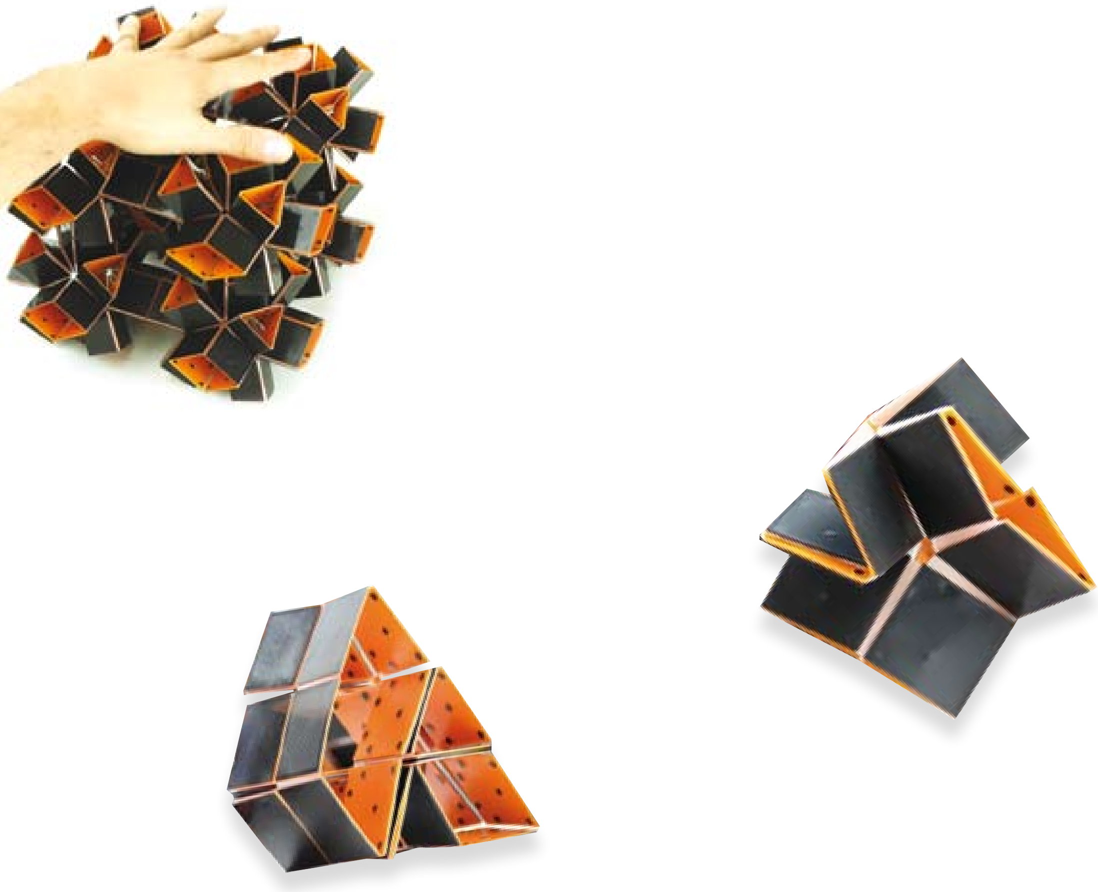
Dutch Materials Agenda

Accelerating Materials Technologies

MaterialenNL Platform



Cover photo: Agustin Iniguez-Rabago, Soft Robotic Matter Group
(Bas Overvelde, NWO Institute AMOLF)

METAMATERIAL PRODUCED WITH 3D PRINTING

Metamaterials have unusual mechanical, acoustic, and optical properties that do not occur in natural materials. They form the building blocks for new robotics, adaptive solar panels, materials that function as computers, and more. (Nature Comm. **10**, 5577 (2019))

Content

Summary and aim

of the Dutch Materials Agenda – Accelerating Materials Technologies

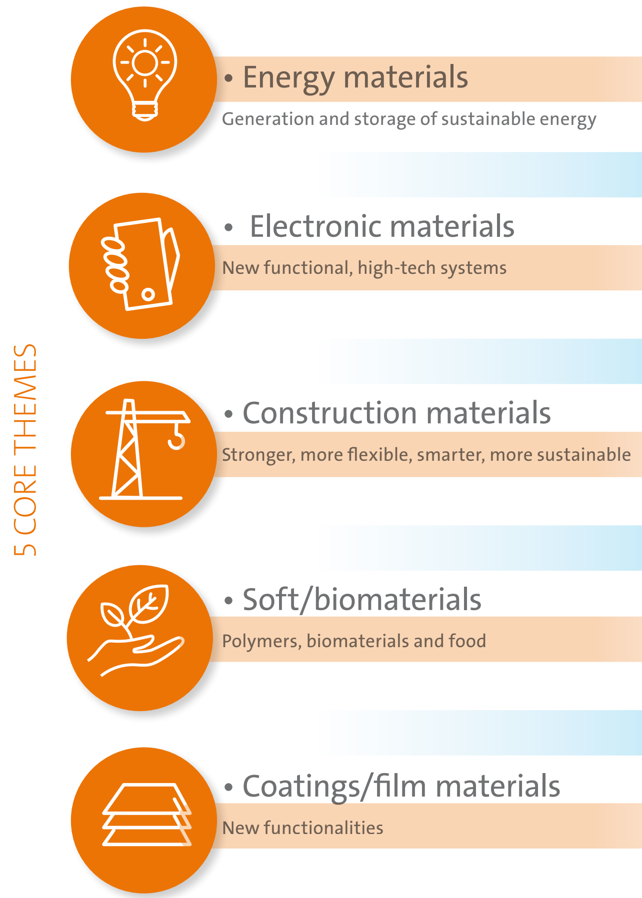
Materials...

New and improved materials have an enormous impact on our everyday lives. Electric cars are entering the market thanks to new battery materials, mobile phones have become more powerful thanks to new semiconductors, and wind turbines are increasingly efficient thanks to new composites and magnets. **The field of materials research is undergoing rapid developments!**

Will we soon be able to make artificial heart valves using a 3D printer? Or produce fuels from sunlight with the help of new catalysts? How can we produce and recycle materials in a fully sustainable manner? New developments in materials research are vital to deal with the enormous challenges we face in the areas of energy, sustainability, and high-tech equipment.

...our economy,

The Dutch economy depends to a large extent on materials. Each year in the Netherlands **more than 75 billion euros in turnover** is generated from the production and export of machines, instruments, metals, and plastics, which to a significant extent are based on materials innovations. More than **one hundred thousand people have a job in this industry**. Each year, we train thousands of researchers; they become experts in the materials field both in the Netherlands and abroad.

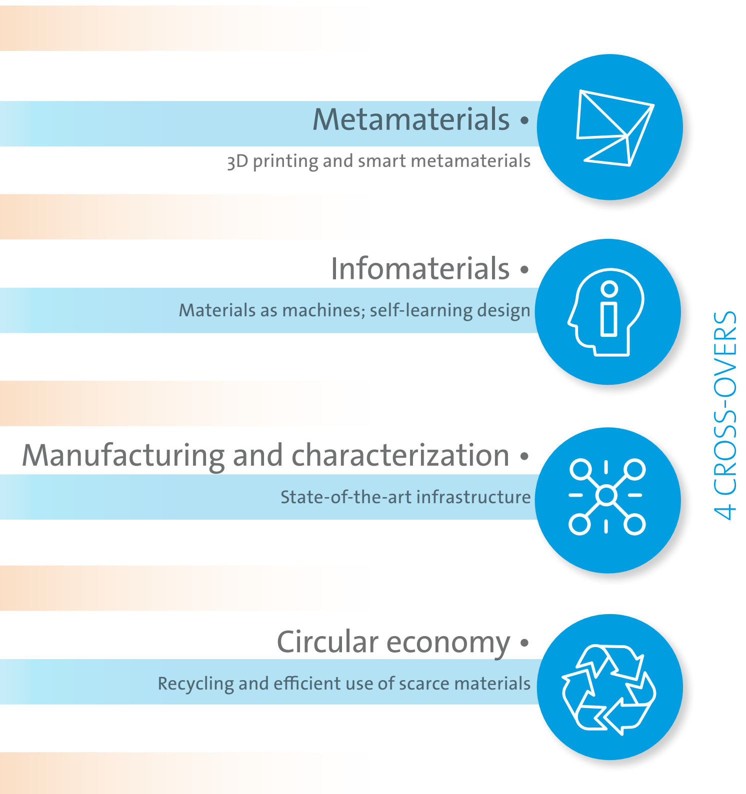


A broadly supported Agenda

This Agenda has been written by the MaterialsNL platform, which brings together academic parties, applied research organizations, universities of applied sciences, industrial parties, and sector organizations on behalf of the Top Sectors Chemistry, Energy, and High Tech Systems & Materials (HTSM), and describes the research directions in which these parties want to collaborate.

...our ecosystem

Why are we so successful in the field of materials in the Netherlands? Our country has an exceptional ecosystem in which universities, research and technology institutes and the materials industry effectively collaborate at a high level on both current and future opportunities. This makes the Netherlands a world leader in the design and production of innovative materials and products. That is why materials make such a huge contribution to our economy.



...and our societal challenges.

Materials lie at the heart of the solution to societal challenges within
- **Energy Transition and Sustainability**
- **Agriculture, Water and Food**
- **Health and Care**
- **Security**
- **Key Enabling Technologies**.

This Agenda presents materials sciences solutions to these societal challenges that also strengthen the earning capacity of Dutch industry. That will enable the Netherlands to maintain its knowledge and economic advantage and to effectively tackle the major problems our society faces. The Agenda makes choices within five core themes and four cross-over themes in which the Netherlands excels and with which we can vigorously develop our strong materials ecosystem that covers both research and industry.

In concrete terms, what do we want to achieve?

The realization of this ambitious Agenda is a matter of urgency and requires a considerable budget. By using this Agenda, the materials field can put together an integrated national research plan **Accelerating Materials Technologies**. The Agenda ties in with the mission-driven innovation programs of the Dutch government and forms the initial step towards an application for funding within the National Growth Fund in 2021.

① Custom designed materials

Materials form the physical basis for almost everything we can observe around us. Where would smartphones, electric cars or energy-efficient buildings be without the correct materials? New advanced materials provide solutions to important societal and technological challenges in the area of sustainable energy generation, circular economy, healthcare, security, and new technologies that strengthen the Dutch economy. Materials science is the discipline that covers the design, production, study, and (re)use of materials in a broad range of dimensions: from the atomic scale, via nano and micro, to the human scale of the objects around us. It is a multidisciplinary field that connects physics, chemistry, engineering, and more.
Materials science teaches us which influence the microstructure - the structure at the smallest scale – has on all of a material's properties, and consequently on its applications. These insights can be used to improve a material's properties – and so those of a product – and to create entirely new advanced properties. In recent years, materials scientists have continued unraveling the relationship between the structure of materials and their properties. This required the development of extremely powerful microscopic techniques to be able to see, manipulate, and control individual atoms and molecules. In addition, materials scientists are developing new (circular) routes for producing materials. New material combinations and geometries create new properties that are completely different from those of the component materials. All of this offers possibilities to produce completely new customized materials.

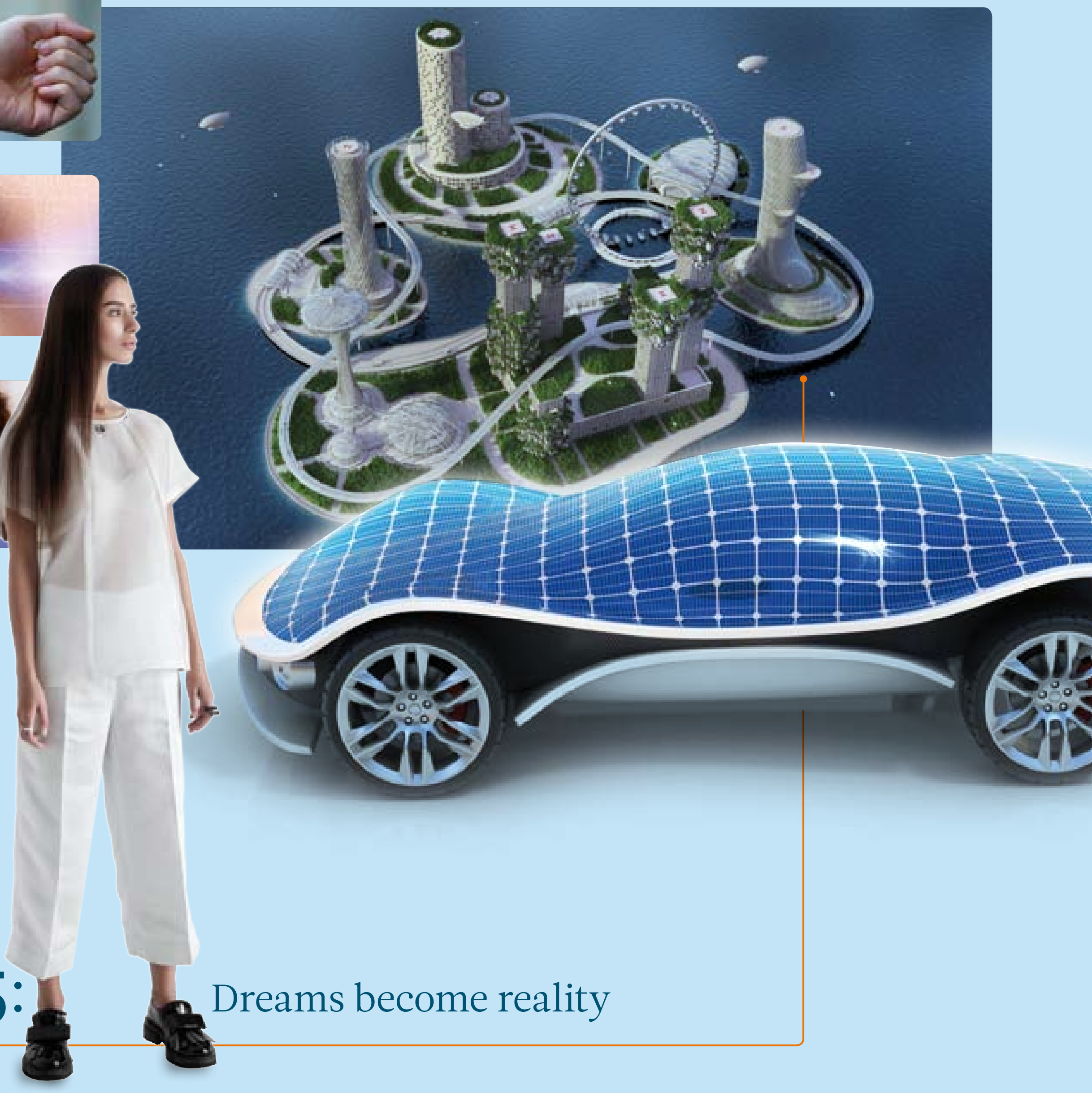
This document describes the unique opportunities that materials research offers to solve our societal problems and at the same time to realize entirely new economic activity.

Marc Hendrikse
Topsector HTSM

Emmo Meijer
Topsector Chemistry

Manon Janssen
Topsector Energy

Albert Polman
NWO Materials Committee
NWA Materials Route



2035: Dreams become reality

It is 2035. You drive through the city in your electric car, which is wirelessly charged with energy completely generated by the sun. The city has undergone an enormous transition; buildings and infrastructure are made from entirely reused materials that repair themselves. At your work, your use neuromorphic computers; smarter than our brains and far more energy efficient than old-fashioned PCs. Your clothes are fully integrated with sensors that monitor your body's functions, such as the condition of your new heart valve that was custom-made for you using a 3D printer.

Materials scientists are in an ideal position to realize solutions to the major challenges our society faces in the areas of energy, raw materials, security, health, and employment. In 2035, newly developed materials have led to breakthroughs in the areas of:

CLIMATE
sustainable energy supply from sun and wind

SUSTAINABILITY
a closed cycle in materials use

HEALTH
artificial tissues and medical sensors for an ageing population

ECONOMY
a new manufacturing industry produces *smart products - made in the Netherlands*

② Innovations and impact of materials

2.1 Materials for the energy transition and sustainability

How do we make our society CO_2-neutral and how do we create a circular use of raw materials?

The Paris Agreement states that by 2030 we must reduce the emission of greenhouse gases by 49% compared to the levels in 1990; by 2050 we want to realize a reduction of 95%. This means we need to have realized a completely CO_2-free power system by 2050. That requires a far more effective use of solar and wind energy. Completely new materials are needed to further improve the conversion efficiency of solar panels and to invisibly incorporate these in the built environment. Larger wind turbines require new fiber-enhanced composite materials that are light, strong, and fatigue-resistant. New corrosion-resistant materials increase the lifespan and reduce the maintenance of offshore wind turbines.

Furthermore, we must develop new systems for energy storage. How can we efficiently convert the energy from the sun and wind into chemical energy in the form of liquid fuels or hydrogen, and how do we increase the storage capacity of batteries and in doing so limit the use of non-scarce materials? Which materials facilitate this? Supercapacitors and energy storage in the form of compressed or liquid air and heat also provide unique possibilities, but these require entirely new materials to make practical applications possible.

By 2050, we also want to have an emission-free mobility for people and goods. The electrical transport needed for this requires the development of batteries with a larger capacity and faster charging capacity, and at the same time a lower weight and manufacture using non-scarce materials. For all mobility applications, lighter metals and composite materials are vital to reduce energy consumption. The construction industry has traditionally been a major emitter of CO_2. New compositions or combinations of traditional building materials such as wood, steel, concrete, and glass for buildings can reduce CO_2 emissions considerably. A specific challenge is removing CO_2 from the atmosphere and converting it into useful hydrocarbons via electrochemical conversion. That requires the development of highly selective catalysts and electrochemical cells.

If we are to produce materials and products more sustainably, we need to realize more effective raw material-component-product chains. The better use of sustainable energy during production, the use of non-scarce materials, and more sustainable production methods (smart industry) are essential aspects of this process. In a sustainably driven, completely circular economy the concept of 'waste' no longer exists: discarded end products are converted into raw materials for new products.
In the Netherlands, we want to use 50% less primary raw materials (mineral, fossil, and metals) by 2030. Design, reuse, and recycling will be essential for guaranteeing the supply security of materials, especially in Europe that has always strongly depended on importing raw materials.
The closing of material cycles requires smart innovations in the design, use, and reuse of building materials. New self-healing materials will last for longer and require less maintenance, and functional coatings will improve the sustainability of materials.

2.2 Materials for agriculture, water, and food

How can we create a sustainable, adequate, and secure food supply and deal with water safely?

The Netherlands has a global reputation in the fields of agriculture, food, and water technology; we have a highly efficient and profitable agriculture and food production. But at the same time, this production has a considerable impact on our soil, water, air, and biodiversity. Realizing a responsible and climate-neutral agricultural and nature system is a considerable challenge. The development of new materials plays an important role in this.

Can we develop new materials and architectures for LED lighting with a color spectrum that enables plants to grow even better? Even smarter sensors to fertilize and harvest agricultural products more effectively? Can we use agricultural products such as starch to produce (bio)materials that are more easily degraded in order to strengthen a circular economy?

Food is also a very interesting material: its structure and composition determine the taste and nutritional value. Dutch food companies and researchers are continuously looking for new food materials and emulsions with the best taste, texture, and shelf life, which is pure materials science! Can we develop more efficient biodegradable packaging materials, with sensors that continue to monitor the food quality over time to prevent food wastage? How can we develop antimicrobial coating materials to make food preparation safer? Innovative, highly selective membranes help to purify water to make it potable and can remove drug residues and other substances from wastewater before it is discharged into the surface water.

2.3 Materials for health and care

How can we live healthier and for longer?

We have set ourselves the goal that by 2040, everyone in the Netherlands will live at least five years longer in good health and that the health inequalities between the lowest and highest socioeconomic groups will have decreased by 30%. Developing new materials and applications will play a vital role in this. Smart biosensors can measure physiological parameters to determine important aspects of the body's condition. This requires new materials that selectively bind with biomolecules combined with effective detection methods. This technology is still in its infancy and has an enormous potential.

Within the body too, intelligent materials can perform diagnostics or administer drugs in dosed amounts.

Can we selectively bind nanoparticles to cancer cells to detect these and subsequently eliminate them using

laser irradiation? Can we program drug capsules to deliver the drug at the right time and place? And how can we produce sensors that pass on information from the body to the outside world while providing for their own energy supply? These new possibilities require completely new combinations of materials, often structured on a nano- or microscale, which combine different functionalities.

Materials play a key role in the manufacture of artificial body parts. 3D printing is a revolutionary technique that can be used to locally produce customized biomaterials, artificial tissue, and organs. This offers fantastic new possibilities. Can we use a 3D printer to produce a customized heart valve? Smartly designing the composition and structure of a material will allow faster and more effective integration in the body. Can we use such an approach to increase the lifespan of an artificial hip joint?

The outbreak of COVID-19 has revealed that it is vital to respond rapidly to an acute demand for vital medical resources such as respirators and face masks. A strong materials infrastructure and industry is essential in this regard.

2.4 Materials and security

How do we guarantee the security of our existence and the supply of vital goods?

Security can longer be taken for granted in our 21st-century society. We continuously have to deal with threats from terrorism, military tensions in the world, and the maintenance of vital transport and trade routes for essential goods.

As a member of NATO, the Netherlands has access to the most modern resources for warfare and terrorism prevention. The development and manufacture of these resources often takes place at specialized companies and builds upon an essential knowledge base that is provided by materials researchers. Can we develop metamaterials with stealth properties to make military objects invisible? Lighter materials make vehicles and vessels more versatile and energy efficient. Advanced 3D printing technology can be used to produce customized materials on location and to replace damaged parts. Clothing produced from composites based on super fibers give military personnel and emergency services workers greater protection and more comfort.

Smart sensors can be embedded in armored constructions made from ceramic matrix composites to determine the condition of transport vehicles and vessels and to predict maintenance tasks. Can we develop self-healing materials that limit the impact on military objects? New battery technology and smart sensors based on new nanomaterials can also find important applications in military infrastructure.

Detecting the presence of very low concentrations of drugs, explosives or dangerous substances requires accurate and specific sensors that provide real-time results at higher sensitivity. Lab-on-a-chip circuits can use microchannels to take air or water samples and test these for pathogenic microorganisms or toxic substances. Sensitive and selective new materials play an important role in this.

Space technologies are completely dependent on high-tech materials. Satellite manufacture requires light, strong, stiff materials with a minimal thermal expansion. The instruments that ensure communication with the earth and perform measurements of the earth's atmosphere and space are based entirely on advanced materials that detect and analyze signals with extreme sensitivity.

2019 • lithium-ion batteries
2017 • cryo-electron microscopy
2016 • molecular machines
2014 • super-resolution microscopy
2011 • quasicrystals

CHEMISTRY

Figure 1
NOBELPRIZES
related to Materials Science since 2010

PHYSICS

2016 • topological materials
2014 • light-emitting diodes
2010 • 2D material graphene

2.5 Materials as a key enabling technology

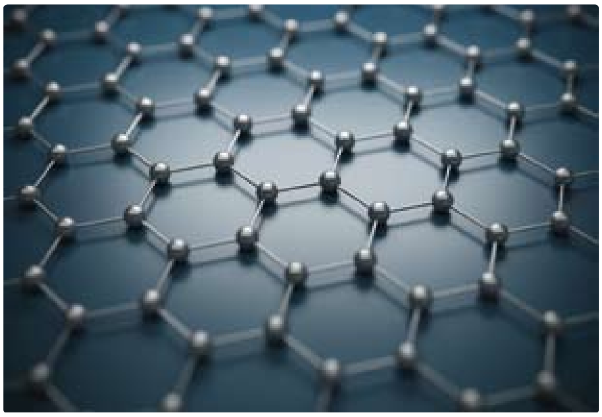
The previous sections described opportunities in materials research for breakthroughs in the societal missions Energy Transition and Sustainability; Agriculture, Water and Food; Health and Care; and Security. In addition, materials play a crucial role in generic and specialized key enabling technologies that are fundamental to solving societal challenges and strengthening the Dutch economy. Key enabling technologies often arise in a bottom-up manner from academic research and subsequently find important applications that nobody expected. They lead to spectacular new scientific discoveries, as shown by a constant stream of Nobel prizes (Figure 1).
Many Dutch companies generate millions or sometimes billions of euros in turnover from key enabling technologies that have demonstrated their market value. In addition, the Netherlands has a large number of startups which have arisen from laboratory discoveries that have subsequently led to commercial products. The continuous developments within the key areas make entirely new technology possible, which is of considerable economic importance for the Netherlands. There are too many examples to state here; we therefore limit ourselves to a few illustrative examples.

Photonics and lighting technologies

Optical 'metamaterials', thin coatings with a specially formed microstructure, can process light signals in a unique manner. This allows for new forms of image processing for applications in self-driving cars or a faster analysis of medical images. Using two-dimensional materials with a thickness of just several layers of atoms, extremely sensitive sensors can be made for medical applications, and optical switches that work at the speed of light. Such switches can be used to increase the speed of telecommunication networks and to realize lighting systems that consume less energy.

Nanotechnologies

Nanotechnology is a generic technology to build up structures and materials layer by layer. It forms the basis of nearly all applications described in the mission-driven chapters above: nanoparticles for the selective release of medicines in our body or in bactericidal coatings for safe food. New nanostructured catalysts for the efficient generation of solar fuel or self-repairing materials.



Such a constant stream of new applications arises because our fundamental understanding of the growth and synthesis of nanomaterials is increasing.

Quantum technologies

With quantum technology, certain computer calculations can be carried out exceptionally quickly, and an almost uncrackable encryption of data becomes possible. The technical realization of this requires special materials that can generate light particles one by one or that can maintain the spin of electrons for a long time. That requires a unique integration of materials science, optics, and electronics. Conversely, a quantum computer might make it possible to design new materials that can lead to entirely new applications.

Digital technologies

The growing trend of big data requires an increasingly larger capacity of our data networks and storage systems. Using new optical technologies, semiconductors and magnetic materials, the information speed and data capacity can be significantly increased.
Now that data centers account for a significant proportion of our energy consumption, new materials and concepts for energy-efficient information processing are essential. New developments in the area of artificial intelligence depend on the latest forms of image processing and the rapid information processing offered by photonics, nanotechnology, and quantum technology.

> “Materials are the physical building blocks that will allow us to make our society sustainable and circular.”

Hans van der Weijde | director programmes | Tata Steel

Advanced materials

Rapid steps are being made in the development of new materials with special mechanical properties. Tata Steel is developing (ultra) high-strength steel that is far stronger than conventional steel but has a far lighter weight. Fiber-reinforced composite material is a mechanical wonder that can tolerate both tensile stress and pressure load. With a high-quality thermoplastic composite material from Toray-TCAC, Dutch companies such as DTC and GKN-Fokker produce aircraft components. In construction materials such as concrete, new innovations are improving mechanical properties and reducing CO_2 emissions. Dutch materials companies are world leaders with their innovations and applications.

Chemical technologies

Chemical reactions lie at the basis of the composition of materials. At the molecular scale, chemists can control the structure and function of molecules (Nobel Prize for Chemistry for Ben Feringa et al., 2016). The big challenge is to steer atomic and molecular assembly in such a way that materials with the desired properties are realized. New advanced coatings, the new 2D (meta-)materials, the synthesis of nanoparticles for medical applications, to name but a few examples, are all driven by new developments in chemical technology. The major challenge is to reduce greenhouse gas emissions by deploying new technologies such as plasma processing and chemical recycling. The circular economy requires new methods for mechanical or chemical recycling and the optimization of materials for this.

Life sciences technologies

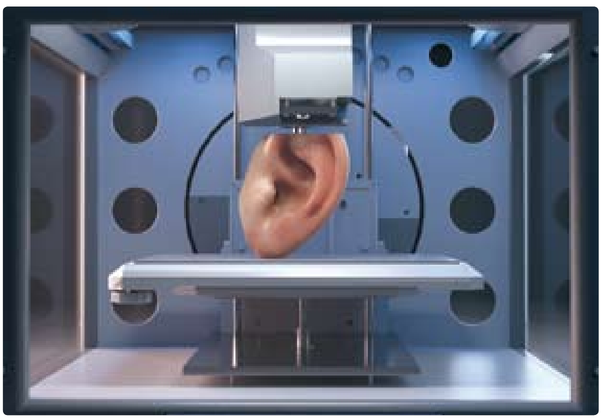
As described in Section 2.3, materials innovations give rise to an enormous improvement in our health. Artificially grown or printed tissues serve as replacements in our body, biosensors monitor our body functions, and nanoparticles are used for diagnostic and therapeutic applications. All these developments are still in their infancy and have a potential that is far greater than we can foresee today. The biggest successes are achieved where materials scientists and medical specialists collaborate directly with each other.

Engineering and manufacturing technologies

In materials research, state-of-the-art (cleanroom) manufacturing techniques and characterization techniques are essential. A high-quality production technology is vital for bringing successful material innovations to the market. The Netherlands is a worldwide leader in this technology. 3D printing is a revolutionary emerging technique in which increasingly complex material compounds are made; soft imprint technology makes nanopatterning possible on large surfaces, and new (roll-to-roll) processes generate thin layers and coatings for a large number of applications. Completely new forms of electron microscopy make it possible to image biological tissue in detail (Nobel Prize Chemistry 2017). Innovations in material analysis often lead to new Dutch startups, and some of these grow into multinationals.

> "This agenda has really helped me to expand my materials research network within the Netherlands!"

Monica Morales-Masis | associate professor of materials science | UT



③ Economic impact of materials

3.1 Contribution of materials to the Dutch economy

The manufacture of material products forms a significant part of the Dutch economy. For example, the manufacture of metal and metal products, machines and tools, and high-value plastics represented a turnover of more than 75 billion euros in 2018 (Figure 2). The top-5 of Dutch export products with the highest added value contains the same three materials-related areas, and in 2018 they added a total of 27 billion euros to the value of exports and therefore to the Dutch gross national product. The continuous innovations in new materials lead to an annually growing economy: for example, the turnover in material products rose by 18% in the period 2015-2018, and in the metal industry alone there are more than 100,000 jobs. At the same time, materials are a fundamental part of the entire Dutch industry and provided almost 800,000 jobs in the Netherlands in 2018.

3.2 Investments for further growth of the Dutch economy

Successful examples from the past reveal that Dutch materials innovations have provided a continuous stream of economic revenues for many years. As shown in Figure 3, the Dutch economy still benefits from discoveries made in the 1970s and 1980s (high-strength fibers, composites, optics). It can also be expected that new investments in materials research in the coming years will lead to billions of euros in revenues throughout the many decades in the coming century.

As an example, Box 1 presents a study by Roland Berger into the effect of further investments in materials research for the coatings industry. Investments in coatings research could yield an increase in the annual turnover of about 4 billion euros in 2030.

3.3 Materials research for the sustainable development goals

The Netherlands is striving to achieve an almost completely CO_2-neutral economy by 2050. Figure 4 provides an overview of the annual CO_2 emissions of the different sectors of Dutch society. Primary energy generation, industry, transport, agriculture, and the built environment all make a considerable contribution to the 180 metric megatons of CO_2 that the Netherlands generates each year.

Innovations in materials research contribute to a strong reduction of CO_2 emissions in each of these sectors. This Dutch Materials Agenda (Appendix A) offers a guide for investment in research so that

Box 1 | Growth potential of the Dutch coatings industry

The coatings sector in the Netherlands has an annual turnover of about 3 billion euros, employs about 6000 people, and has an annual growth of about 6%. As described in Chapter 2, specialist coatings make new applications possible in the medical and food industry, construction materials, new systems for the generation of sustainable energy, and far more. Thanks to years of investments in coatings research, the Netherlands leads the way in academic research: coatings research in the Netherlands occupies the second place in the citation impact of the top-10 largest European countries in coatings research.

Further investments in coating materials research will lead to a large number of new innovations and new products: anticorrosion coatings, coatings that adapt to their environment, foils to improve solar panels, and more. This Dutch Materials Agenda (Appendix A) describes the new research directions to achieve these objectives. With this approach, the Netherlands will maintain its leading position in coatings technology.

An intensification of further investments in coating innovations and research infrastructure could increase the annual growth of the coating industry to about 7%. In 2030 that will yield a turnover for the industry that is 4 billion euros higher than in 2018.

Figure 2 | Top-10 Dutch export sectors

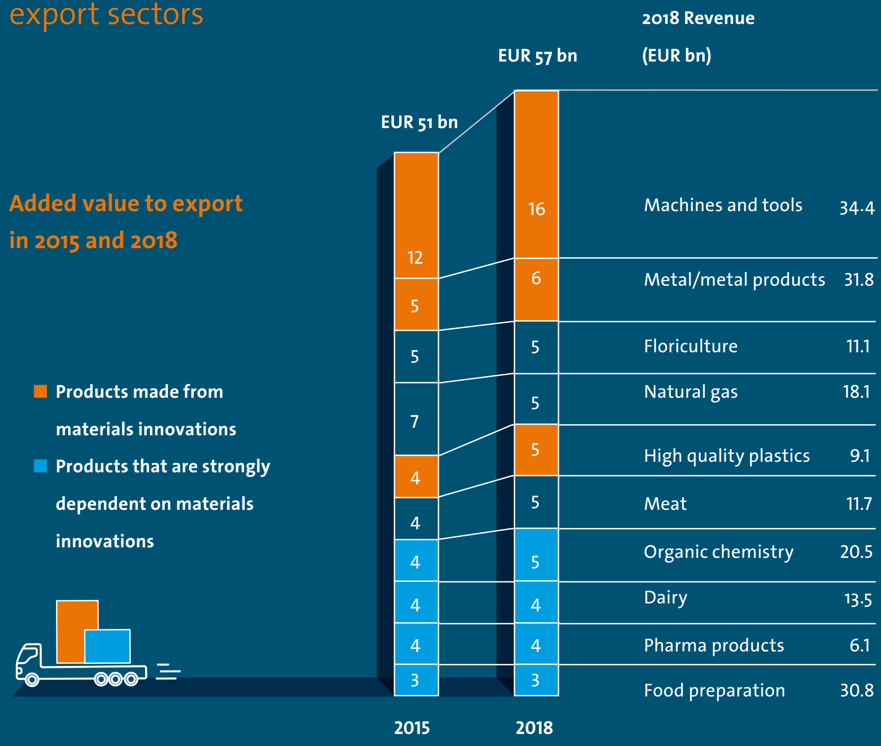
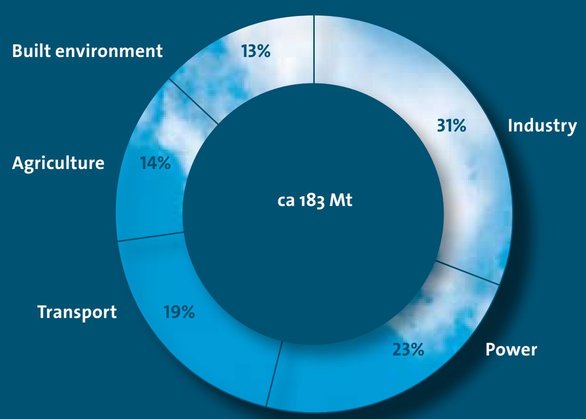


Figure 3 | Material innovations provide a continuous revenue many years after the initial discovery

Discovery	Product	Company	Turnover 2019 (€ millions)
1970s	Synthetic fibers, para-Amid	AkzoNobel/Teijin Aramid	>1.000
1980s	Aluminum/glass composite	AkzoNobel/Fokker/GKN	771
1980s	Lithography technology	Philips/ASML	3.700
1990s	Thermoplastic fibers, Dyneema	DSM	338

Figure 4 | Annual CO_2 emissions per sector



Materials innovations can help to reduce the emissions in all sectors. The Netherlands is striving to achieve an almost completely CO_2-neutral economy by 2050.

Source: Roland Berger (2020)

we achieve our objectives for 2050. Increasing the sustainability of primary energy generation by using solar and wind energy combined with new energy storage systems is described in Section 2.1. As an example, Box 2 presents an analysis for strengthening the Dutch industry for solar panels. New investments in materials research and other areas have the potential to establish an industry with an annual turnover of more than 1 billion euros, which will reduce the annual CO_2 emissions by more than 4 million metric tons CO_2/year.

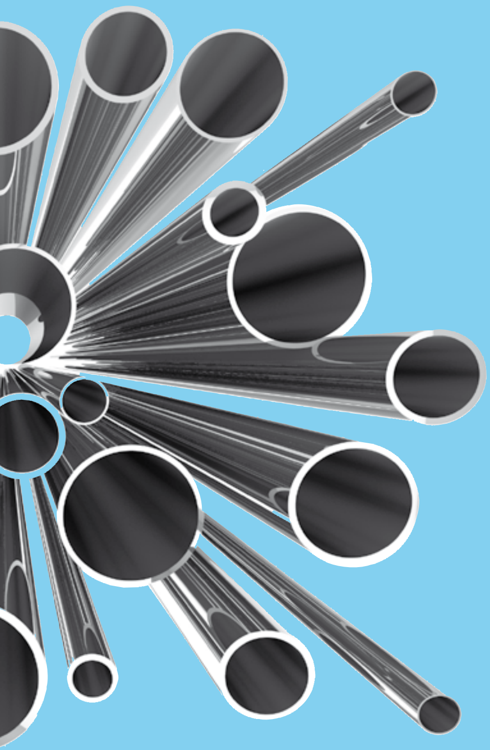
Furthermore, in the coming years, a growing reduction in CO_2 emissions will be achieved through the electrification of transport, partly made possible by new battery materials. Emissions in the built environment will be reduced, on the one hand by the use of more sustainable primary energy sources and on the other hand by the development of new construction materials and techniques that emit less CO_2 (see Section 2.5). Adapting industrial processes to strongly reduce their CO_2 emissions is a considerable challenge. As an example, Box 3 presents an analysis of the sustainable manufacture of steel.

> "New materials and material technologies are vital if our industry is to remain at the cutting-edge of innovation."

Rolf van Benthem | corporate science fellow DSM | professor of coatings technology | TUE

Box 2 | A stronger Dutch industry for solar panels

Worldwide, solar energy still only accounts for 1% of the total energy generation. If the international objectives are to be achieved, then the worldwide production of solar panels needs to increase by a factor of 20 to 40; an enormous challenge. This offers unique economic opportunities for the Netherlands. The solar energy sector in the Netherlands already provides 22,000 jobs. The worldwide turnover in solar energy related technology exceeds 100 billion euros.
The National Climate Agreement of the Netherlands states that in 2030, 70% of our electricity must be generated from renewable sources. A considerable part of that will come from solar energy, for which the Netherlands has a strong ecosystem. Dutch research institutes are developing new concepts and have a prominent position (second place in the European citation statistics). Various companies in the Netherlands and other European countries manufacture equipment for the production and testing of solar cells, solar panels, systems, and installations. However, the manufacture of solar cells, panels and other components in Europe only takes place on a small scale. That is a big strategic risk and a missed opportunity. It makes the Netherlands dependent on other countries outside of Europe for such an essential part of the energy infrastructure. Furthermore, the enormous economic potential of a global market of more than 100 billion euros that will grow more than tenfold in the coming years is an opportunity that we will largely miss.
Recent developments provide a new perspective for the Netherlands and Europe. Due to further automation, the production of solar cell technology is also becoming competitive in the Western world. Local production leads



Box 3 | A future-resilient Dutch steel and metal products industry

The manufacture of steel and metal products forms one of the biggest industrial branches in the Netherlands and is a crucial part of the Dutch economy. More than 100,000 people are employed in this sector, which has an annual turnover of more than 30 billion euros in the Netherlands. The Netherlands has a prominent position in materials research (second in the citation statistics for steel-related publications of the 10 biggest countries in steel research in Europe). Metallurgy researchers collaborate closely, and the Materials Innovation Institute M2i fulfils a strong coordinating role.

The worldwide steel and metal industry is extremely competitive and continuous innovations are necessary for the Netherlands to survive in this competition. With the development of special types of steel and steel-based products, the Netherlands has managed to maintain a good position so far. Due to the implementation of European rules for the trading of CO_2 emission rights, steel products will strongly increase in price in the coming years. The Dutch steel industry must therefore adjust its course to maintain a strong position and to retain economic strength for the Netherlands. The industry will not be able to survive without these innovations.
In the short term, the capture, conversion, and storage of the CO_2 emitted during the production process is a solution. Parallel to this, revolutionary new production methods will be developed in which sustainably generated electrical heating will be used at a large scale, possibly combined with the use of hydrogen. That could reduce the CO_2 emissions by 40%. In addition, an even greater recycling of steel products (more than 85% is currently recycled) will further reduce the energy consumption in this sector. New innovations in the manufacture of steel and steel products provide fantastic economic opportunities. Roland Berger predicts a large growth potential if the Netherlands creates a technological lead in this new technology, with possibly billions of euros in turnover and a large number of new jobs. Conversely, failing to keep up would mean that this industry will ultimately not survive in the Netherlands.

Bron: Roland Berger (2020)

to lower transport costs, which is relevant due to the lowering prices of solar cell/panel technology. This trend will be strengthened further by the arrival of integrated solar energy components and systems, such as power-producing building elements, which are highly suitable for local production. Internationally, the Netherlands plays a leading role in that area. In addition, our strong position in advanced technology and the prospect of strict European standards in the area of integral quality and the environment create opportunities for bringing high-quality, sustainable products onto the market. All these new developments provide unique opportunities for setting up new solar cell/panel technology, specifically in Europe. European initiatives have been brought together in the Solar Manufacturing Accelerator, which contains companies such as Meyer Burger Technology (Germany), ENEL Green Power (Italy), and consortia such as Genuine European Solar and 5GW+ Green Fab, in which many Dutch bodies also participate, such as the Dutch company Energyra and Dutch applied research institute TNO. Roland Berger supposes that within this European context, with the right investment and subsidies, it should also be possible to establish a competitive solar panel industry in the Netherlands with an annual turnover of more than 1 billion euros. The electricity generated from these panels will reduce the annual CO_2 emissions by more than 4 million metric tons CO_2/year. This Dutch Materials Agenda (Appendix A) describes the investments needed in materials research that will enable Dutch solar cell technology to remain at the international forefront.

④ Research themes
from thee Dutch Materials Agenda

This Dutch Materials Agenda was written on behalf of the MaterialsNL Platform that was established in 2019. The aim of the platform is to bring together researchers from universities, NWO Institutes, applied technology organizations, universities of applied sciences, companies, and other materials organizations to further strengthen collaboration and technology transfer in the area of materials. The platform was established by the Top Sectors Chemistry, Energy, and HTSM. The names of the members of the MaterialsNL Platform are stated in Appendix B. One of the Platform's first initiatives was writing this Dutch Materials Agenda.

The strong synergy present in the materials field is partly due to the coordination started in 2015 under the initiative of the former NWO divisions of Physics (FOM) and Chemistry (CW) with support from Technology Foundation STW (now NWO Domain Applied and Engineering Sciences), as a result of which the Theme Committee Materials was established as an advisory committee of NWO. This resulted in the publication of the first strategic vision report 'Dutch Materials – Challenges for Materials Science in the Netherlands' in 2016. The Theme Committee of NWO also initiated the route 'Materials - made in Holland' of the Dutch Research Agenda (NWA) and forms the management of this route. Previously, the establishment of technological top institutes, such as NIMR/M2i, DPI, and TIFN, was vital for organizing the materials field in subareas.

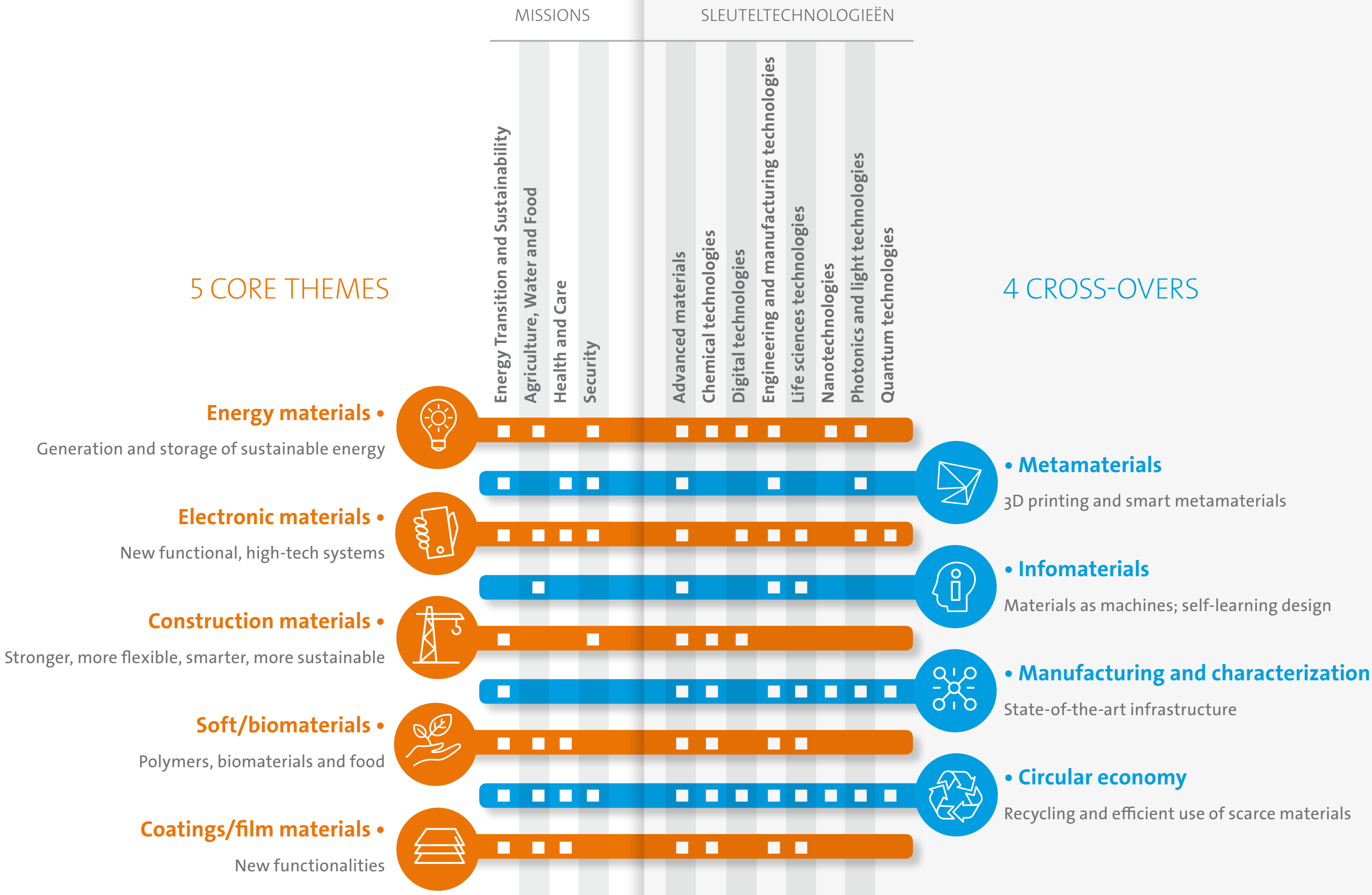
Under the leadership of this broadly composed MaterialsNL Platform several workshops have been held to obtain input from the Dutch materials community for this Dutch Materials Agenda and to further encourage collaboration between materials scientists and companies. In total, about 250 materials scientists contributed to the content of this Dutch Materials Agenda.

Figuur 5 | Workshop *Materials - made in Holland*, November 26, 2019

The Dutch materials community is therefore very well organized, and it supports the research themes from this Dutch Materials Agenda. Chapter 2 described how materials research can provide solutions to societal problems within the missions Energy Transition and Sustainability; Agriculture, Water and Food; Health and Care; Security; and the Key Enabling Technologies. There are also many interconnections between all of these challenges. The Dutch materials community wants to tackle the challenges with a coordinated research plan that contains five core themes (Figure 6). The integration of the five core themes and the four cross-over themes with the missions and key enabling technologies is illustrated in Figure 6. Appendix A provides a detailed description of the scientific challenges.

Figure 6 | Core themes and cross-connections with this Dutch Materials Agenda

...and how these relate to the societal missions and key enabling technologies



"Strong connections with the materials field are vital for our success as a scale up."

Matthijn Dekkers | CTO | Solmates

⑤ Dutch ecosystem
for materials research

5.1 Universities, NWO institutes and universities of applied sciences

Dutch materials research is realized by research groups at nearly all universities in the Netherlands as well as the NWO Institutes AMOLF, ARCNL and DIFFER. In total, about 200 assistant, associate, and full professors at universities and about 30 research group leaders at NWO institutes lead programs for materials research. Together they supervise more than 1000 PhD students and postdocs in materials research. In addition, each year hundreds of master's students are trained in materials science in master's programs related to materials. Many of them find a job in the Dutch materials industry.
Seven universities of applied sciences carry out practice-oriented research under the leadership of professors in materials science. For many decades, Dutch materials research belongs to the best in the world as revealed by international citation analysis.

5.2 Technological research organizations and institutes

The Netherlands has a large number of organizations and institutes that focus on the technical aspects and applications of materials research: Brightlands Materials Center, Brightsite, Deltares institute for applied research in the field of water, Polymer Research Platform (DPI), Institute for Sustainable Process Technology (ISPT), the Materials Innovation Institute (M2i), Netherlands Aerospace Centre (NLR), the Netherlands Organisation for Applied Scientific Research (TNO), the Top Institute Food and Nutrition (TIFN), and Wetsus European centre of excellence for sustainable water technology. In addition, Field Labs and Open Innovation Centers play an important role in the collaboration with small and medium-sized enterprises. In recent years, various public-private partnership projects have also been realized at the regional level (Figure 7).

5.3 Dutch materials industry

The Netherlands has a large number of knowledge-intensive materials industries (Figure 9). The large multinationals AkzoNobel, ASML, Dow, DSM, Philips, Shell, Tata Steel, and Unilever have large R&D laboratories in the Netherlands. These laboratories have a long history of translating science into technology, and strong relationships exist between these laboratories and universities and research institutes in the Netherlands. Many small and medium-size enterprises bring a wide range of materials-related products to the market.
In addition, there is a strong manufacturing industry that acts as a supplier for the materials industry or as a manufacturer of analysis equipment for the industry and the academic world. Dutch materials companies work closely together with academic partners and much of the long-term research is realized in public-private partnerships.

The field of materials science is also an ideal breeding ground for startups that emerge from academic research groups and technology institutes (Figure 10).

Figure 7 | Examples of Field labs and Open Innovation Centers

Digital Factory for Composites
DFC, South-Holland

SAM|XL
South-Holland

Development Centre for Maintenance of Composites
DCMC, Brabant

ThermoPlastic Composites Competence Centre
TPC NL, Overijssel

Automated Composites & Metal Manufacturing and Maintenance
ACM3, Flevoland

Figure 7 | Materials ecosystem in the Netherlands

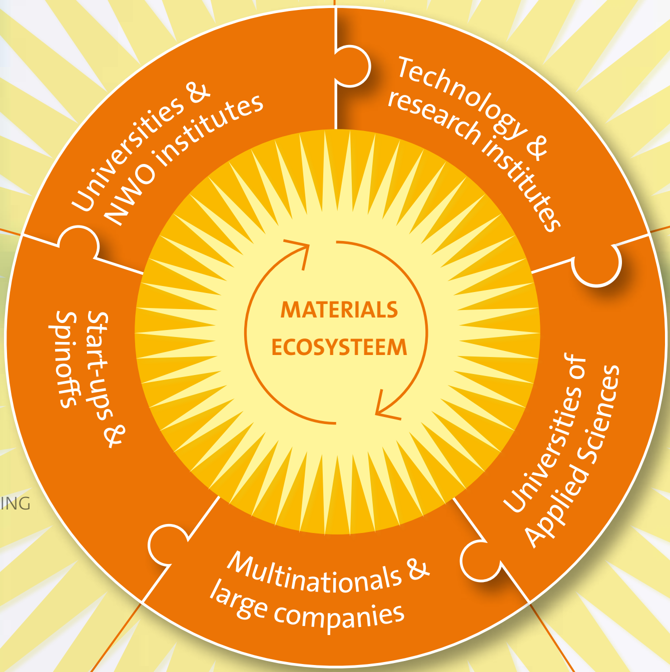
UNIVERSITIES
- Eindhoven University
- Delft University of Technology
- Groningen University
- Free University Amsterdam
- Leiden University
- Maastricht University
- Radboud University
- University of Amsterdam
- University of Twente
- Utrecht University
- Wageningen University and Research Center

NWO-INSTITUTES
ARCNL
DIFFER
AMOLF

Universities & NWO institutes
- Perform leading research led by ~200 professors in universities and ~30 group leaders in NWO institutes
- Train >1000 academic researchers (PhD and post-docs) and hundreds of master students each year who work on materials-related topics

Technology & research institutes
- Conduct top-notch research in the fields of advanced materials, polymers, food & nutrition, energy, health, etc., in-house or in collaboration with universities and academic partners
- Employ more than 2,000 scientists and technicians for materials research

TECHNOLOGY INSTITUTES
Brightlands
Brightsite
Deltares
DPI
ISPT
M2i
NLR
TNO
TIFN
Wetsus



Start-ups & spin-offs
- Shape and disrupt sectors with materials innovation based on profound scientific knowledge

MATERIALS CHARACTERIZATION
LPM
Dens
Delmic
Confocal
Cryosol
MiLabs
DSG
Nearfield Instruments
FuQon
Lumicks
In Ovo

THIN FILMS/COATING
Qlayers
Lusoco
Lipocoat
Solmates
Sponsh
Luch
Octo

OPTICAL INSTRUMENTS
Xio Photonics

BIOMATERIALS
Innocore

ENERGY MATERIALS
Physee
LeydenJar

Universities of Applied Sciences
- Conduct practice-oriented research on various topics
- Train the new generation of employees for the materials industry

SUSTAINABLE PLASTIC
NHL Stenden
Windesheim

COMPOSITES
InHolland Hogeschool

NANOMATERIALS
Zuyd

HIGH TECH SYSTEMS & MATERIALS
Saxion
Fontys

NEW MATERIALS & SUSTAINABILITY
Avans Hogeschool

Multinationals & large companies
Build sizeable business on commercialization of materials innovation and/or products/services that include materials innovation

COATINGS
AkzoNobel
DSM

CHARACTERIZATION TECHNIQUES
Thermo Fischer Scientific
Malvern Panalytical

BIOPLASTIC
Avantium
Corbion

FOOD
Danone
Avebe
Unilever
FrieslandCampina

SEMICONDUCTORS
NXP
ASM
Levitech

INDUSTRIALS
DAF
Nedal
Damen
VDL
Demcon
Tata Steel

INSTRUMENTS
ASML
LioniX
Océ
Philips

Bron: Roland Berger (2020)

Figure 8 | Companies that are involved in materials research

...and that are either located in the Netherlands or located elsewhere but have a significant research/production activity in the Netherlands (non-exhaustive list), with the missions and/or key enabling technologies to which the companies contribute.

		MISSIONS				KEY TECHNOLOGIES							
COMPANIES	PRODUCTS	Energy Transition and Sustainability	Agriculture, Water and Food	Health and Care	Security	Advanced materials	Chemical technologies	Digital technologies	Engineering & manufacturing technologies	Life sciences technologies	Nanotechnologies	Photonics and light technologies	Quantum technologies
AkzoNobel	paint, coatings	■				■	■						
ASMI	semiconductor equipment								■		■	■	
ASML	EUV lithography							■	■		■	■	
Avantium	bioplastics	■	■			■	■				■		
Avebe	starch products	■	■			■	■						
BASF	catalysts, coatings	■	■	■		■	■			■	■		
Bronkhorst High-Tech	flow measurement and control		■	■					■				
CRH	building materials	■				■	■						
Corbion	food and biochemicals	■	■			■	■			■			
Danone	food products		■	■		■	■			■			
Damen	shipbuilding	■				■			■				
DAF	trucks	■						■	■				
Demcon	machine construction			■					■		■	■	
DSM	functional polymer materials	■	■	■	■	■	■			■			
Dow Benelux	polymers	■	■	■	■	■	■			■			
DTC	aerospace					■	■		■				
Dura Vermeer	construction & infrastructure	■				■	■		■				
GKN Fokker	systems for aerospace					■	■	■	■				
Friesland Campina	food products		■	■		■	■			■			
Fujifilm	coatings					■	■		■		■	■	
Heijmans	construction	■				■			■				
Kingspan	insulation materials	■				■							
Lanxess	polymers	■				■	■						
Lionix	optical instruments					■			■		■	■	
Malvern Panalytical	material characterization					■			■		■	■	
Medtronic	biomedical			■					■	■		■	
Micronit Microfluidics	microfluidic instruments					■			■		■	■	
Nedal	aluminum extrusion	■				■			■				
Nouryon	(specialty) chemicals	■	■	■		■	■			■			
Nyrstar	metals	■				■	■						
NTS	machine components	■		■	■	■		■	■	■	■	■	
NXP	semiconductor components	■							■		■	■	
Océ/Canon	printers, photocopiers					■	■	■	■		■	■	
Paques	recycling, waste treatment	■				■	■			■			
Pervatech	membranes		■			■					■		
Philips	biomedical technology			■		■		■		■	■	■	
Photonis	photodetectors				■	■						■	
PPG	coatings	■				■	■						
Prorail	rail transport	■				■							
QCP	polymers	■				■	■						
RWS	transport	■				■			■				
Sabic	polymers	■	■	■		■	■			■			
Shell	oil and gas technology	■				■	■						
Signify	lighting	■				■		■	■			■	
SKF	bearings	■				■	■		■				
Synbra	packaging	■				■	■						
Tata Steel	steel and metal products	■				■	■		■				
Teijin Aramid	high-performance fibers	■				■	■						
Tempress	ovens	■							■				
Thales	sensor systems				■	■			■		■	■	
Thermo Fisher	microscopes, reagents		■	■					■	■	■	■	
Toraytech	composites	■				■	■		■				
Unilever	food, biopolymers		■	■		■	■			■	■		
VDL	metals, plastics, high tech	■				■			■			■	

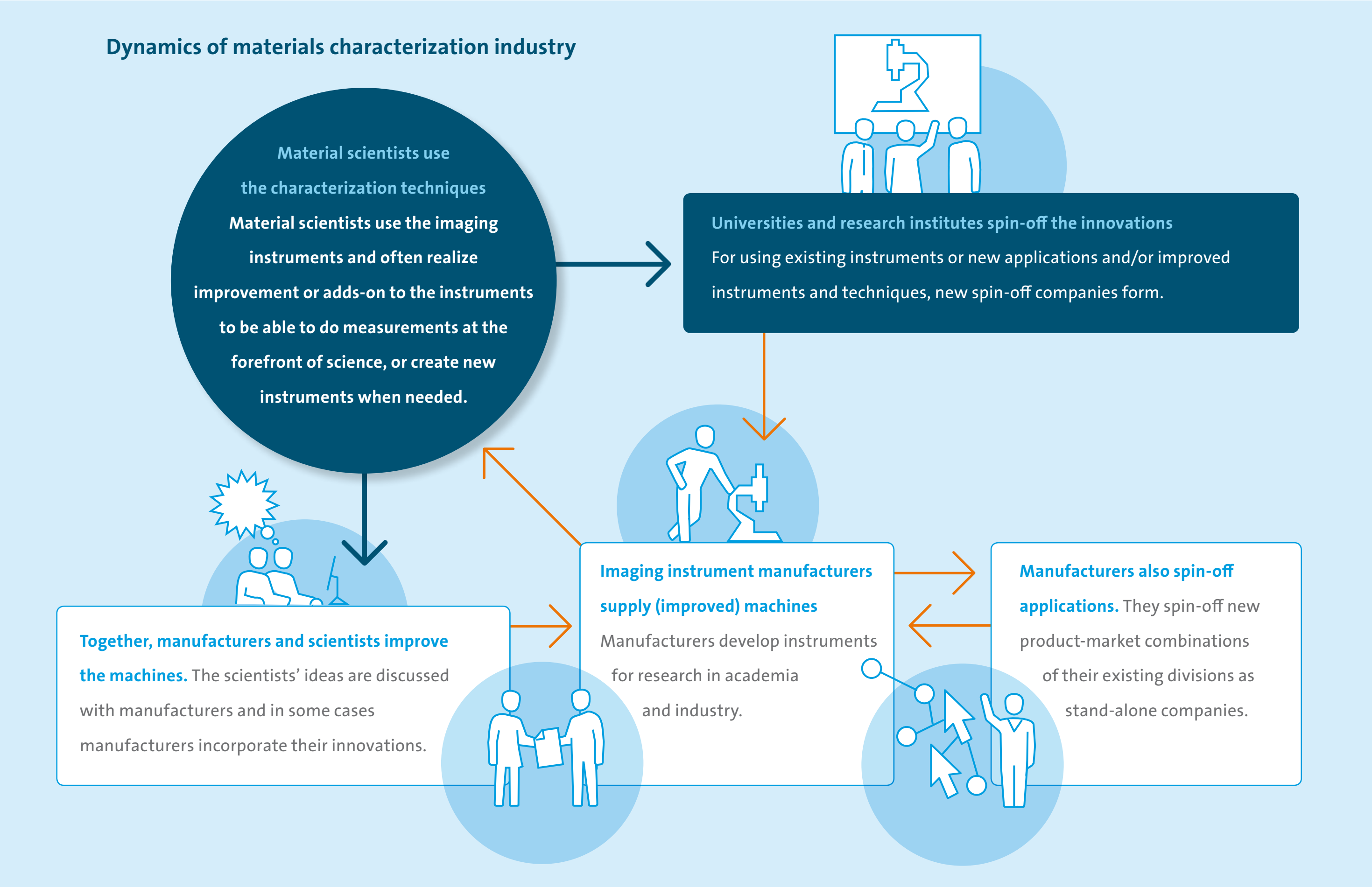
Figure 9 | Materials-related startups

...with the missions and/or the key enabling technologies to which the companies contribute (non-exhaustive list).

START-UPS	PRODUCTS	MISSIONS: Energy Transition and Sustainability	MISSIONS: Agriculture, Water and Food	MISSIONS: Health and Care	MISSIONS: Security	KEY TECHNOLOGIES: Key Enabling Technologies	KEY TECHNOLOGIES: Advanced materials	KEY TECHNOLOGIES: Chemical technologies	KEY TECHNOLOGIES: Digital technologies	KEY TECHNOLOGIES: Engineering & manufacturing technologies	KEY TECHNOLOGIES: Life sciences technologies	KEY TECHNOLOGIES: Nanotechnologies	KEY TECHNOLOGIES: Photonics and light technologies	KEY TECHNOLOGIES: Quantum technologies
3DPPM	recycling 3D printing materials	■				■								
Admatec	3D printing ceramics, metals	■				■			■					
Airborne	composite structures	■			■	■			■					
Allotropy	engineering plastics	■			■	■	■							
Amsterdam Scientific Instruments	pixel detectors								■		■	■		
Applied Nanolayers	graphene layers					■			■					
Concr3DE	3D printing of materials	■				■			■					
Cristal Therapeutics	nanomedicines			■			■			■	■			
Cumapol	recycling	■				■	■							
Cure	recycling	■				■	■							
Delmic	correlative microscopy		■	■				■	■			■		
Encapson	coatings for medical instruments			■		■	■			■				
Ingell technologies	hydrogel syst. for drugs			■		■	■			■				
InnoCore Pharmaceuticals	polymer syst. for drugs			■		■	■			■				
Ioniqua	polymers	■				■	■							
Heros	recycling	■				■								
HQGraphene	graphene on 2D materials					■					■			
Leiden Probe Microscopy	material characterization										■	■		
Levitech	growth/deposition thin layers					■	■		■					
Lightmotif	laser surface control								■					
Mattech	lead-free soldering materials					■			■					
Materiomics	biocompatible surfaces			■		■								
Mineralz	recycling	■				■	■							
MX3D	3D printing metal	■				■			■					
Octopolus	polymer syst. for drugs			■		■				■				
Omics2Image	molecular imaging			■								■		
PMC Recycling	recycling	■				■	■							
Qlayers	coating machines					■	■							
Ramlab	3D printing of metals	■				■	■							
SCIL	nanoimprinting	■				■			■		■	■		
Shapeways	3D printing materials					■								
Single Quantum	light detectors											■	■	
Solmates	growth and deposition thin layers					■	■							
Spinnovation Analytical	materials analysis through NMR								■		■			
Surface Preparation Laboratory	surface preparation					■			■					
Surfix	nanocoatings			■		■	■				■			
SyMO-Chem	customized materials synthesis					■								
Triboform	simulations					■								
XIO Photonics	optical instruments											■		
VSParticle	nanoparticle synthesis					■	■				■			

Figure 10 | Innovation cycle for startups in material analysis

Researchers at academic or technology institutes develop new concepts from which spin-offs arise. Some grow into multinationals (Figure 11).



Bron: Roland Berger (2020)

Together, these small companies provide employment for several hundred employees, and their existence demonstrates the considerable vitality of the Dutch materials ecosystem. Their growth often strongly depends on the collaboration of academic partners and technology institutes as an effective innovation cycle that all parties benefit from (Figure 11).
Some Dutch startups grow into multinationals with a turnover of millions or billions of euros, such as FEI/ThermoFisher, Malvern Panalytical, and ASML (Figure 12). Continuous investment in materials research will keep yielding new startups in the Netherlands in the future, from which new multinationals will emerge that can make a major contribution to the Dutch economy.

5.4 Dutch facilities for materials research

State-of-the-art materials research requires a high-quality infrastructure. With all its material organizations, the Netherlands has a modern collection of specialized equipment for realizing research. A number of large and expensive facilities have been set up as user facilities: the cleanroom facilities of NanoLab, the electron microscope consortium NEMI, the high magnetic field lab HFML, the free-electron laser FELIX, and the neutron and positron techniques of RID. In addition, universities and institutes are developing specialized equipment that is sometimes made available as a facility for external users. Dutch researchers also make successful use of large European material analysis facilities such as ESRF (Grenoble, France) for X-ray analysis and ESS (Lund, Sweden) for neutron analysis. The deployment and training of highly qualified technical and scientific support staff is essential for managing and maintaining the technical infrastructure. Continued investments in infrastructure are vital if the Netherlands is to continue participating at the forefront of research.

> "New investments in research infrastructure are essential for realizing breakthroughs in materials research."
>
> Jilt Sietsma | professor of materials science and engineering | TUD

5.5 Dutch materials research in an international context

Dutch research is strongly linked with the programming of the current European research program Horizon 2020. In this program, materials science is embedded in the European key enabling technologies (KETs), which enable the European industries to maintain their competitive position and expand into new markets. Within Horizon 2020, nanotechnology, advanced materials, advanced production processes, and biotechnology are technologies that strongly overlap with this Dutch Materials Agenda.
Horizon Europe, the new program for research and innovation of the European Union (2021-2027) has a budget of 96 billion euros and focuses on global challenges and the European industrial competitive ability. Industrial technologies, advanced materials, circular industry, and CO_2-free and clean industries are main themes just like they are in this Dutch Agenda Materials. It is vital that Dutch researchers participate in the forthcoming major European research programs that are aimed at materials science research and innovation. This Dutch Materials Agenda describes research themes the Netherlands excels in. It can therefore help to obtain a significant part of the Horizon funding for Dutch researchers.
The European Union has the intention of being climate neutral by 2050. To this end, the European Commission has drawn up the 'European Green Deal', an action plan to switch to a clean, circular economy, restore biodiversity, and reduce pollution. The Green Deal will be shaped in the coming years, and it has a direct relationship with the theme Energy Transition and Sustainability described in Section 2.1 of this Agenda. Dutch researchers are therefore well positioned to participate in the Green Deal initiatives and to spend funds from this in the Netherlands.

Figure 11 | Innovation cycle for startups in material analysis **researchers at academic or technology institutes develop new concepts from which spin-offs arise. Some grow into multinationals (Figure 12).**

FEI/Thermo Fisher	Malvern Panalytical	ASML
Electron microscopes for materials analysis	X-ray and microscopy instruments for materials analysis	Wafer steppers for lithography for chip production
>700 employees in the Netherlands	1,000 employees in the Netherlands	>6,000 employees in the Netherlands
annual turnover in the Netherlands 264 million euros (2018)	global annual turnover 448 million euros (2019)	global annual turnover 11.8 billion euros (2019)

Bron: Roland Berger (2020)

6 Funding of the Dutch Materials Agenda

This report describes the materials sciences research questions within the societal missions Energy Transition and Sustainability; Agriculture, Water and Food; Health and Care; Security; and the Key Enabling Technologies. It describes Focus Areas in which Dutch researchers are strong and want to consolidate their strengths. Together, these researchers are capable of formulating and realizing successful, large, coordinated research projects. If we want to retain our welfare and at the same time tackle societal challenges, then new groundbreaking materials technologies are essential.

> "Thanks to this agenda, the strong Dutch materials eco-system is exceptionally well organized for generating new innovations."
>
> Christa Hooijer | director of science, unit industry | TNO

NWO – programming Knowledge and Innovation Covenant (KIC): NWO makes about 120 million euros available each year within the KIC 2020-2023 for research that fits within the strategic choices of the Mission-driven Top Sectors and Innovation Policy. This Dutch Materials Agenda describes materials research at the heart of the three Top Sectors Energy, Chemistry, and HTSM and right across the four societal missions, and serves as input for the annual strategic programming within the *mission* line of the KIC. Each year, calls can be published for large, focused materials programs that fall within the main core themes described in this Dutch Materials Agenda (Appendix A). This Dutch Materials Agenda can also serve as a basis for proposals within the *Demand* and *Strategy* lines of the KIC.

Top Sectors Chemistry, Energy, and HTSM: the Dutch Materials Agenda can serve as a guideline for the Top Sectors to initiate focused research programs using their own funds.

Societal missions: the mission-driven approach of the four major societal challenges ensures a connecting impulse for materials research in the Netherlands via separate project calls, such as MOOI, and the use of funds from government ministries.

Non-thematic programs NWO, Dutch Research Agenda (NWA): the composition of this Dutch Materials Agenda has brought together Dutch materials science researchers and with that inspired the establishment of joint research proposals to NWO and NWA. In the future, this Dutch Materials Agenda shall continue to play that role. This Dutch Materials Agenda can also serve as a basis for thematic programming within the thematic programming of the NWA. Within the NWA, materials is a separate route in addition to the relevant routes Energy transition, Circular economy and resource efficiency, and Measuring and detecting. There are close connections between the MaterialsNL Platform and these NWA routes.

National Growth Fund: this Dutch Materials Agenda will provide the basis for an integrated proposal for the National Growth Fund in which the impact of materials research on societal themes and the strengthening of the Dutch economy will take center stage. For this, a National Program Materials – Accelerating Materials Technologies will be put together in consultation with all parties involved. This program will focus on nationally supported investments into fundamental research, technology development, and product development.

Ⓐ Materials Research Focus Areas & Cross-overs

This appendix describes 9 Focus Areas that each address the societal challenges, building on the strengths of the Dutch materials ecosystem. Each Focus Area covers the entire chain from fundamental research through technological development to industrial applications. All 9 Focus Areas will lead to important scientific discoveries and breakthrough innovations; key research directions are described in each Focus Area description. An important element in all topics is that they require multidisciplinary integration of physics, chemistry and engineering. Moreover, each of them requires a combination of experimental methods and theoretical/computational modelling. The Focus Areas and Enabling Themes concern medium-term (2-5 years) and long-term (5-10 years) goals: research that is typically not carried out by industry (alone).

FOCUS AREA 1 Energy materials

Mitigating climate change is one of the biggest societal challenges today. It concerns the transition from a society based on fossil fuels to one based on renewable energy to minimize CO_2 emissions into our atmosphere. Such a transition requires efficient harvesting of renewable energy, efficient storage at different timescales and for stationary as well as mobile applications, and efficient conversion. Several key enabling technologies have already put us on the right path towards large-scale renewable energy applications, which can be well-integrated in various application areas, ranging from the built environment to agricultural landscapes and water bodies.

Photovoltaic (PV) panels convert sunlight directly into electricity, wind turbines convert the wind's kinetic energy into electricity, and geothermal energy can be harvested and used for heating purposes or can be converted into electricity. Electricity can be stored in solid-state batteries for (mostly) short-term use or mobile application, and flow batteries offer large-scale storage. Electro-catalysis uses electricity to form hydrogen or other chemical fuels that can be used to alleviate the intermittency

of solar and wind power through (long-term) energy storage and to enable the use of clean fuels in transportation. To combat climate change, we need to rapidly apply the existing technologies at a large scale and we need to further develop technologies that should lead to increased efficiencies, lower costs, and (enhanced) sustainability. Major breakthroughs in materials design and fabrication are therefore essential, with the circular use of materials as a boundary condition. A few key examples are described below.

Harvesting Today, commercial photovoltaic systems are limited to an energy conversion efficiency of only 20%. If this could be increased to 30 or 40%, it would strongly reduce the land area needed for large-scale utilization of PV (which is at least a hundred thousand square kilometers around the world). Higher efficiencies will also lower the costs to the desired 0.01-0.02 €/kWh. In addition, novel, semi-transparent, colored and flexible PV materials are needed to efficiently and invisibly integrate PV into buildings, landscapes, and infrastructure, and so PV materials should be customized by design features, such as transparency and color. To reach these ambitious goals, a broad range of novel materials and concepts must be explored, including flexible perovskite films, earth-abundant semiconductors, tandem cell designs, transparent conductors, hybrid materials, two-dimensional materials, selective contact layers, inexpensive III-V semiconductors, light management architectures, and ultrafast low-cost and customizable manufacturing. In wind energy, major materials breakthroughs have already led to large-scale implementation of multi-MW wind turbines. At these very large scales, novel materials with extreme strength at low mass, and with very high wear and corrosion resistance are needed. Materials design for geothermal energy production is needed to arrive at cost-effective solutions.

Storage In battery technology, a further increase in energy density (J/kg) is needed for widespread application in electric transportation, including aviation. Lithium-ion batteries have enabled a booming electric vehicle market but suffer from high costs and the use of scarce materials. Key research areas include the replacement of lithium as an energy carrier by sodium or magnesium, the development of carbon- and silicon-based electrode materials and new (nanostructured) separators and electrolytes to improve battery performance, or the replacement of liquid electrolytes by solid-state battery materials to increase the energy density, lifespan, and safety. Polymer supercapacitors are promising for short periods of storage but require novel lamination technology and improved electrical breakdown resistance. Flow batteries offer large-scale storage with minimal material use but require improved electrodes, membranes, and electrolyte materials. Heat storage can become important but is currently associated with challenges for materials design including corrosion resistance and cost-effective insulation. Novel materials for more efficient hydrogen storage under high pressure are also needed. These materials could be applied in compressed air storage systems for large-scale grid applications.

Conversion Electrolysis to use electricity to generate hydrogen is currently in scale-up phase. In (photo) electrocatalysis the best solar-to-fuel efficiency (PV electrolysis) demonstrated so far is 20%, leaving much room for improvement. In electrocatalysis, the key challenge is creating new selective and durable (molecular) catalyst materials, made from earth-abundant materials or minimum amounts of rare elements, which produce methanol or ammonia from carbon dioxide/nitrogen and water or that generate hydrogen and oxygen from water. The generation of high-end chemicals can also be realized with electrocatalysis, which may become an integrated part of the system. Practical realization of solar fuel generators requires the complex integration of materials, liquids, and gases in one system, together with electronic circuitry and light. Using similar technology, the conversion of CO_2 to liquid or solid materials is a key, new energizing technology that requires novel dedicated catalysis and CO_2 capturing concepts.

FOCUS AREA 2 Electronic materials

A major part of our economy is driven by industry that turns materials into high-tech electronic systems with a practical functionality, such as computing, data storage, internet and mobile communications, or sensing and actuating. In the past decades, continued miniaturization of computer chip design has led to a tremendous increase in computing power and data storage density. In parallel, long-distance, optical communication technology has brought about the internet, and novel micro- and millimeter-wave technology has created mobile communication networks. Yet, major challenges lie ahead to further drive innovation and keep this important industry sector healthy.

Energy efficient computing and data storage The continued miniaturization in recent decades following Moore's law is coming to an end as we approach the atomic scale. In parallel, due to the increasing information processing density, power consumption has now become a major limitation in computer design. Therefore, alternative methods to process and store information in a more energy-efficient way are highly desirable ('green ICT'). One revolutionary new approach is inspired by the operation of the human brain, in which reconfigurable neuromorphic materials are developed in which controllable and dynamically adjustable electrical conductivity or magnetic properties emulate neurons and synapses. Another emerging revolution is quantum computation, which based on quantum mechanical principles would enable enhanced scaling of the computational power with the number of bits. These new technologies require new, extreme materials with yet unexplored (quantum) properties. One recently emerged family consists of functional 2D-materials, such as transition-metal dichalcogenides with unique optical and electrical properties that can find applications in ultra-fast and ultra-compact data processing. New hybrid material systems (organic/inorganic or semiconductor/superconductor) and fabrication methods, such as printing, have to be explored to open new regimes. The acceptance and implementation of many of these new materials and device concepts in large-scale technological applications would benefit enormously from compatibility and integration with existing Si CMOS technology. In all these new technologies materials scarcity, refurbishment and recycling must be taken into account.

Opto-electronics Analog optical computing is an exciting emerging technology in which optical meta-surfaces and metamaterials are designed to perform mathematical operations on optical signals with very low energy use. All novel computing and data storage concepts require novel materials and geometries that do not exist today. New opto-electronic materials are required to further enhance the efficiency of light sources (LED and lasers) including hybrid solutions with semiconductors and phosphors. These light-emitting materials are important for applications such as large-scale lighting and quantum information distribution.

Sensors and actuators, internet of things Extreme efficiency also makes it possible for devices to harvest energy from their environment: phones or biosensors that are charged by body heat or movement, or medical implants that are powered by the conversion of ATP. The development of novel sensors and actuators creates a bottom-up network of energy-harvesting devices that can also communicate with each other (internet of things). Many applications lie ahead, such as optical, mechanical, and electrical sensors for autonomous mobility or sensors to monitor water quality or food packaging or health. Opto-mechanical circuits, that integrate light and mechanical motion enable extremely sensitive measurements. All of these devices must be reliably packaged to enable stable operation under extreme conditions.

FOCUS AREA 3 Construction materials

Construction materials can be defined as the set of materials that primarily serve load-bearing functions under thermal, mechanical, chemical, or physical loads for longer periods of time. This poses special requirements on the structure of the material, how it is processed and methods to monitor its performance over time. Construction materials are an important class of materials, both in terms of volume and economic value.
As an example, the building and construction sector uses 50% of all raw materials, accounts for 40% of the total energy consumption, and 30% of total water consumption in the Netherlands. As a result, construction has been selected by the Dutch government as one of the first value chains to switch to a circular economy. By 2050, buildings and other structures in the Netherlands must be built,

(re)used, maintained, and demolished sustainably, be energy neutral, and circular.

Key material classes are:

Metals needs to make more efficient use of the binder (cement), resulting in higher eco-efficiency and strength, and to create lighter structures that can follow both modern design rules and consume less resources and energy. Concrete materials and cement can be based on recycled materials or waste streams of industries (like steel) thus reducing the CO_2 footprint.

Fiber-reinforced materials (composites) are relevant for aircraft, wind turbines, the automotive industry, buildings, and bridges. Composites generally have a positive impact during the use phase; a long service life, low maintenance, partly thanks to their lightweight applications, and a low CO_2 footprint. Material development is needed for further performance improvement to reduce weight, knowledge on how the material performs when in use (e.g. repair, lifetime prediction) as well as recycling options.

Wood is seen as a natural and environmentally friendly material. Challenges are related to quality assurance and durability when exposed to moisture or wood-deteriorating termites. Creep under load can be a problem leading to failure.

Other materials like glass, asphalt, and stone are continuously undergoing improvements and changes based on in-depth understanding of structure-property relations. Also in these areas, circularity and use of non-primary resources is an essential topic. Examples are load-bearing glass structures, stones which absorb CO_2, or asphalt with optimized particle packing that features less resources and energy consumption, lower vehicle fuel consumption, and long lifetime.

For construction materials, innovations at all TRL levels are essential in:

Optimizing the design of new material compositions and structures, reducing material intensity, and using materials with the longest lifespan produced with environmentally benign production processes. New design rules, smart solutions such as optimum particle packing, 3D-printed structures, and self-healing materials will reduce material consumption and increase the time to failure.

Extension of the safe life of structures and devices reducing the need for new materials and the related CO_2 footprint. A far better understanding of aging processes has to be developed to allow for timely maintenance. The challenge is to predict and control degradation, such as fatigue and corrosion. Combining degradation-prediction models and monitoring data of the degradation states is crucial for this. Sensors with multiple-decade lifetimes have to be developed to monitor the condition of structures and loads. A related field is to investigate the degradation mechanisms that arise when structures are used beyond their intended lifetime. Another related field is that of life extension by suitable protective layers or coatings, like corrosion- or sunlight-protective coatings.

Re-using or recycling of end-of-life materials and components to the maximum extent. Separating combined constituents is required for optimum re-use, e.g. separating reinforced concrete to its ingredients steel, cement (paste), and aggregates.

Material combinations are increasingly applied in constructions using the strength of different materials. Classic examples are reinforced concrete and steel sandwich panels. In those cases, specific attention has to be paid to the design of constructions to enable easy dismantling and/or recycling.

FOCUS AREA 4 Soft/biomaterials

The Netherlands has a strong community in soft materials research with many world-leading academic groups. The soft matter community has strong relations with industry in HTSM, agri-food, chemistry, TNO, and Wetsus. Soft materials, like (bio-)polymers, colloids, and emulsions, are increasingly present in our everyday lives. Characterized by low binding energies and structural disorder, the mesoscopic components of soft materials may arrange spontaneously into highly complex structures that permit targeted and unusual mechanical, optical, electronic, catalytic, or biological properties. Soft matter is an amalgamation of distinct research fields and technologies and is intimately linked and of vital importance to

many of the other Focus Areas: coatings (structural color, adhesives, self-healing), energy materials (electrodes, supercapacitors, membranes, batteries, catalysts), electronic materials (self-assembled nanostructures), designed materials, 3D-printing, and info- materials. A large group of soft materials that we interact with is plastics and composites. Soft materials also make up our own body; complex materials systems whose mechanical and biological functioning is dictated by biopolymer meshworks and regulatory biochemical networks. The last decade has seen tremendous advances in the understanding of the structure-function relation for both natural and synthetic soft matter, but we are still far from a truly multi-scale understanding of their performance.

Bio-inspired materials design There are excellent opportunities at the interface between biophysics and supramolecular chemistry to produce new types of bio-inspired materials. Durable adhesives that work in aqueous environments are inspired by mussels, self-repairing

polymer materials are inspired by living tissues, and biocompatible smart materials are templated on the cellular cytoskeleton and serve as metamaterials with programmable mechanical performance.
Anti-bacterial surfaces for packaging and processing are an important field. Biophysical concepts provide novel pathways to control the self-assembly of (patchy) colloids and nanoparticles using DNA and designer peptides in combination with novel colloidal building blocks for directed self-assembly.

Hierarchical self-assembly Our understanding of the basic principles of hierarchical self-assembly in biology also inspires new man-made materials based on inorganic chemistry. A better insight in the laws and possibilities of hierarchical self-assembly will enable us to structure matter over multiple length scales and to add new properties and functionalities at each self-assembly step. If we gain control over self-assembly, we can make smart materials to order, and we can use raw materials more efficiently.

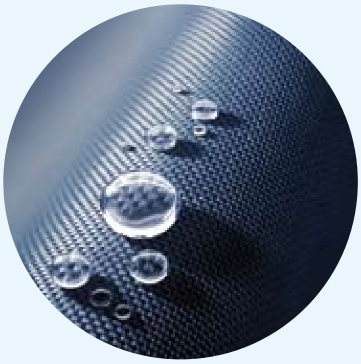
Active materials The physics and chemistry of out-of-equilibrium processes in living matter inspires entirely new possibilities for materials science. For example, the combination of synthetic building blocks with biological motors can enable small, soft robots. By combining insights from systems biophysics and synthetic biology with materials engineering we can create stimuli-responsive biofilms, and materials with genetically programmed properties. At the boundary between materials and devices, new biomedical soft materials can autonomously perform diagnostic or therapeutic actions, such as biosensors or drug delivery.

Self-healing and recyclable materials In nature, living systems (plants, organs) last surprisingly long, because they are capable of repairing themselves. Once they have served their purpose, they may be re-used in other materials. Inspired by this, self-healing and recyclable materials have been developed that repair themselves with the help of bacteria or can be degraded into the building blocks from which they were made. Extending these concepts to other materials, such as synthetic polymers, ceramics, and metals, will enable us to make self-repairing turbine engines, wind turbines, coatings or highways, and recyclable high-performance plastics.

FOCUS AREA 5

Coating/film materials

Coating technology is a stronghold of the Dutch knowledge landscape with leading academic groups and internationally renowned and innovative companies including SMEs. The key scientific questions in this field revolve around surface functionality, resulting from surface self-orientation and self-structuring during drying or processing. Compared to structural (soft) materials, coatings and thin films have a far higher surface-to-bulk ratio. For reasons of (cost-) efficiency, it is therefore more attractive to apply surface functionalized coatings on top of a structural material than to modify the entire structural material for surface functionality. Almost all industrially manufactured objects are combinations of structural and superficial materials, separating



surface functionality from bulk properties as defined by engineering constraints. For instance, the aluminum alloy used for aerospace hull construction is selected for its high strength at low weight but needs corrosion prevention and cleanability from a coating layer. Similarly, a polyurethane material can be chosen as an inflatable cardiovascular catheter balloon material based on its mechanical properties but needs an ultra-low friction coating to operate safely when placing a stent.

Improved coating functionalities While coatings are finding many applications already, many key functionalities require strong improvements while their sustainability needs to be increased. The improvement of corrosion resistance of metals is still highly desirable, with non-toxic solutions. Improved coating materials can help eliminate unwanted chemical reactions that reduce the performance and life in lithium-ion batteries. Next-generation waterborne, radiation curing, and powder coatings can offer a lower carbon footprint and improve indoor air quality. Optical coatings on solar panels, and aerodynamically optimized coatings on wind turbine blades can enhance renewable energy output. Increased durability of protective and decorative coatings is pivotal for many outdoor applications, and membranes for energy-saving or water purification separation processes need increased service lifetimes as well. Increased insight in the mechanisms of all these degradation processes is essential to enable new technologies and expand their use.

Self-healing and responsive coatings

Responsive coatings can adapt to light, humidity or heat and can help make a building become energy-neutral and have a healthy climate. In the future, textile fiber coatings may integrate with wearable computers that respond to environmental stimuli or monitor body functions. Self-cleaning coatings remove liquid or dust autonomously through their (super) hydrophilic/phobic properties, while anti-soiling coatings can prevent dusty solids from adhering on their surface. Self-healing capabilities can be incorporated into coatings to increase service lifetime by repairing damage, for example by transporting material from ‘reservoirs’ to the damaged area, such as self-healing scratches in automotive paints. Active scavenging or (chemo) absorption of unwanted species in packaging films can help to establish the ideal atmosphere for safe storage of food and medicine. Sensing and signaling embedded in food packaging materials, to probe for heat, oxidative stress, pH change, or microbial activity inside the packaging, for example, will help in the prevention of food waste.

Coating-biomaterial interactions

A special coating category deals with the interface between materials and biology: tissues and cells. Coatings can act as scaffolds to stimulate cell growth and tissue integration. In the future, 3D (printed), layer-on-layer deposition of material-cell combinations could enable the growth of artificial organs from a patient’s own cells without an immunogenic response. In contrast, negative coating-biomaterial interaction is desired in bactericidal surfaces to create hygienic conditions and sterile environments in hospitals, sanitary facilities, or food preparation facilities. There is a strong societal need for mechanically and chemically robust antimicrobial coatings that are not vulnerable to microbial adaptation, as are antibiotics. Most recently, anti-viral coatings have become highly relevant as well.

CROSS-OVER 1 Metamaterials

In our daily life all objects around us are ‘materials’. Traditionally, materials were sourced from nature and exploited for their intrinsic material properties to suit the needs of society. Nowadays we increasingly face the situation in which we design materials based on combinations of various materials and morphologies. These combinations can be on the atomic, micro, macro, and mesoscopic scale. Enormous opportunities lie ahead if we can develop techniques and concepts to design and build materials that will have new, exiting, and predictable structure and properties. At the same time, designed materials should be manufactured in a sustainable way and enable the circular economy, which means that recyclability should already be considered in the initial stages of the material design stage. Within this focus, a multitude of material classes can be mentioned, from which we highlight metamaterials and high-performance materials.

Metamaterials are a class of artificially architectured materials, which are designed to generate material properties that go beyond those of the ingredient materials. The (internally architectured) shape therefore leads to behavior that the material itself (i.e. the material in a fully dense state) could never demonstrate. These ‘materials’ exhibit exotic functionalities, such as pattern and shape transformations in response to mechanical forces. The unprecedented properties offered by metamaterials have a myriad of applications in various areas of science and technology.

High-performance materials

Developing novel materials often starts with combinations of existing materials. This enables the creation of materials with new properties that do not exist today and that have a wide range of applications. Metals can be considerably improved via a controlled micro/nano- structure.

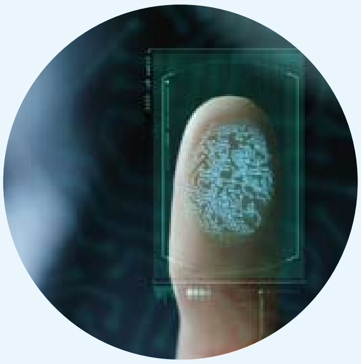
Fiber-reinforced polymer composites and thermoplastic composites are examples of macro-scale material combinations that combine strength and light weight. High-performance materials properties are high strength, high formability, low weight, high temperature resistance et cetera and find applications in maritime, aviation, construction, and the automotive industry. Offshore wind applications, for example, require self-healing materials, materials with a high corrosion resistivity and new composites.

Additive manufacturing 3D-printing is a revolutionary new technology that opens the way to create new hybrid and graded materials with a controlled structure and superior properties. It can create structures that are otherwise impossible to manufacture, increasing manufacturing efficiency and reducing materials use. 3D-printing techniques are in their infancy, and only a limited range of suitable materials are available. New dedicated materials are required, suitable for 3D-printing, with the desired properties.

Cross-over The design of materials is an area with strong links to the other areas of this report. Atomic-scale modelling of properties of material combinations is essential to design thin-film coatings, electronic materials, electrical steel et cetera. The toolbox developed for designed materials can be used in all these areas. Current and future digital technologies, including artificial intelligence, will allow the generation of so-called digital twins, a virtual representation, which can be used to understand and predict the performance of designed materials.

CROSS-OVER 2 Info-materials

The interface between materials scientists and machine learning (ML) is rapidly expanding, leading to completely new ways to understand materials and design new materials. Moreover, the processing of data in physical systems, living and non-living, is emerging as an important topic of research.



Machine Learning (ML) is the branch of artificial intelligence that, inspired by how the brain recognizes patterns, uses computers to analyze data without being explicitly programmed. ML algorithms learn by example, and ML has become a reality with the availability of big data – large datasets that allow the computer to classify or recognize patterns. In the past decade, ML has enabled self-driving cars, automated translation, speech recognition, effective web search, and a vastly improved understanding of the human genome. ML is becoming an important element in the toolbox of material scientists, just like computer simulations have become an important tool in the past decades. ML provides many new opportunities for the analysis and classification of materials data, thus fueling the formation of a range of open-access, large-scale materials databases. ML techniques are being used to interpret data (e.g. recognize patterns in chemical reactivities or electronic properties) but also learn from data (e.g. extract rules) and predict new data through surrogate models. In addition, ML is emerging as a key platform for the design of materials, with key examples including the prediction of new chemical and metallic compounds, as well as the rational design of molecules and metamaterials. Hence, ML for materials may lead to many tangible applications that may help the acceptance of ML in society.

Information processing As the continued miniaturization of silicon-based hardware is gradually reaching its limits, power consumption is becoming a major limitation for computing; the explosion of extremely large-scale computing in machine learning is compounding this challenge. Alternative methods to process and store information are highly desirable. By using (non-) linear elements and network structures, a variety of complex materials are now able to process patterns of light, electrical signals, or mechanical stresses. Key developments include mechanical and acoustic computation suitable for extreme or low-energy (microscale robotics) environments, optical meta-surfaces for high-speed, optical signal processing, brain-inspired neuromorphic computing, hardware implementations of machine learning, and molecular computation using proteins and DNA. In this emerging research field, the conventional boundaries between materials and devices are now dissolving, with the study and design of new forms of matter that can be programmed to store and process information.

Cross-over The tools developed in machine learning will impact many areas in this Agenda. Moreover, the questions and solutions provided by information processing materials closely link to key challenges in the area of electronic materials.

Industry Machine learning is essential for all companies involved in materials research. In parallel, DNA-based and neuromorphic computing are now rapidly being developed in industry as a novel route for massively parallel information processing. Info-materials can be game changers, providing major new business opportunities, even with as yet non-existent products in so far non-existent markets.

CROSS-OVER 3 Making and characterizing materials

Research for innovation of materials requires state-of-the-art, experimental equipment for making and characterizing materials. This applies to all stages of materials research, from fundamental research all the way to industrial upscaling. Since equipment is often specialized and expensive, the academic infrastructure is also frequently used by industry and is therefore essential for the entire materials landscape. Dedicated technical and scientific support staff are essential to run and maintain such infrastructure. For materials science infrastructure, the following subdivision can be made:

Basic infrastructure, required in each materials science laboratory according to the local lines of research, partly in situ to directly or indirectly observe dynamic processes in materials. Local researchers need easy access to such equipment. Examples are equipment for:

- manufacturing, like chemical reactors, furnaces, film deposition equipment, 3D printers;
- materials processing, like forming, joining, recycling;
- structure and composition characterization, like optical and electron microscopy, X-ray diffraction, surface analysis, chemical analysis;

- property and performance characterization, like mechanical testing, magnetic, optical, electrical, electrochemical, and thermal characterization, durability testing.

Highly specialized equipment, unique facilities which are, besides local use, also accessible for researchers from other institutions and which require dedicated scientists. Examples are Atom Probe Tomography (TUE), Angle-Resolved Photoemission Spectroscopy (UvA), Cathodoluminescence microscopy (AMOLF), Low-temperature Scanning Tunneling Microscopy (LEI, ARCNL), and Rutherford Backscattering Spectrometry (TUE).

Large national infrastructure operated as a user facility. External researchers can apply for measuring time and collaborate with dedicated scientists. Examples are High Field Magnet Laboratory HFML and free-electron lasers FELIX (RUN), NanoLab cleanrooms (AMOLF, RUG, TUD, TUE, UT), National facility for electron microscopy NEMI (RUG, TUD, UU), and Reactor Institute Delft for neutron- and positron-based materials research (TUD).

European user facilities that are financed by several European countries, such as the ESRF synchrotron facility (DUBBLE beamline) and the ESS (Lund) for neutron analysis. External researchers apply for beam time and are assisted by dedicated beam scientists. Travelling and accommodation costs are often provided.
Maintaining this infrastructure is essential for the Netherlands to stay upfront in materials research. Key challenges are to cover the running and maintenance costs for basic infrastructure and funds for replacement of basics instruments, and to secure continuity in the support for highly specialized equipment and large-scale national infrastructure.

Start-ups Dutch materials researchers have a strong tradition in developing novel instruments to carry out state-of-the-art research, and this often forms the basis to found spin-off companies.

CROSS-OVER 4

Circular economy and resource efficiency

Sustainable use of material resources is essential to accommodate the growth of the world's population. This requires a significant change of the current extract-make-use-waste-dispose economy, including the reduction of the related CO_2 footprint. The Dutch government targets 100% circularity in 2050 through three basic strategic directions:

1 Raw materials in existing supply chains must be used in a high-quality manner. This gain in efficiency can lead to a reduced need for raw materials in existing chains;
2 If new raw materials are necessary, fossil-based, critical, and non-sustainably produced raw materials must be replaced by sustainably produced, renewable, and generally available raw materials. In this way, we make our economy not only more future-proof but also less dependent on fossil sources and the import of these resources. We also retain our natural capital as a result;
3 We must develop new production methods, design new products, and restructure sectors. We must also promote new ways of consumption. This leads to other chains that give additional impetus to the desired reduction, replacement, and utilization.

The focus is on three priority lines of research:
1 design for circularity,
2 circular value chains and processes,
3 trust, behavior, and acceptance.
Each of these three lines of research require multi- and transdisciplinary materials innovations as outlined in the NWA route Circular economy and

resource efficiency, the Knowledge and Innovation Agenda Circular Economy as well as the EC action Plan on Circular Economy (March 2020).

Important topics include:

Replacement of fossil feedstocks by renewable feedstocks An increased use of renewable feedstocks in the production of polymeric materials is inevitable. In the mid to longer term, producing and using biobased materials will be important, such as modified natural biopolymers and biobased monomers. Mechanical and chemical recycling processes (fed by energy from renewable resources as wind or solar energy) will be important to obtain a truly circular use of carbon. Half-products of these new and existing chemical processes are converted into pure and 'virgin' organic materials. In addition, the chemical industry is continuously looking to obtain full selectivity in multi-step and complex syntheses with lower materials and energy use. Many commodity materials with additives such as lubricants, heat stabilizers, or pigments require circular alternatives, as sorting, separation and recycling require less complex material formulations. We can make use of the natural (bio)degradability of materials or to specifically design 'triggered degradation concepts' enabling the development of materials with a short or long lifespan. If unintentionally released in the environment, they will degrade in useful components, such as nutrients to prevent accumulation of hazardous materials in the biosphere. All these developments will require new measuring and detection technologies for quality control.

Replacement and retrieval of scarce metals Many economically important materials are based on elements that are scarce in the earth's crust (lithium, cobalt, nickel etc.). Novel strategies to replace these elements with less-rare counterparts, without loss of functionality, are required. Also, energy-efficient and CO_2-neutral recycling of these components retrieved by urban mining, for instance, is a priority topic, as well as increased durability of devices, modular designs, and refurbishment approaches. Measurement and detection and predictive modelling throughout the value chain must be developed. Synergies with smart industry, AI, business models, and consumer behavior must be found in digital twins for these new production routes and be an integral part of the materials research.

Cross-over Resource efficiency is crucial for all other areas in this Agenda and the materials and characterization techniques in the other areas are instrumental for achieving a truly circular economy. Energy research, in particular, will strengthen the sustainable recovery and recycling of materials and vice versa.

APPENDIX B

Members of the MaterialsNL platform, NWO committee materials

MaterialsNL Platform – National organization of universities, NWO Institutes, universities of applied sciences, technology institutes, and companies and organizations for the national coordination of materials research.

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APPENDIX

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MaterialenNL Platform

ChemistryNL

Credits •

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An electronic version of this Agenda and analysis of Roland Berger are available at www.materialennl-platform.nl

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