU imports.

How: Creating incentives for circular strategies.

Advantages and disadvantages/risks:

- Advantages: waste reduction; possible reduction of embodied CO_2 and energy; reduced impact on the environment and local communities (e.g., by minimising landfilling).
- Disadvantages/risks: need for policy harmonisation in different regional contexts.

Impact: Minimising the risk of supply chain disruption; capacity building in circular strategies.

- **Policy option four: Foster industrial symbiosis and cross-sector material flow by supporting innovation infrastructure, symbiosis readiness assessments, and digital marketplaces.**

What: Optimising waste and by-product management.

Why: Specific industrial sectors may need significant investment for waste management.

How: Implementing cross-sectoral material flow networks.

Advantages and disadvantages/risks:

- Advantages: resources allocated to waste management can be reinvested.
- Disadvantages/risks: resistance to innovation (e.g., need for modifying established industrial processes).

Impact: Reduction of costs associated with waste management and import of raw materials; cross-sectoral knowledge sharing and collaboration.

- **Policy option five: Mandate third-party verified LCA/EPDs for environmental performance claims, as per the Green Claims Directive, to combat greenwashing.**

What: Any entity claiming to meet environmental, social, and economic requirements needs impartial LCA and EPDs.

Why: Avoid greenwashing.

How: Environmental, social, and economic assessment performed by third-party actors.

Advantages and disadvantages/risks:

- Advantages: impartial assessment; standardisation of impact assessment methods.
- Disadvantages/risks: needs significant economic investment; possible conflicts of interest.

Impact: Increased public trust, specifically in relation to social and environmental impact.

■ Policy option six: Strengthen incentives for research, prototyping, and adoption of new recycling and upcycling technologies.

What: Fostering basic and applied research into sustainable advanced materials and adoption of recycling and upcycling technologies.

Why: Recycling requires new research to understand material properties and technologies to recycle them properly.

How: Dedicated calls for funding to facilitate access.

Advantages and disadvantages/risks:

- Advantages: drivers for EU leadership into sustainable advanced materials.
- Disadvantages/risks: impact on member states' budgets.

Impact: Creation of research networks into sustainable advanced materials; enhanced industry-academia collaboration.

■ Policy option seven: Supporting higher education programmes and curricula into circularity and advanced materials.

What: Renewing and modernising the educational offering available in European higher education institutions.

Why: Increasing EU competitiveness in advanced materials and circularity.

How: Funding the setup of dual/double degrees and university networks at EU level.

Advantages and disadvantages/risks:

- Advantages: specific and effective training in comparison with the current educational landscape.
- Disadvantages/risks: bureaucratic barriers and fragmented regulations at the level of individual member states.

Impact: Training a new generation of graduated students and researchers; increased EU competitiveness.

- **Policy option eight: Facilitate rapid scale-up of successful circular pilots into broad industrial applications through collaborative platforms and public-private partnerships.**

What: Implementation of new circular solutions at the industrial scale.

Why: Addressing the gap between academic research and the market ("Valley of Death").

How: Creative incentives for collaboration and promoting entrepreneurship.

Advantages and disadvantages/risks:

- Advantages: improved technological transfer and increased public trust.
- Disadvantages/risks: needs significant investment in scale-up infrastructures.

Impact: Research funding efficiency; enhanced academia-industry collaboration; job creation.

- **Policy option nine: Develop Digital Product Passports (DPPs) and AI-driven solutions for traceability, disassembly, efficient recycling, and matching secondary raw materials to high-value applications.**

What: Improve resource efficiency and end-of-life management.

Why: Inefficiency in the management of end-of-life products.

How: Improving design, traceability, and reuse/recycling.

Advantages and disadvantages/risks:

- Advantages: improved transparency and compliance with regulations; waste reduction; possible reduction of embodied CO_2 and energy.
- Disadvantages/risks: possible need for new standards may delay the process; significant investment in AI infrastructures needed.

Impact: Reducing the dependency on (imported) virgin raw materials; optimisation of material flows; capacity building in AI.

- **Policy option ten: Promote sustainable reconstruction.**

What: Urban and infrastructural reconstruction, environmental remediation.

Why: Destruction of building and civil infrastructures; environmental contamination and soil degradation by heavy metals and fuel residues.

How: Sustainable construction based on low-CO_2 materials; soil amendment and restoration of fertility, e.g., by biodegradable nano-carriers of nutrients.

Advantages and disadvantages/risks:

- Advantages: reduced environmental impact associated with construction
- Disadvantages/risks: possible higher costs compared to conventional approaches

Impact: Sustainable communities; job creation; capacity building.

- **Policy option 11: Expand the availability of high-quality, updated open-access sustainability databases to lower barriers for evidence-based decision-making and transparent environmental communication.**

What: High-quality, open-access databases for sustainable advanced materials.

Why: Lack of open-access databases for impact assessment input.

How: Set up working groups at EU level for sustainability data mining and database creation.

Advantages and disadvantages/risks:

- Advantages: facilitating multi-criteria impact assessment and policies based on quantitative criteria.
- Disadvantages/risks: intellectual property issues; industry reluctance to share sensitive data.

Impact: Knowledge sharing; capacity building in impact assessment.

7.3.2. Policy options related to manufacturing, scaling, and infrastructure

- **Policy option 12: Set up and fund local innovation spaces to test advanced materials and manufacturing methods, especially for SMEs and startups.**

What: Create safe and flexible spaces where companies, researchers, and universities can try out new materials and production techniques, without worrying about regulations right away.

Why: Help move ideas from laboratories to the real world, make it easier to get certified, and allow teams test their innovations in practical, everyday conditions.

How: Use public and European funding (like Horizon Europe or IPCEI), share equipment and facilities, and get regulators involved early, so they understand the tech from the start.

Advantages and disadvantages/risks:

- Advantages: encourages collaborative innovation and reduces investment risk.

- Disadvantages/risks: requires inter-institutional coordination and financial sustainability and the risk of fragmentation if not harmonised at the European level.

Impact:

- Short term: rapid validation of technologies.
- Medium term: acceleration of commercialisation.
- Long term: robust regional innovation ecosystems.

■ Policy option 13: Build flexible infrastructure and regional hubs to help scale-up.

What: Shared, modular regional hubs with pilot lines, open-access equipment, and digital tools where companies, especially SMEs, can test, validate, and scale production processes.

Why: Many innovations stall in the lab for lack of funding, equipment, and real-world scale-up facilities; hubs bridge research and manufacturing and lower barriers to commercialisation.

How: Use EU, national and public–private co-investment (under IPCEI-style or EIC-blended funding models) for long-term operational and capital support; create modular, interoperable facilities and connect RTOs, academies, and industry, providing access terms tailored to SMEs.

Advantages and disadvantages/risks:

- Advantages: reduce entry costs for new players and promote interoperability and cross-learning.
- Disadvantages/risks: requires significant investment and risk of duplication if not coordinated at European level.

Impact:

- Short term: improved pilot testing capacity.
- Medium term: efficient process scaling.
- Long term: European advanced manufacturing network.

■ Policy option 14: Incentivise circular material design through funding schemes that prioritise microstructure-driven alloy development and the use of e-waste and scrap materials.

What: Support the design of circular materials, especially sustainable microstructure-based alloys, and waste recycling.

Why: Reduces dependence on critical raw materials and improves life cycle sustainability.

How: Targeted grants, tax credits, integration into circular economy and sustainable metallurgy programmes.

Advantages and disadvantages/risks:

- Advantages: promote sustainability and resilience and reduce environmental impact.
- Disadvantages/risks: requires new design and certification methodologies and possible industrial resistance due to initial costs.

Impact:

- Short term: recycling pilot projects.
- Medium term: new sustainable alloys.
- Long term: significant reduction in industrial waste.

■ Policy option 15: Strengthen collaboration between universities and industry by supporting tech transfer offices, research centres, and innovation clusters.

What: Strengthen knowledge and technology transfer structures through performance-based funding.

Why: Improve the connection between basic research and industrial application, accelerating innovation. Competitive funding serves as a fundamental piece in supporting innovation hubs and public-private partnerships to accelerate commercialisation.

How:

- Competitive funding linked to transfer indicators (patents, spin-offs, licences).
- Support for regional clusters.
- Support the integration of SMEs and startups for a dynamic innovation chain to boost Europe towards a consolidated prosperity programme grounded in advanced materials.
- Encourage SMEs to integrate into technical platforms and become members of public–private partnerships as an optional action, benefitting from simplified regulatory measures for these types of engagements, enabling, and facilitating faster market entry and scale-up.

Advantages and disadvantages/risks:

- Advantages: increases the efficiency of the innovation ecosystem and encourages impact orientation.
- Disadvantages/risks: risk of prioritising quick results over in-depth research and need for clear and comparable metrics.

Impact:

- Short term: increased number of collaborations.
- Medium term: effective technology transfer.
- Long term: more competitive European ecosystem.

■ Policy option 16: Speed up certification and regulation by involving regulators early and aligning standards across EU member states.

What: Facilitate market entry for innovative materials by speeding up certification and regulation processes.

Why: This avoids delays and helps companies bring innovations to market faster.

How: Create pilot programmes with regulators, develop shared standards, and coordinate with EU agencies.

Advantages and disadvantages/risks:

- Advantages: reduces regulatory uncertainty and accelerates industrial adoption.
- Disadvantages/risks: requires political will and intergovernmental coordination and risk of regulatory overload if not simplified.

Impact:

- Short term: more agile certification.
- Medium term: greater market confidence.
- Long term: consistent European regulatory framework.

■ Policy option 17: Launch PCPs to reduce the risk associated with emerging technologies and create early market opportunities for sustainable materials.

What: Use public procurement to create early demand for sustainable materials and reduce technological risks.

Why: It activates the market, validates technologies, and supports innovators in the early stages.

How: PCP calls at national and European level, SSbD criteria, collaboration with local administrations.

Advantages and disadvantages/risks:

- Advantages: stimulates demand and investment and reduces the technological 'valley of death'.
- Disadvantages/risks: requires inter-administrative coordination and risk of low adoption if not well communicated.

Impact:

- Short term: validation of emerging technologies.

- Medium term: creation of initial markets.
- Long term: consolidation of sustainable value chains.

Policy option 18: Create pathways to integrate product and material development in parallel, as markets demand products, not materials alone.

What: Co-located ecosystems and pathways that align material R&D with product development so engineers, customers and investors advance together (addressing TRL, but also customer readiness (CRL) and investment readiness (IRL)).

Why: Markets buy products, not raw materials. Misaligned development (high TRL but low CRL/IRL) blocks scale-up; cost-driven design choices (e.g., Hungarian company Zoltek successfully made carbon fibre affordable for wider industrial adoption by involving cost-driven design decisions in parallel with material development).

How: Establish technological parks and innovation ecosystems where material developers, product designers and manufacturers co-locate. In such environments, startups, SMEs, and large firms are embedded in an innovation community that enables rapid prototyping, validation, and market deployment.

Advantages and disadvantages/risks:

- Advantages: faster route to market; improved product-market fit; higher investor confidence; reduce wasted R&D.
- Disadvantages/risks: needs coordinated funding and governance; relies on effective industry participation.

Impact: Shorter commercialisation cycles, higher market uptake of advanced materials, and stronger investor-driven scale-up.

7.3.3. Policy options related to basic research

Policy option 19: Support interdisciplinary research and innovation programmes that integrate materials science, biotechnology, AI, and engineering.

What: Support interdisciplinary R&D programmes to accelerate materials development.

Why: Funding support for basic research and interdisciplinary approaches is essential to develop new advanced materials.

How: Specific calls in Horizon Europe, incentives for interdisciplinary consortia, integration of biofoundries and autonomous laboratories.

Advantages and disadvantages/risks:

- Advantages: accelerate innovation and promote technological convergence.
- Disadvantages/risks: requires specialised training and coordination between disciplines and risk of duplication of effort if not managed well.

Impact:

- Short term: new functional prototypes.
- Medium term: predictive design platforms.
- Long term: innovation ecosystem based on AI and synthetic biology.

■ Policy option 20: Focus on training skilled researchers in interdisciplinary research areas.

What: Education and training programmes that build interdisciplinary expertise in advanced manufacturing, process engineering and digital technologies, tailored to material science, scale-up, and industry needs.

Why: Europe lacks sufficient local graduates and attracted talent with the combined technical, digital and cross-disciplinary skills required for advanced materials and related industries.

How:

- Reform curricula to shift focus to interdisciplinary knowledge and digital skills.
- Increase awareness of career opportunities in advanced materials to attract and retain talent in Europe, particularly in knowledge-intensive industries and SMEs.
- Cross-border collaborations and EU-wide coordination, especially in science and education, through EU programmes such as Erasmus+, the Chips Act, Advanced Materials Academy, and industry partnerships, which will soon include the forthcoming Advanced Materials Act.

Advantages and disadvantages/risks:

- Advantages: larger pipeline of job-ready technologists; fill industry needs for technologists and talents in the advanced materials-dependent areas.
- Disadvantages/risks: requires sustained funding and coordination; risk of unequal access across regions; potential brain drain if industry opportunities are insufficient.

Impact: Increased workforce capacity for advanced materials and manufacturing; improved regional growth and long-term competitiveness; prosperous and coherent progress towards welfare and comfort, particularly for European citizens.

- **Policy option 21: Ethical and economic aspects should be included in the policy briefs and regulatory frameworks, including new functionalities or components. Thus, we can ensure that policy decisions promote responsible innovation while maximising societal benefits.**

What: Promote a framework to integrate advanced materials with new functionalities or/and new components, in products, considering SSbD approaches for their creation, together with ethical and cost analysis.

Why: This will enable introducing new advanced materials into the market with a 360-degree vision, reducing the risk of rejection from industry (due to the cost) and society (due to ethical aspects).

How: Funding opportunities to make a deep cost analysis by introducing these new advanced materials into the product; generating FAIR data related to the physicochemical properties of the new components, and new functionality that affects the final product (applicability, sustainability, reducing in the toxicity, cost, etc).

Advantages and disadvantages/risks:

- Advantages: reduce the initial costs for new players and increase the social acceptance.
- Disadvantages/risks: it will require a significant investment to generate the FAIR data and platform where the new players can consult these datasets.

Impact:

- Short term: improving in investment and funding opportunities.
- Medium term: generation of FAIR datasets with experimental data and simulation.
- Long term: AI-assisted platform to understand the impact of the integration of new functionality and/or components in the advanced material, and subsequently the new product considering cost-effectiveness and social acceptance.

7.3.4. Policy options related to digitalisation, data, and AI

- **Policy option 22: Encourage and eventually enforce FAIR data practices, where all data in materials science—including negative results, input files, codes—from academic research groups are freely shared.**

What: Creation of FAIR databases for materials science data.

Why: For the training of AI/ML models for various purposes (from data exploration on “similar” data to active workflows for materials design). AI/ML needs data points recording bad performance, so it is vital that data from “failed” experiments and calculations are also made available.

How: Create incentives (e.g., mechanisms to cite data not related to peer-reviewed publications) and eventually (when the annotation of the data is mature, see next policy option) made it a compulsory practice for funding.

Advantages and disadvantages/risks:

- Advantages: reduce the repetition of same research, boost research by finding new interpretation in old or otherwise discarded data.
- No foreseeable disadvantages.

Impact:

- Short term: possibility to develop more accurate AI/ML models.
- Medium term: possibility to test research hypothesis "on the fly".
- Long term: reshape how research is done, as only the "necessary" new data will be produced (i.e., faster and more energy/cost-efficient research).

■ Policy option 23: Promote and fund the creation of consortia that develop metadata schemas, taxonomies, and ontologies that truly allow for the sharing of accuracy assessments.

What: Annotation of data that ensures interoperability and reusability.

Why: To support AI/ML modelling, data need to be properly annotated, possibly at several levels of semantic expressiveness. In particular, proper annotation enables replicability and reproducibility.

How: Funding consortia that develop annotation schemas (metadata, taxonomies, ontologies), in conjunction with existing databases, where the community can contribute. In the funding of annotation schema development should be paired with existing (and further developed) databases, where the funded consortia can demonstrate the reusability of the data.

Advantages and disadvantages/risks:

- Advantages: boost research by providing findability/accessibility to data that can be understood and re-used by the community, including (but not limited to) AI/ML training.
- Disadvantages/risks: none if the policy is successful, unless considering risk of possible dual (mis) usage.

Impact: This is inherently a medium-/long-term policy. In the short term, there is little benefit as the annotations schema will not be paired to enough data to harvest benefits. In the medium and long term, the impact is huge, essentially a gamechanger.

Policy option 24: Promote the development of codes for materials simulations, both in including advanced modelling techniques and improving the codes' scalability towards (and beyond) the exascale.

What: Promote the further development of the well-established simulation codes, where Europe is an undisputed leader.

Why: Europe is an undisputed leader in well-established simulation codes and simulation codes in materials science are one of the most valuable sources of high-quality data. They can provide the basis for designing and discovering new materials, avoiding a possibly expensive synthesis and experimental characterisation, when not necessary.

How: Funding could be allocated to the maintenance and advancement of existing codes, while simultaneously supporting the development of new codes, particularly those incorporating advanced, state-of-the-art modelling techniques. Emphasis could be placed on extreme parallelisation and optimising the balance between energy consumption and accuracy.

Advantages and disadvantages/risks:

- Advantages: possibility of avoiding expensive (money and energy) synthesis and characterisation and allowing mostly in-silico development of materials.
- Disadvantages/risks: large scale calculations are also energetically expensive; hence codes and usage of workflows could be developed to minimise the energy cost for the necessary accuracy.

Impact: short, medium, long-term reduction of time and energy consumption for materials development.

Policy option 25: Fund the development of end-to-end robotic labs for the discovery and design of novel materials, with a particular focus on energy-efficient implementations.

What: Fund research developing AI/ML tools to implement fully automatised design/discovery workflows, including AI/ML modelling, computational modelling, and synthesis/characterisation.

Why: Shortening time and reducing wastes in materials design/development.

How: Funding the development and implementation of automatised/self-driven workflows. The effort is both in the AI/ML development (necessity of reliable uncertainty quantification. Etc.) and the implementation (interfacing various models and hardware).

Advantages and disadvantages/risks:

- Advantages: a gamechanger—humans are needed only for crucial decisions.

- Disadvantages/risks: biased models can lead to overlooking possible solutions and would be difficult to inspect complex AI/ML workflow.

Impact: shortening the time and reducing energy consumption for materials development and design.

7.3.5. Policy options related to policy and governance

- **Policy option 26: Establish a dedicated coordination mechanism for advanced materials within the European Commission.**

What: A dedicated coordination mechanism and unit for advanced materials could be embedded within the European Commission to ensure coherent governance and science-based foresight across its Directorates-General.

Why: The diversity and complexity of advanced materials require a permanent policy and analytical unit with a flexible coordination mechanism that links research, regulation, and innovation communities, providing independent assessments and anticipatory policy advice on emerging material technologies. Furthermore, coordination of research and regulatory activities is key to ensure SSbD advanced materials.

How:

- Create or designate an EU Coordination Office for Advanced Materials to align research, regulation, and industrial policy.
- Ensure this body acts as a hub connecting the Commission, Member States, agencies (ECHA, EFSA, JRC), and stakeholders, and embeds SSbD principles across initiatives.
- Evaluate the suitability of existing OECD and ISO test guidelines for advanced materials (e.g., 2D materials, self-assembling, or hybrid systems).
- Fund the development of new SSbD-aligned methods for physicochemical characterisation, environmental fate, and toxicity testing.
- Promote international harmonisation and shared reference materials to support regulatory consistency.

Advantages and disadvantages/risks:

- Advantages: improved coordination by and within the EU Commission; policy coherence between regulatory developed under REACH, CLP and/sectorial legislation and research and innovation funding activities; single hub that can reduce fragmented efforts across Member States, level playing field and reduce regulatory uncertainty for innovators and industry; streamlined SSbD support and international leadership within governance of advanced materials.
- Disadvantages/risks: bureaucratic inertia and creating what could potentially be additional institutional layers of governance; overlap with existing regulatory bodies (e.g., ECHA, EFSA and

JRC) that could create confusion about risk assessments, test development and standardisation responsibilities; concerns about increased regulatory oversight that might be perceived by some stakeholders as overregulation and potentially prolonging innovation-to-market timelines; lack of involvement of Member States and loss of ownership of the challenges related to advanced materials; resource demands with regard to funding and staff that requires long-term political commitment.

Impact: Streamlined EU governance, reduced fragmentation; improved test methods and standardisation; boosted responsible innovation and EU competitiveness and greater public trust, lower environmental risk.

■ Policy option 27: Systematically assess and strengthen existing governance frameworks.

What: Complete periodical evaluations of existing governance frameworks and address identified weaknesses. These should be performed by European Commission staff every four years and supplemented with independent analysis.

Why: Only by assessing existing governance frameworks periodically, can it be ensured that these are up to date when it comes to addressing the rapid development of advanced materials.

How:

- Review whether current EU legislation (e.g., REACH, CLP, product safety, waste) adequately covers advanced materials and their specific properties.
- Identify and explore regulatory gaps, particularly around materials that do not fit existing substance or product definitions.
- Where needed, update provisions to ensure early integration of SSbD criteria in design, testing, and commercialisation stages.

Advantages and disadvantages/risks:

- Advantages: leverages existing DGs, agencies, and legal frameworks whereby avoiding bureaucratic expansion and duplication; fewer resources needed to implement periodic reviews compared to standing up a new coordination unit as in option one; does not require new mandates or institutional negotiations within the European Commission and thus easier to adopt; periodical assessments allow the Commission to respond to emerging risks or innovations in a timely, evidence-based way; embeds adaptive governance through routine feedback loops between science, policy, and regulation; fits into the EU's existing "evaluate first" approach (REFIT, Fitness Checks), ensuring consistency with broader governance norms; evaluations directly feed into updating REACH, CLP, and product-specific laws, ensuring stronger regulatory fit for advanced materials; enables systematic mapping of areas where novel materials fall outside current legal definitions or risk assessment frameworks.

- Disadvantages/risks: periodical reviews risk lagging behind rapid developments in advanced materials; early detection of risks or opportunities may be delayed compared to option one; lack of insurance of cross-sectoral coherence between research, innovation, and regulation; uptake of review results into legislative reform will depend on Commission priorities and political cycles; multiple parallel reviews could lead to duplication or inconsistent conclusions and potential redundancy without a central mechanism; each review cycle could restart analytical work, leading to inefficiency and slower learning and loss of institutional memory.

Impact: Reactive, incremental improvement focused on evaluation and adaptation of existing laws targeting improvements to REACH, CLP, and product regulations (e.g., definition, test requirements and enforcement); stability and reduced uncertainty about major institutional changes that encourages SSbD integration early in the innovation processes, but potentially also slower innovation feedback; improves alignment between legislation and real-world risks that might fail to prevent emerging issues in time; transparent, periodical reviews enhance accountability although regulatory action could be perceived as having been implement too late if new material risks materialise.

■ Policy option 28: Ensure that environmental, health, and safety (EHS) and SSbD-relevant data are generated and adequately funded.

What: It must be ensured that EHS and SSbD-relevant data are generated, and the research activities are initiated and adequately funded**.**

Why: Without the generation of EHS and SSbD-relevant data, we will not be able to know the risks of advanced materials and obtain advanced materials that can be documented to be SSbD. If knowledge gaps are not addressed, these will otherwise continue to persist endlessly.

How:

- Support independent small, medium, and large research projects with EHS of all/several categories of advanced materials, similar to the work that has been performed with the NanoSafetyCluster.
- Mandate generation of high-quality EHS data for advanced materials as a condition of EU or national research funding.
- Require all EU-funded R&I projects on advanced materials to include a SSbD work package addressing hazard, exposure, and circularity.
- Support open and interoperable databases following FAIR data principles, enabling regulators and innovators to access and reuse SSbD-related information.

Advantages and disadvantages/risks:

- Advantages: ensures the formation of a solid EHS evidence base that supports integration of SSbD; FAIR data sharing; reduces scientific EHS uncertainty; fosters responsible research and innovation within advanced materials; helps build public trust; and generates EHS information that can be used to prevent harm.

- Disadvantages/risks: high EHS research funding needs; slow generation of results that are regulatorily useful; risk of fragmented or inconsistent data; increased cost and complexity for projects; balancing openness with IP protection.

Impact: Better regulatory preparedness and SSbD implementation; improved testing methods and international harmonisation; strengthened competitiveness and data-driven innovation; reduced EHS risks.

■ Policy option 29: Monitoring production and commercialisation.

What: Monitor the development in production volumes and commercialisation including information about what, how and why advanced materials are used in production and consumer products as well as number of sold units, concentrations, duration of use, etc.

Why: Information about the current and future production and applications of advanced materials is required to complete human and environmental exposure assessments, which again is a prerequisite for risk assessment.

How:

- Develop traceable registries or reporting mechanisms for advanced materials entering the market, capturing production volumes, uses, and applications.
- Link monitoring data with exposure models and life cycle assessment to support risk and sustainability assessments.
- Encourage post-market surveillance and feedback loops to ensure continuous learning and adaptation of SSbD criteria.

Advantages and disadvantages/risks:

- Advantages: ensures that data needed for realistic human and environmental exposure assessments are generated for advanced materials; provides the European Commission with the quantitative data needed to link material properties of advanced materials and uses to exposure pathways; insight of where and how materials are used informs SSbD assessments, implementation of risk management and preventive measures, end-of-life management, and waste policy alignment; monitoring data can feed directly into risk prioritisation, classification updates, and the refinement of SSbD criteria across different advanced material categories; registries and reporting mechanisms enhance visibility of material flows through supply chains, enabling accountability and due diligence; enables timely identification of high-priority material groups for regulatory action or research investment; detects trends in commercialisation of emerging materials before potential risks escalate and thereby supports anticipatory risk governance; and data on use patterns and product concentrations can inform consumer safety initiatives and labelling efforts.

- Disadvantages/risks: monitoring diverse materials, products, and use contexts of advanced materials requires extensive coordination between the European Commission, industry, etc.; duplication with existing databases (e.g., REACH registration, SCIP, or product registries); SMEs may find reporting obligations burdensome and might need technical support when reporting on data that might be proprietary; industry might find disclosure of production volumes or use patterns unacceptable for competitive reasons; monitoring data may be incomplete or non-comparable across Member States without standardised formats that again, might take a long time to develop and harmonise; ensuring the accuracy and reliability of self-reported data requires enforcement capacity and auditing mechanisms; new digital infrastructure and expertise will have to be in place to establish traceable registries and linking them to exposure models and SSbD information requirements.

Impact: Empirical market data improves accuracy of exposure modelling for advanced materials; more robust exposure and SSbD assessments will provide the foundation for targeted and proportionate regulatory responses; strengthens the European Commission's ability to monitor market dynamics, ensuring that regulatory frameworks keep pace with innovation; data integration across REACH, CLP, waste, and product safety frameworks enhances coherence and transparency; creation of databases linking production, use, and exposure information; compliance costs could be significant for producers; transparency about where and how advanced materials are used can foster public confidence and acceptance.

Policy option 30: Ensure adequate and relevant test methods and analytical tools and risk assessment frameworks for advanced materials.

What: Develop, validate, and update test methods and analytical tools and risk assessment frameworks.

Why: Without adequate and relevant test methods and analytical tools, it is not possible to assess the hazards of advanced materials, which is a prerequisite for risk assessment. The usefulness of existing risk assessment framework is questionable when it comes to advanced materials, and these might have to be revised and adapted

How:

- Evaluate the suitability of existing OECD and ISO test guidelines for advanced materials (e.g., 2D materials, self-assembling, or hybrid systems).
- Fund the development of new SSbD-aligned methods for physicochemical characterisation, environmental fate, and toxicity testing.
- Promote international harmonisation and shared reference materials to support regulatory consistency.

- Review and revise traditional risk assessment frameworks to reflect SSbD's preventive and life-cycle-based approach, considering functionality, safety, and sustainability together.
- Ensure coherence between chemical, environmental, and product safety assessments when it comes to risk assessment of advanced materials.
- Adopt flexible tools such as grouping and read-across approaches, integrated approaches to testing and assessment (IATA), and life-cycle sustainability assessment (LCSA).

Advantages and disadvantages/risks:

- Advantages: tailored methods that capture the unique physicochemical, biological, and functional properties of advanced materials that traditional tests may overlook; harmonised and validated test methods (OECD, ISO) enable comparability across studies, sectors, and jurisdictions reduce duplicate testing, saving time and resources across regulatory systems; ensures risk assessments reflect the real behaviour of advanced materials; evaluation of SSbD early in the innovation process through the embedding of SSbD principles in testing; better hazard and sustainability data help avoid replacing one risky material with another poorly understood alternative; active EU participation in OECD and ISO method development positions Europe as a global leader in responsible materials governance; integration of computational and grouping approaches (IATA, read-across) reduces testing costs and supports ethical, animal-free science.
- Disadvantages/risks: it can take many years and significant funding to develop, validate, and gain international acceptance for new methods; collaboration across regulatory agencies, standardisation bodies, and scientific communities required; updating legal frameworks (e.g., REACH annexes) can take significant time and effort even when new methods are validated; some advanced materials (e.g., advanced polymers, adaptive, self-assembling, or multifunctional ones) may challenge existing testing paradigms; harmonising analytical techniques across laboratories remains difficult, especially for novel or hybrid materials; combining life-cycle, exposure, and hazard data into coherent SSbD-aligned assessments requires new conceptual and computational models; method development is a long-term commitment with benefits that may only emerge after a decade or more.

Impacts: The European Commission will be able to make decisions based on robust, validated, and material-specific evidence; alignment across chemical, product, and environmental regulation will be ensured and handling of advanced materials will be consistent; embedding SSbD principles into testing frameworks makes sustainable innovation the default expectation rather than an exception; strengthened linkages between risk and sustainability assessment foster integrated, system-level evaluations; use of computational and mechanistic approaches (QSARs, IATA) that reduce testing time and animal use; clear, standardised test methods help innovators anticipate regulatory requirements and streamline product development; EU-based companies benefit from global recognition of harmonised testing data; development and compliance with new methods may temporarily raise costs for testing; better testing methods and frameworks enhance early detection of hazards, reducing environmental and health impacts; and finally, transparent, science-based assessment frameworks will increase public confidence in advanced materials.

Policy option 31: Align institutional and regulatory responsibilities around SSbD implementation and embed SSbD and adaptive governance in research and innovation.

What: Focus on aligning institutional and regulatory responsibilities around SSbD implementation overall including advanced materials.

Why: The alignment of institutional and regulatory responsibilities around SSbD implementation would affect the development of advanced materials without it necessarily centring around advanced materials.

How:

- Clarify mandates and improve coordination among EU agencies and Member States to avoid overlaps or blind spots.
- Establish joint SSbD task forces that coordinate data generation, test method validation, and early identification of regulatory needs.
- Integrate SSbD into existing EU policy instruments such as the Chemicals Strategy for Sustainability, Advanced Materials 2030 Initiative/International Advanced Materials Initiative (IAM-I)[64], and Green Deal Industrial Plan.
- Promote SSbD as a standard in advanced materials R&I, ensuring that safety and sustainability guide early design decisions.
- Institutionalise horizon scanning, foresight exercises, and early-warning systems (e.g., OECD Early4AdMa) to anticipate governance needs.
- Support feedback mechanisms that allow regulatory learning from research outcomes and market monitoring.
- Involve scientists, regulators, industry, and civil society in co-creating SSbD criteria for advanced materials.
- Use transparent communication and participatory foresight to address uncertainties and build public trust in innovation processes.
- Align policy narratives and funding priorities with the SSbD philosophy, ensuring advanced materials contribute to the European Green Deal, circular economy, and zero-pollution goals.
- Encourage industry commitments and labelling schemes that visibly demonstrate SSbD compliance and sustainability performance.

Advantages and disadvantages/risks:

- Advantages: clear institutional mandates and alignment of responsibilities across EU agencies (e.g., ECHA, EFSA, JRC) and Member States that can prevent overlaps and regulatory blind spots; integration of SSbD into existing policies ensures that SSbD principles are applied consistently across sectors and materials including advanced materials; horizon scanning, foresight, and

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[64] https://www.iam-i.eu/

early-warning systems improve the European Commission's ability to anticipate and respond to emerging technological risks including those emerging from advanced materials; embedding the SSbD further in the implementation of the Green Deal, Circular Economy, and the Chemicals Strategy for Sustainability helps deliver on cross-sectoral goals (e.g., zero pollution, competitiveness, climate neutrality) of Europe; creates feedback loops between research, regulation, and market monitoring to allow continuous policy learning and iteration; involving scientists, regulators, industry, and civil society in the implementation of the SSbD principles builds legitimacy and mutual understanding; clear expectations about SSbD responsibilities reduce uncertainty for innovators and investors; and rransparent communication about risks, benefits, and uncertainties of advanced materials strengthens societal acceptance.

- Disadvantages/risks: alignment of effort across of the European Commission, agencies, and Member States requires strong political leadership and consensus-building abilities; parts of the European Commission and agencies may resist changes perceived as infringing on their existing responsibilities or expertise; differences in administrative capacity and political commitment across Member States could create uneven progress; effective foresight, monitoring, and coordination structures require stable, long-term financial and human resources; embedding SSbD and adaptive governance requires new interdisciplinary skills in both policy and research communities; establishing new coordination bodies or task forces may temporarily increase bureaucratic complexity; shifting from traditional risk management to an integrated SSbD and foresight-driven model demands significant adaptation within institutions; without concrete incentives, industry and researchers may view SSbD as an additional layer of compliance rather than a strategic advantage.

Impact: Consistent integration of SSbD across EU strategies ensures a unified approach to advanced materials, chemicals, and sustainability; regular foresight and feedback mechanisms create a living governance system that evolves with scientific and technological change; clear mandates reduce inefficiencies and ensure coordinated responses across agencies and levels of governance; policy learning mechanisms ensure that regulatory needs inform research agendas, closing the science–policy loop; aligned SSbD expectations facilitate early integration of safety and sustainability, reducing redesign and compliance costs later; embedding SSbD in EU R&I funding fosters innovation that is both competitive and compliant; labelling and transparency mechanisms create market value for sustainable and safe products; co-created governance frameworks and transparent communication strengthen public confidence in EU innovation; and ensures that materials innovation actively supports climate neutrality, zero pollution, and circular economy transitions.

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Annexes

Annex 1: Supplementary table

Materials classes with examples and their applications[65].

Classes	Examples	Functions	Applications
Quantum materials	Topological insulator (Bi_2Se_3) Kagome metals (AV_3Sb_5) Magnetic topological ($MnBi_2Te_4$), New quantum properties (twisted bilayer graphene) YBCO/ReBCO tape, Fe-pnictide, high-pressure hydride superconductors	Quantum coherence protection Exotic transport phenomena Volatile state protection (stabilisation) Unconventional superconductivity, Correlated electron behaviour	Quantum devices Information: memory (storage) and handling Magnetic confinement for nuclear fusion Improved superconductors for better magnets for example in MRIs, electric power transmission grid worldwide; future nuclear fusion
Wide-bandgap/ultrawide-bandgap semiconductors	SiC, GaN,(In,Ga)N, β-Ga_2O_3, diamond	High-field operation, high thermal conductivity, fast switching, radiation hardness	Power electronics, radio frequency, harsh-environment operation, radiation-hardened electronics
Other semiconductors	Binary pnictides (Ga,In) P; lead-halide perovskites, (In,Ga)ZnO	Radiation-tolerant charge transport, self-healing and defect-tolerant semiconductors tunable band gaps	Radiation and particle detectors, radiation-hardened electronics
Multi-component metal oxides	Doped metal oxide films, 1D-2D materials	Active and passive electronics, transistors and memristors, digital and analogue electronics	Displays; electronics that are transparent, flexible, and conformal; augmented reality, neuromorphic synapse and memory; active integrated sensors
Smart paper and textiles	Nanocellulose, ionic gels, functionalised fibres, photochromic nitrocellulose	Sensing features for monitoring body signal and colour change, mechano-responsive feature, biodegradable systems	Smart packaging; disposable (bio)sensors; smart active electronics; surfaces, energy, environment; smart skins and clothing

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[65] The table presents some examples informed by the working group's expertise and does not aim to be exhaustive.

Flexible electronic (other), low-weight electronics for biomed and space applications	Organic semiconductors, lead-halide perovskites, metal oxides	Mechanical flexibility, low-temperature processing, conformal optoelectronics	Biomedical; energy conversion; lighting; augmented reality; displays, sensors
Smart/functional polymers	Self-healing elastomers, shape-memory (polyurethane), electronic-conducting polymers	Stimulus-responsive, reversible mechanical and chemical adaptation, intrinsic conductivity	Wearables, soft robotics
Thermoelectrics	Bi_2Te_3/Sb_2Te_3, skutterudites, half-Heusler alloys	Heat-to-electricity conversion (Seebeck generator), active cooling (Peltier heat pump)	Waste-heat harvesting, self-powered detectors; low-power generators
Ferroelectrics/ piezoelectrics	Doped HfO_2 (CMOS-friendly ferroelectric), PbZrTitanate (PZT), AlN/(Sc,Al)N	Switchable polarisation, piezoelectric response, electro-mechanical coupling, dielectric tunability	Non-volatile memory, radio frequency filters, actuators
Metamaterials and photonic crystals	Negative-index/ gradient metasurfaces; electromagnetic invisibility cloaks, opal gemstones, Bragg mirrors (1D photonic crystal); photonic crystal fibres; woodpile structures (3D photonic crystals); diatoms	Engineered optical and electromagnetic response, sub-wavelength light control, noise control	Lenses, cloaking (invisibility), compact optics, super-resolution imaging, sensing
Auxetic and architected lattice and cellular materials	Re-entrant foams, micro-lattices, metal foams	Negative (rare) Poisson ratio, mechanical energy absorption, programmed mechanical response	Crash absorber, blast protection; conformal stents; lightweight transportation frames, topological insulators
Metal- and covalent-organic framework (MOF, COF) materials	HKUST-1 MOF, ZIF-8 MOF, boronic ester COFs, imine-linked COFs, benzoxazole COFs, β-Ketoenamine COFs	High porosity, tunable chemistry, selective sorption, catalytic and sensing functions	Gas storage and separation, adsorbents to remove environmental pollutants, drug delivery, catalysis, sensing
Hydrogen storage and other hydrogen materials	Complex hydrides metal hydrides, intermetallics, high entropy alloys (HEA)	Reversible H_2 storage, fast H diffusion, catalysis, superconducting phases	Energy storage and conversion, supercapacitors, H_2 economy components, superconductivity
Electrocatalysts and photo-catalysts	Single-atom catalysts, NiFe oxyhydroxides for oxygen evolution (OER), TiO_2 and g-C_3N_4 (photocatalysis)	Better charge-transfer kinetics, better active catalytic sites, solar-driven redox activity	Clean fuels, CO_2 reduction, water splitting
Solid-state ion conductors	Several garnets and argyrodites; Zr-Si phosphate glasses (NASICON)	Fast solid (super)ionic conduction, electro-chemical stability, safe ionic transport	Solid-state batteries, fuel cells, and electrolysers

Bio- and bioinspired-materials	Hydroxyapatite composites, nacre-like laminates, spider silk-like fibres; nucleotide polymers	Biocompatibility, adaptive mechanical behaviour, hierarchical toughening	Bio-implants, actuators for soft devices, batteries
Sustainable and biodegradable materials	Polyactide; cellulose nanofibres; chitosan, hemp/flax natural fibres; biopolymers	Environmentally benign, tunable functional response, biodegradability	Microfluidic paper-based analytical devices, µPADs for medical and pharmaceutical diagnostics
Plasmonic materials	Gold(Au), silver (Ag), copper (Cu), palladium (Pd), platinum (Pt), aluminium (Al) nanoparticles; carbon-based materials such as graphene and carbon nanotubes (CNTs)	Hot-carrier generation, tunable infrared and visible optical properties	Hot-carrier solar cells, integrated photonics; sensing technologies such as biosensors and spectroscopic sensors
Transparent/conductive oxides	Indium tin oxide (ITO), aluminium-doped zinc oxide (AZO); transparent ceramics (spinel, aluminium oxynitride)	Optical transparency with electrical conduction, wide bandgap, infrared transmission	Displays, windows, infrared domes
2D materials	Transition metal dichalcogenides (TMDs) (MoS_2/WSe_2), MXenes ($Ti_3C_2T_x$), and graphene	Ultra-thin structure, large surface area, high conductivity, and tunable chemical characteristics	Tunable electronics, electromagnetic interference (EMI) shielding, energy storage, smart sensors, catalysis
Low-temperature, liquid-based materials	Lead-halide perovskites and their 2D variants; organic, molecular and polymeric, and organic semiconductors, some metal oxide semiconductors	Wide possible substrate range, low-cost preparation, damage self-healing, tunable bandgaps	High-efficiency photovoltaics and LEDs, light and high-energy radiation, and particle detectors
Perovskite oxides and correlated oxides	$(La,Sr)MnO_3$, LSM $(La,Sr)CoFeO_3$ LSCF $SrTiO_3$/$LaAlO_3$ interfaces, (Zn,Sn)O Ga-doped ITO nickelates/manganites	Tunable charge transport, solution processability, excitonic opto-electronics, tunable absorption and emission	Catalysis, solid-oxide fuel cell cathodes; solid electrolytes (ionics), memristors
High-entropy materials	High entropy alloy (HEA), such as CoCrFeMnNi; high-entropy ceramics (carbides/borides)	Configurational entropy stabilisation, high strength and toughness, thermal and oxidation resistance, tunable lattice disorder, H_2-sorption	Strength and toughness at extreme temperatures, oxidation resistance for energy and H_2 storage systems
Ultra-high-temperature ceramics (UHTCs)	ZrB_2, HfB_2, HfC	Extreme temperature stability, oxidation resistance, high thermal conductivity, structural integrity above 2000°C and up to 3000°C	Hypersonic systems, thermal protection systems

Structural composites and fibres	Carbon- and glass fibre-reinforced polymer, CFRP/GFRP, SiC/SiC ceramic and metal matrix composite CMC, MMC and ultra-high MW polyethylene, synthetic silk fibres	High (specific) strength, tailored anisotropy, damage tolerance, lightweight structural performance	Aerospace, lightweight armour, turbines
Phase-change and resistive-switching	GST ($Ge_2Sb_2Te_5$), HfO_X /TaO_X memristors	Reversible phase transformation, resistive switching, thermal energy storage	Non-volatile memory, in-memory computing, thermal energy storage

General references: MOF/COF, high-entropy alloys (HEA) (mixed-metal or high-entropy MOFs) (Marrett et al., 2025); biomaterials, bioinspired materials, and biodegradable materials, smart papers/textiles, flexible electronics, smart/functional polymers (Shaji et al., 2025); metamaterials, photonic crystals, and plasmonic materials (Badloe & Rho, 2024); semiconductor materials (perovskites, ferroelectrics, III-V compound semiconductors, organic semiconductors, and low-dimensional materials) (Zheng et al., 2025); photocatalysts, electrocatalysts, 2D materials, 0D materials, 1D materials, COF (Chauhan & Srivastava, 2025); Ultra-high temperature ceramics (J. Li et al., 2025); metal oxides and ceramics (Maeda et al., 2024); transparent and conductive oxides and plasmonic materials (Sekkat et al., 2024); phase-change materials, semiconductors (H. Chen & Ravichandran, 2025); auxetic, architected lattice, and cellular materials (Benedetti et al., 2021).

Annex 2: Background and main processes

Responsibilities and working structure within the Scientific Advice Mechanism

The members of the Group of Chief Scientific Advisors (GCSA) have produced its Scientific Opinion on Advanced Materials, which sets out evidence-based policy recommendations. The Advisors involved with the project have been Naomi Ellemers (chair), Adam Izdebski (deputy chair), Martin Kahanec, Rafal Łukasik, Dimitra Simeonidou, Rémy Slama and Mangala Srinivas, as well as Nicole Grobert in her capacity as chair of the GCSA until May 2025. The Science Policy, Advice and Ethics Unit at DG RTD (SAM Secretariat) has assisted the Advisors in the development of the Scientific Opinion.

SAPEA has been responsible for independently producing the evidence review report that informs the Scientific Opinion. Within SAPEA, Euro-CASE has served as lead Academy Network for the topic. Mariana Rei, SAPEA Scientific Policy Officer of Euro-CASE, has coordinated the report's development, with the support of the SAPEA team of scientific policy officers: Anda Popovici (YASAS), Carly Seedall (Academia Europaea), Céline Tschirhart (ALLEA), Louise Edwards (Academia Europaea/Cardiff University), Frederico Rocha (EASAC), Hannah Macdonald (FEAM), Guna Dauvarte (FEAM), and Sara Saba (ALLEA). In accordance with the SAPEA quality assurance guidelines[66], the peer review process was managed by another SAPEA Network, YASAS, supported by Anda Popovici. The additional industry and innovation workshop on advanced materials was organised by Carly Seedall (Academia Europaea).

To jointly coordinate the project within the SAM, regular SAM coordination team meetings took place, chaired by the GCSA chair. The participants from SAPEA included the co-chairs of the SAPEA working group, a Board member of Euro-CASE (lead Academy Network for the topic), and SAPEA staff members.

Selection of experts

In line with the SAPEA quality assurance guidelines, SAPEA set up an interdisciplinary working group with 22 members based in 14 countries. The two co-chairs of the working group, Anke Weidenkaff and Olli Ikkala, were proposed by the lead Academy Network Euro-CASE. Following assessment of their declarations of interest, the co-chairs were approved by the SAPEA Board.

The call for nominations for the working group was issued by SAPEA in January 2025, describing the scope, timeline and areas of expertise required. SAPEA received a total of 133 nominations and suggestions for the working group. 59 additional suggestions were added to the initial list of nominations to cover for expertise gaps, especially in the social sciences domain and on digitalisation and AI. These experts were identified through desk research by the Academy Networks, bibliographic analysis by Cardiff University and following suggestions by the co-chairs and SAM Secretariat.

The selection committee for the working group met on 22 April 2025. The committee comprised:

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[66] https://scientificadvice.eu/how-we-work/how-we-gather-evidence/

- Working group co-chairs (Anke Weidenkaff and Olli Ikkala)
- Board member of the lead Academy Network, Euro-CASE (Patrick Maestro)
- President of Academia Europaea (Donald Dingwell), as a second Academy Network

The selection committee was asked to choose experts according to demonstrated excellence in one or more of the fields listed in the call for nominations. The areas of diversity taken into account included:

- interdisciplinarity, with all relevant disciplines and fields included
- broad geographical coverage of Europe, including widening countries
- participation of underrepresented gender
- inclusion of early- and mid-career researchers (EMCRs).

The final working group of those who accepted the invitation from SAPEA was 22 members, including the two co-chairs. 36% were female, 23% were mid-career researchers and a further 9% were early-career, making a total of 32% EMCRs. 13 European countries and one non-European country were represented in the group. Five experts (23%) came from widening countries.

The composition of the working group was approved by the SAPEA Board. All working group members were required to complete the standard Declaration of Interests form of the European Commission, which were then assessed by SAPEA in accordance with SAPEA's quality guidelines. The completed DOIs are published at the SAM website alongside the evidence review report for a period of six months.

Evidence review process

Working group

The working group met six times between June and November 2025, via online and hybrid meetings. An additional preparatory meeting was held in May 2025. Between meetings, the working group worked collectively online on successive drafts of the report.

Industry and innovation workshop

To address question two of the Scoping Paper, SAPEA organised an industry innovation workshop focused on advanced materials. The workshop took place on 4 June 2025 and engaged 17 stakeholders representing the advanced materials industry landscape and innovation chain. Participants explored practical solutions to strengthen the uptake of research into innovation and addressed systemic challenges in the field.

The workshop aimed to:

- Understand how innovative products can be developed from advanced materials research, addressing the gap between academic laboratories and industrial manufacturing.
- Evaluate the risks associated with investment in advanced materials research.

- Identify mechanisms to unlock new functionalities across sectors and stimulate new business models and innovation markets.
- Explore ways to enhance alignment and feedback loops between basic research and industrial needs, supporting the broader adoption of advanced materials by industry.

The report of the workshop is published separately, as a companion document to the evidence review report, and is available on the SAM website. The invited participants are listed in the Annexes.

Expert workshop

An expert workshop was held in Brussels on 22 September 2025 as a hybrid meeting. Its purpose was to receive feedback on the draft evidence review report from the wider expert community. 13 invited experts from nine European countries and one non-European country (Canada) spoke at the workshop (see Annex 5 – Acknowledgements for details). In all, there were 47 in-person and online participants.

The workshop started with an overview of the report by the co-chairs, followed by a keynote presentation by an invited international expert. Each of the main chapters of the report was then introduced by the responsible chapter lead or co-lead, with feedback given by two discussants each. A final session was dedicated to a critique of an early draft of the evidence-based policy options. The main points of feedback were considered by the working group at a dedicated meeting.

The report of the workshop is published separately, as a companion document to the evidence review report, and is available on the SAM website. The invited experts are listed in the Annexes.

Peer review

A double-blind peer review process was coordinated by the Scientific Policy Officer at YASAS, in accordance with the SAPEA quality guidelines. Four reviewers representing a diverse and complementary range of disciplines relevant to the key themes of the report provided feedback (see Annex 5 – Acknowledgements). This feedback was systematically addressed by the working group in a dedicated meeting. The main actions taken included the following:

- The Executive Summary was amended to address reviewers' comments. This included adding a summary of policy options (Chapter 7) and addressing missing elements (Chapters 4 and 6); introducing the top five key messages from the report; adjusting the definition of advanced materials to ensure alignment with Chapter 6; and ensuring overall consistency with the main report.
- One new figure was incorporated (Figure 3 – Sankey diagram, in Section 2.5.).
- Several tables and boxes were revised. For example, Table 5 (on materials design and functionalities) and the table in Annex 1 (on materials classes) were updated based on reviewers' comments. Box 4 (on emerging materials and high entropy alloys) was shortened, and Box 5 was revised to provide a broader perspective on 2D materials. Box 2 (on classes of advanced materials) and Table 1 (focusing advanced materials and their possible applications) were also revised for better structure and contextualisation.

- Key terms were identified in each chapter, and their definitions were added to a glossary at the end of the ERR, along with a list of acronyms. Several terms were also clarified throughout the report in response to specific reviewer comments: for example, the definition of 'digital twins' in Section 5.4.1.
- Additional references were added to correct imbalances between heavily referenced sections and those lacking evidence. Notably, Section 3.4.1 was revised to ensure consistent referencing. Section 4.4. was fully rewritten to reflect the latest scientific evidence and provide a deeper discussion, following a reviewer's recommendation.
- Redundant content, particularly between the Executive Summary and the Conclusions, was reduced. Some sections were also revised to ensure balance throughout the chapter. For example, Sections 3.2.2. and 4.3. were extensively edited to streamline and shorten the text, and Sections 4.5. and 5.3. were expanded.
- Areas where reviewers indicated missing information were strengthened across all chapters, with additional literature cited when needed. Some edits were made to ensure accuracy as well.

The SAPEA Board approved the final outcome of the peer review process.

Plagiarism check

In accordance with the SAPEA Quality Guidelines, a plagiarism check on the final version of the evidence review report was run by Cardiff University using Turnitin software. The results were checked at Cardiff University and also by the Scientific Policy Officers of the lead Academy and YASAS, and some references were added.

Publication

This evidence review report has been handed over to the Group of Chief Scientific Advisors and was published in spring 2026, together with the industry and innovation workshop report and the expert workshop report. All documents can be accessed on the SAM website[67].

Literature review

The review team at Cardiff University is made up of information specialists and methodologists. It undertook a preliminary literature review between January and March 2025, in response to a request from the SAM Secretariat in the European Commission. This review was also provided to the working group at its preparatory meeting in May and in the first meeting in June, for background information. It included a rapid overview of some of the main themes in the literature on Advanced Materials in the European context, drawing from both academic and grey literature, with emphasis on:

- Definitions of advanced materials
- Strategic and policy background
- Data analysis and other indicators

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[67] https://scientificadvice.eu/

- Safety, sustainability, circularity
- Innovation, including open innovation and collaboration platforms, digitisation, FAIR data, stakeholder engagement and interdisciplinary working, assessment tools and governance structures.

For the evidence review report, the working group relied on its own knowledge of the literature, and no additional requests were made to the Review Team.

Annex 3: Glossary of key terms

A

Advanced composites: Engineered combinations of at least two distinct materials (e.g. fibres and matrices) designed to achieve superior mechanical, thermal or other properties compared with conventional materials.

Advanced manufacturing: Production systems and equipment that integrate advanced materials and technologies (e.g. electronics, automation, additive manufacturing) to deliver enhanced performance or efficiency.

Advanced materials: Materials intentionally designed to have new or improved properties or structures to deliver specific functional performance, including both "high-tech" new materials and "low-tech" materials engineered in novel ways.

Advanced textiles and fibres: Textile materials whose composition, structure or surface treatments provide enhanced functionalities (e.g. high strength, smart sensing, or special barrier properties) beyond conventional textiles.

Artificial intelligence/machine learning (AI/ML): Artificial Intelligence develops and studies digital systems that perform tasks normally associated to human intelligence such as perceiving, classifying, learning, abstracting, reasoning, and acting. It includes, e.g., if-then rules, data mining, and machine learning. Machine learning develops and studies algorithms that learn predictive and/or descriptive models from data using statistics and (typically intensive) computational resources.

B

Biocidal Products Regulation (BPR): EU Regulation governing the placing on the market and use of biocidal products (e.g. disinfectants, preservatives), including nano-enabled biocides.

Biofoundry: A facility that uses high-throughput, automated technologies to accelerate the engineering of biological systems through a standardised workflow. It combines robotics and AI to design and test microorganisms for producing advanced materials.

Biomimicry/bioinspiration: The study of emulating and mimicking nature to develop new technologies or materials functions, where researchers have used it to help solve human challenges.

Biotechnology: The use of biological processes, organisms or systems to produce products that have the potential to enhance human life.

C

Carbon capture and utilisation (CCU): A process that captures carbon dioxide emissions from industrial sources and converts them into usable products or materials. Bio-CCU refers to carbon dioxide capture through biological processes from flue gases (or atmosphere).

CEN: European Committee for Standardization; develops European standards (EN/CEN/TS) relevant to advanced materials, composites, nanotechnologies, and plastics.

CEN/TC 249: CEN Technical Committee on Plastics; among other tasks, works on standards for testing plastic biodegradability in various environments.

CEN/TC 352: CEN Technical Committee on Nanotechnologies; develops standards for nanomaterials, including waste management and release/detection of nanoparticles.

CEN/TS 19101: Technical Specification "Design of FibrePolymer Composite Structures" that aims to put fibrepolymer composites on a similar footing to traditional construction materials in structural design codes.

Chemicals Strategy for Sustainability (CSS): EU strategy under the European Green Deal aiming for a "toxic free environment", reforming chemicals regulation, addressing polymers, and promoting SSbD chemicals and materials.

Circular Economy Action Plan: EU action plan to promote circularity across sectors, including focus on difficult to recycle composite waste and plastics.

Circularity: Circularity refers to practices that optimise resource use and minimise waste across the entire production and consumption cycle, emphasising sustainability and economic efficiency.

CLP Regulation: EU Regulation on classification, labelling and packaging of substances and mixtures; aligns hazard classification and labelling with the UN Globally Harmonized System of Classification and Labelling of Chemicals (GHS) and is tightly linked to REACH.

Coatings: Surface layers applied to substrates (e.g. paints, varnishes, functional coatings) that can contain advanced or nano-enabled components to provide protection or new properties (anticorrosion, self-cleaning, etc.).

Construction Products Regulation (CPR): EU framework that sets harmonised conditions for the marketing of construction products, including those containing advanced materials, gels, or foams.

Critical Raw Materials Act (CRMA): EU Regulation addressing security of supply of critical and strategic raw materials, relevant for advanced materials and light alloys that depend on such inputs.

Crystallography: The scientific study of the arrangement of atoms and molecules in crystalline solids and their structures and properties. It uses techniques like X-ray diffraction to analyse the scattering of waves (like X-rays, neutrons, or electrons) by a crystal's atomic lattice to determine the crystal's internal structure.

D

Deep learning: Machine learning performed by training deep artificial neural networks, i.e., neural networks with at least one hidden layer. Such networks include all artificial neural networks used these days, such as fully connected, convolutional, graph network, transformers, etc.

Deoxyribonucleic acid (DNA): The macromolecule that carries genetic information for the development and functioning of an organism. DNA has a double helix conformation, and each strand is composed of adenine (A), cytosine (C), guanine (G), or thymine (T).

Digital Product Passport: A digital record associated with a product providing key information along its life cycle (e.g. composition, recyclability, SSbD data), enabling traceability and circularity.

Digital twins: "A set of adaptive models that emulate the behaviour of a physical system in a virtual system getting real time data to update itself along its life cycle. The digital twin replicates the physical system to predict failures and opportunities for changing, to prescribe real time actions for optimising and/or mitigating unexpected events observing and evaluating the operating profile system". This definition comes from (Semeraro et al., 2021), a systematic review paper focused on the definition of the term "digital twin".

DMEL (Derived Minimal Effect Level): Exposure level associated with a low but non-zero risk (often used for non-threshold effects like some carcinogens) when a DNEL cannot be set.

DNEL (Derived No Effect Level): Health based exposure level for a substance under REACH, derived from toxicological data; exposure below the DNEL is considered not to pose a significant risk.

E

Early4AdMa: Early screening framework developed in OECD's nanomaterials work to flag potential safety or sustainability issues of new advanced materials before they reach mass markets.

ECHA: European Chemicals Agency; the EU body responsible for implementing REACH, CLP and several other chemicals-related regulations, including nanoform registrations.

End-of-life (EoL): The stage within a product's life cycle corresponding to a loss of functionality that determines the termination of its intended purpose.

Engineered living cells: Cells intentionally genetically modified to achieve specific properties by altering a cell's behaviour, function, or characteristics (e.g., novel materials with self-healing or self-repairing properties).

Environmental Limit Values (ELVs): Maximum permitted concentrations or emissions of pollutants (e.g. at discharge points), used as control tools in environmental legislation.

Environmental Quality Standards (EQS): Legally set concentration thresholds for pollutants in environmental compartments (e.g. water) used to protect human health and ecosystems.

ESG (environmental, social, governance): Corporate framework for assessing and reporting environmental, social and governance performance, into which SSbD for advanced materials can be integrated.

F

FAIR data principles: Data management principles that require data to be *findable, accessible, interoperable and reusable,* enabling digital ecosystems for safety and sustainability assessment.

G

Gels and foams: Soft materials with, respectively, a high fraction of gas or liquid dispersed in a solid or semi solid matrix, used for a wide range of applications, including medical devices and construction products.

Genome: The complete set of genes, i.e., DNA and RNA, present in a cell or organism, containing all the information needed for the cell or organism to build and maintain itself.

Governance of innovation: The ways in which public authorities, industry and other stakeholders steer the direction, speed and impacts of innovation, including through policy, regulation, funding, and stakeholder engagement.

Green chemistry: Approach to chemical design and engineering that reduces or eliminates environmental impact and the generation of hazardous substances.

H

Hierarchical assembly: Controlled process of building complex materials, such as advanced materials, by organising atoms into molecules, molecules into nanostructures, and nanostructures into macro-scale material.

High-entropy: Material design strategy by increasing the disorder of a system for creating multi-component materials. This strategy allows control over various properties through entropy-dominated phase stabilisation, atomic disorder with lattice distortion, sluggish diffusion kinetics, and synergy among multiple components.

High performance polymers: Polymers with exceptional thermal, chemical, or mechanical resistance (e.g. Teflon, Kevlar) used in demanding applications such as aerospace, electronics, or advanced packaging.

Horizon Europe: The EU's main research and innovation funding programme (2021–2027), which supports many projects on nanosafety, SSbD and advanced materials.

I

IAM4EU: Future European partnership planned to coordinate research and innovation on advanced materials and associated infrastructures at EU level.

Industrial symbiosis: Circular strategy aimed at the utilisation of waste, by-products, energy, and other resources from a given industrial sector to a different one.

Innovation ecosystem: The network of actors, institutions, infrastructure, markets, and regulations that collectively shape the development, commercialisation, and societal use of new materials and technologies.

Innovation sandbox: A controlled environment where companies and researchers can safely test new technologies and processes before full-scale production without the risk of failure.

Integration and coherence: Principles calling for coordination across sectors (environment, industry, trade, health) and levels of governance so that policies on advanced materials do not conflict or create gaps.

K

Kagome metals: The atoms in kagome (Japanese for "basket") metals are arranged in interlocked triangular patterns, which force electrons into complex quantum states, including ones required for superconductivity. These metals have "built-in amplifiers" that lead to much stronger quantum effects than in common metals. With their crystal structure and electronic behaviour, they show "spontaneous symmetry breaking", which implies going beyond basic physics.

Knowledge transfer offices (KTOs): Organisational units, often in universities or research institutions, that manage the transfer of knowledge and technology from academia to the business sector and society.

Knowledge Readiness Levels: A staged framework indicating how mature and actionable knowledge is for policy and innovation, analogous to technology readiness levels.

L

Large-language model (LLM): Neural-network-based AI model with a massive number of parameters trained on large amounts of text data to understand, generate, and process natural language. LLMs are used for a wide range of applications, including summarising, translating, and answering questions.

Learning factories: Complex learning environments for the manufacturing context that contain authentic replicas of real production systems and value chains, so that participants can learn based on experiences, in a hands-on fashion. For didactic reasons, they are simplified and reproduced inside a lab to train students. Learning factories have been used in universities and industry for many years.

Life cycle assessment (LCA): Method to evaluate environmental impacts associated with all stages of a product's life (from raw material extraction to disposal or recycling).

Light alloys: Metal alloys with relatively low density (e.g. aluminium or magnesium-based alloys) offering high specific strength and used in sectors like aerospace and transport.

M

Malta Initiative: EU driven initiative to coordinate and fund the development and updating of OECD Test Guidelines for nanomaterials and advanced materials, strengthening regulatory test methods.

Material flow: The movement and transformation of raw materials, components, and products throughout a system, process, or supply chain, from extraction to production, consumption, and eventual recycling or disposal.

Material loop: A closed or circular system in which materials are continuously recovered, reused, or repurposed, minimising waste and the need for virgin resources.

Medical Devices Regulation (MDR): Regulation (EU) 2017/745; EU law governing safety and performance of medical devices, including devices that incorporate nanomaterials or advanced gels/foams, with higher risk classification for nano-containing devices.

Mission-driven economy: An R&D and industrial policy paradigm in which governments set bold, outcome-oriented missions (e.g. climate neutrality) and organise funding and innovation around delivering them.

N

Nanoform: A specific form of a substance that meets nanomaterial criteria (e.g. particular size range, shape, surface treatment) and must be registered with nano-specific data under REACH.

Nanomaterials: Materials containing particles in the nanoscale (typically around 1–100 nm) where size dependent properties and behaviours may differ significantly from the bulk form and raise specific regulatory and safety questions.

NanoSafety Cluster (NSC): EU community/cluster of research projects and stakeholders working on the safety of nanomaterials and advanced materials, providing input to roadmaps and governance discussions.

Nanotechnology: A broad term for techniques and technologies that create, manipulate, or use materials at the nanoscale, often leading to novel functionalities and regulatory challenges.

New approach methodologies (NAMs): Non-animal or reduced animal testing methods (e.g. in vitro, in silico, omics-based approaches) that can be used for hazard and risk assessment of advanced materials.

O

OECD Working Party on Manufactured Nanomaterials (WPMN): International forum that develops and updates test guidelines and guidance for nanomaterials and, increasingly, advanced materials.

One Health: An approach that recognises the interconnection between human, animal and ecosystem health and promotes coordinated, multidisciplinary action across these domains.

Organoids: Tissue-engineered, self-organised 3D cellular structures derived from person's tumour cells or stem cells that mimic some functions of native organs. Organoids are used in the lab to study the formation and development of normal tissues and diseases, to design and test new drugs, and to evaluate the performance of therapies/treatments.

P

Packaging and Packaging Waste Regulation (PPWR) - Forthcoming EU Regulation that will require all packaging, including advanced polymer packaging, to be recyclable or reusable and to meet recycled content targets by 2030.

Polymer: A large molecule or macromolecule composed of repeating structural units, i.e., monomers, which are covalently bonded.

Polymers Requiring Registration (PRR/PPRR): Subset of polymers that, under planned REACH reforms, will have to be registered based on criteria such as molecular weight distribution, hazardous functional groups and potential health or environmental concern.

Precautionary principle: A policy principle stating that when there is scientific uncertainty about potential serious or irreversible harm, regulators may take preventive action even without full scientific proof of causality.

Prevention principle: The idea that known risks should be avoided or reduced at the source rather than managed only after harm has occurred.

Product Environmental Footprint (PEF): EU method for quantifying environmental performance of products across their life cycle using harmonised indicators.

Proportionality (in risk governance): The requirement that regulatory responses and risk management measures should be commensurate with the nature and magnitude of the risk.

R

RCR (risk characterisation ratio): Ratio of estimated exposure to DNEL (or other reference value); RCR ≤1 suggests acceptable risk, whereas RCR >1 indicates potential concern and need for additional risk management.

REACH: EU Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals; the core chemicals law that requires data generation, registration and risk assessment for substances placed on the EU market.

Regulatory preparedness: Proactive effort by regulators to anticipate emerging materials and technologies, identify knowledge gaps, and adapt regulatory frameworks and test guidelines in advance of large-scale deployment.

Regulatory sandbox: Controlled environment where innovations (including advanced materials) can be tested under real or near-real conditions with temporary, tailored regulatory arrangements to learn and inform future rules.

Responsible innovation: An approach that aims to align innovation processes with societal needs, values and ethical principles, involving early stakeholder engagement and anticipation of impacts.

Responsive materials: Materials with the capacity to switch physicochemical properties in response to external stimuli.

Risk governance: The set of principles, processes, and institutions used to identify, assess, manage, and communicate risks in a transparent, participatory, and proportionate manner.

RoHS Directive: EU Restriction of Hazardous Substances Directive for electrical and electronic equipment; limits the use of specific hazardous substances in such products.

S

Safe and sustainable by design (SSbD) - Extended concept that integrates both safety and sustainability (environmental, social, and economic) criteria into design, development and innovation of chemicals and materials from the outset.

Safe by Design (SbD): Approach in which safety considerations (e.g. toxicity, exposure potential) are integrated proactively into early stages of material and product design and development.

SSbD framework (EU): Voluntary EU guidance and assessment framework (developed by the JRC) providing criteria and a stepwise process for evaluating the safety and sustainability performance of chemicals and materials, including advanced materials.

Safety Data Sheet (SDS): Standardised document providing hazard, exposure and risk management information for a substance or mixture; requirements under REACH Annex II now include nanoform specific information.

Scalability: The ability to increase production from small laboratory batches to large industrial quantities without compromising on efficiency or quality.

Self-heal: Ability of a material to restore functionality after damage or micro-cracking. In materials science, self-healing is essentially a synonym of self-repair.

Self-monitoring: Monitoring of emissions, discharges or product performance carried out by operators or companies themselves, often under regulatory oversight.

Side-stream: A secondary material, by-product, or waste flow generated alongside the main product in an industrial or manufacturing process. It can often be recovered, treated, or repurposed as a resource in other processes.

Simulation: Numerical solution, performed in a computer, of equations modelling physical/chemical properties or processes. One can use a trained AI/ML model to perform a simulation of a system property/process, but also other more traditional techniques (e.g. numerical solutions of ordinary and partial differential equations).

Social life cycle assessment (S LCA): Life cycle assessment focusing on social and socio-economic impacts (e.g. labour conditions, community effects) of products and materials.

Standardisation: The process of developing agreed test methods, terminology, and technical specifications (often via CEN, ISO, or OECD) to support regulation, market functioning, and risk assessment of materials.

Strategic autonomy (EU): The EU's ability to pursue its policy goals and industrial priorities (e.g. in advanced materials, AI, critical materials) without excessive external dependence, especially in a geopolitically competitive context.

Synthetic biology: The field that combines engineering principles with biology. Its aim is to design and build new biological parts, devices, and systems, or to redesign existing ones. It often uses computational design and genetic editing tools like CRISPR.

T

Transparency and communication: Risk governance principles that emphasise open sharing of information, explicit discussion of uncertainties and trade-offs, and avoiding hidden agendas.

U

Urban mining: The process of recovering valuable materials, components, or energy from waste streams and existing anthropogenic stocks—such as buildings, electronic devices, landfills, and discarded products.

V

VAMAS: Versailles Project on Advanced Materials and Standards; an international initiative launched in 1982 to develop standards and characterisation methods for advanced materials.

W

WEEE Directive: Waste Electrical and Electronic Equipment Directive; sets rules for collection, recycling, and recovery of electronic waste in the EU.

Z

Zero-dimensional (0D) materials: Quantum dots—i.e., nanoparticles in which all three dimensions are in the nanometre range. They are typically just a few nanometres in size, small enough to exhibit quantum effects, primarily size quantisation (cf., 2023 chemistry Nobel prize).

Annex 4: List of acronyms

AAM	Alkali-activated materials
AI	Artificial intelligence
API	Application programming interface
CBE JU	Circular Bio-based Europe Joint Undertaking
CCU	Carbon capture and utilisation
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CERN	European Organization for Nuclear Research
CLASCO	Climate Neutral and Digitised Laser-Based Surface Functionalisation of Parts with Complex Geometry
CLP	Classification, labelling and packaging
CMR	Carcinogenic, mutagenic and reprotoxic
COF	Covalent organic framework
CRO	Contract research organisation
C-SI	Crystalline Silicon
CSP	Concentrated solar power
CSS	Chemicals Strategy for Sustainability
DG RTD	Directorate-General for Research and Innovation
DLP	Digital light processing
DNA	Deoxyribonucleic acid
DNEL	Derived No-Effect Level
E-LCA	Environmental life cycle assessment
ECHA	European Chemicals Agency
EFSA	European Food Safety Authority
EIC	European Innovation Council
EIT	European Institute of Innovation and Technology
EPD	Environmental Product Declaration
ERC	European Research Council
ESFRI	European Strategy Forum on Research Infrastructures
ESRF	European Synchrotron Radiation Facility
FAIR	Findability, accessibility, interoperability, and reuse
GHG	Greenhouse gas
GMO	Genetically modified organism
HaP	Halide perovskites
HEA	High-entropy alloys
IAM-I	Innovative Advanced Materials Initiative
IATA	Integrated approaches to testing and assessment
IoT	Internet of Things
IPCEI	Important Projects of Common European Interest
IRISS	International ecosystem for accelerating the transition to Safe-and-Sustainable-by-Design materials

ISO	International Organization for Standardization
JRC	Joint Research Centre
KTO	Knowledge transfer offices
LED	Light Emitting Diode
LCA	Life cycle assessment
LCC	Life cycle costing
LLM	Large-language model
MDR	Medical Devices Regulation
MFCA	Material flow cost accounting
ML	Machine learning
MOF	Metal–organic framework
NSC	NanoSatery Cluster
OECD	Organisation for Economic Co-operation and Development
PARC	Partnership for the Assessment of Risks from Chemicals
PCP	Public procurement programme
PET	Polyethylene terephthalate
PLA	Polylactic acid
PRR	Polymers Requiring Registration
PV	Photovoltaic
RCR	Risk characterisation ratio
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RIVM	Rijksinstituut voor Volksgezondheid en Milieu (Dutch National Institute for Public Health and the Environment)
RNA	Ribonucleic acid
RoHS	Restriction of Hazardous Substances
RTO	Research and technology organisations
S-LCA	Social life cycle assessment
SLA	Stereolithography
SOE	Solid oxide electrolysis
SSbD	Safe and sustainable by design
TRL	Technology readiness level
UNEP	United Nations Environment Programme
WEEE	Waste Electrical and Electronic Equipment
WPMN	OECD Working Party on Manufactured Nanomaterials
ZIF	Zeolitic imidazolate framework

Annex 5: Acknowledgements

SAPEA wishes to thank the following people for their valued contributions and support in the production of this report.

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The working group members who wrote this report are listed at the start of this report.

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Nominating academies, young academies, learned societies and academy networks

- Academy of Engineering, Portugal
- Academy of Sciences of Lisbon
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- Accademia Nazionale dei Lincei, Italy
- Austrian Academy of Sciences
- British Academy
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- Latvian Association of Young Researchers
- Lithuanian Academy of Sciences
- National Academy of Science and Engineering (acatech), Germany
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