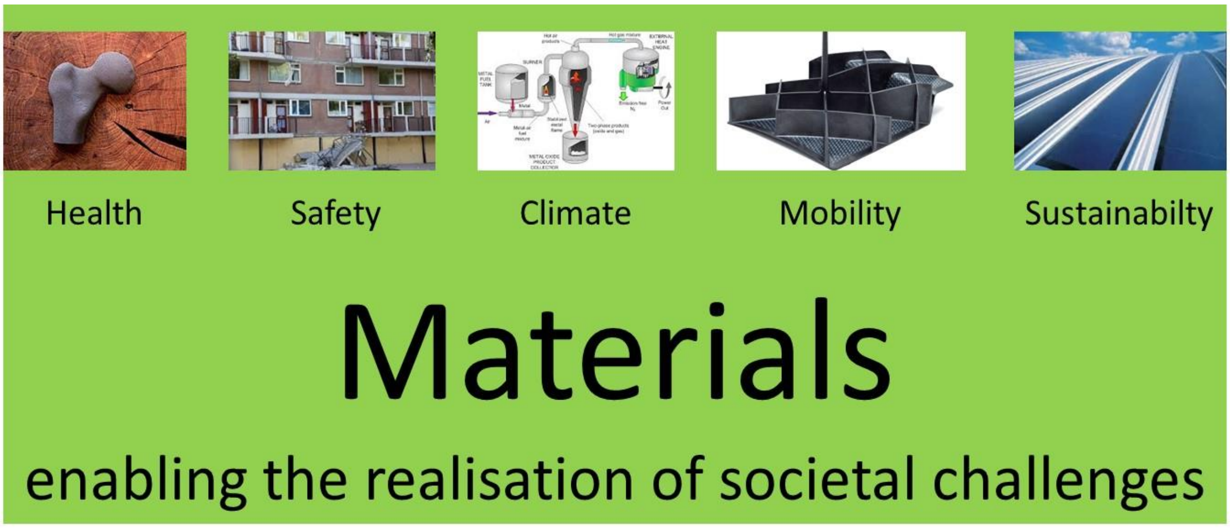
ROADMAP “HIGH TECH MATERIALS”



European societal themes addressed in this roadmap

Mastering the design, research and development of new and improved materials will remain key for achieving the goals of the National and European Innovation Policy. For this reason Advanced Materials play an essential role in Horizon 2020 as one of the four Key Enabling Technologies (KETs) essential to develop European industrial capabilities[1], allowing European industries to retain competitiveness and capitalise on new markets.

Developments in materials are vital to solve a wide range of technological challenges that society is facing today, from reliable and predictable operation of systems and products to sustainable energy production and utilisation, as well as safe and energy efficient transportation and healthy living. Scarcity of specific materials requires alternative production routes or substitution. In addition the increasing focus on circularity demands for entirely novel approaches in materials design and utilisation.

World-wide market for this roadmap, now and in 2025

It is widely recognized that timely start of R&D on new materials is vital to establishing a sustainable society[2]. From a strategic perspective, advanced materials are at the basis of many new applications. Consequently this field, ranging from R&D to economically viable manufacturing, is regarded worldwide as a driver for sustainable economic growth. Mastering advanced materials helps to transform – mature as well as embryonic – industries from resource intensive to knowledge intensive ones. In line with other independent sources the Commission’s European Competitiveness Report 2010[3] indicated global revenues in materials of EUR 646 billion (around 2006/2008), growing to over EUR 1 trillion by 2015, equalling a compound annual growth rate (CAGR) of 6 %.

Competitive position of the NL ecosystem (market and know-how)

Materials science is the discipline that studies design, manufacturing, structure, dynamics and performance of materials. It is a multidisciplinary field that includes elements of physics, mathematics,

[1] *http://ec.europa.eu/research/industrial_technologies/materials_en.html*

[2] ***4th WORLD MATERIALS SUMMIT;*** *Materials: A key enabling technology for secure energy & sustainable development, October 12-15, 2013, Strasbourg, France*

[3] *European commission (2010), European Competitiveness Report 2010 Luxembourg: Publications office of the European Commission*

chemistry, biology and engineering. Materials science studies cover a broad range of length scales from atomic scale all the way up to the macro-scale.

Many excellent academic research groups reside in the Netherlands resulting is a very strong Dutch Materials Science field with a citation impact of 1.7 times the world average[4]. A remarkable number of knowledge intensive industries, global multi-nationals with R&D labs in the Netherlands as well as young innovative start-ups reside in The Netherlands. Academic and industrial partners have a good track record of collaboration in joint research programs. This establishes an excellent basis for innovations that strengthen the Dutch economy.

2. Applications and technologies

State of the art review (industry and science)

Innovations in materials are essential to enable the realisation of societal themes for a broad range of market segments[5]. As a result the research is diverse and this roadmap deals with nine industrial sectors: Aerospace, Automotive, Civil, Energy, Maritime, Medical, Professional and Consumer Products, Rail and Security. The focus is not only on the HTSM market segments but a significant material developments component supports the topsectors Energy, Life Sciences & Health, Agri&Food and Water. In addition a strong link exists with the topsector Chemistry as many materials developed within this sector find their applications in the High Tech sector.

Future developments in present and new markets

Main drivers for the **Transport** sector include reduction of emissions and energy consumption, combined with increasing attention for safety and reliability. Important trends are the introduction of materials with an improved weight over strength ratio, more efficient engines working at higher temperatures and reduction of friction losses in the drive train. Developments should deliver robust production processes and products that operate with zero disturbances at affordable costs. New ductile Ultra High Strength Steels will be introduced into the **Automotive** market requiring the development of new alloying strategies. Coatings have to be developed that resist higher temperatures. Fundamental insight in the metallurgical and physical background of metals production is required to accurately control process conditions arriving at the desired microstructures and properties. The need for zero disturbances in the **Rail** sector leads to introduction of materials that combine excellent fatigue properties with reduced wear.
Hybrids and composites will increasingly be used in the transport sector where combination of low weight and high strength is essential. This is extremely important for the **Aerospace** sector, where morphing materials and structures will be introduced allowing robots to switch between hard en soft states. Additive manufactured components will increasingly be used for more complex structures and components.
In **Maritime and Offshore** applications high temperatures and pressures combined with abrasive and corrosive environments put severe demands on the materials to be used. Additional functionality will be provided through coatings and materials delivering special properties like anti-fouling and self-healing. The general trend in the transport sector to use tailored materials and hybrid solutions, will require development of novel joining techniques like welding and adhesive bonding. In the **Civil** sector buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU[6] and Construction and demolition waste (CDW) accounts for approximately 25% - 30% of all waste

[4] *Dutch Materials, Challenges for Materials Science in The Netherlands – report of the FOM Materials Foresight Committee, version 30-11-2015*
[5] *Portfolio for Research and Innovation, The Dutch National Research Agenda,2017*
[6] *http://ec.europe.eu/energy/,2015*

generated in the EU[7]. Securing resource and energy efficiency are key drivers to improve sustainability of buildings and civil constructions. Securing resource and energy efficiency are key drivers to improve sustainability of buildings and civil constructions. New cements and road pavements, and alternative components (e.g. bio-materials) are increasingly being applied and waste materials are upgraded for re-use. Another driver is aging of structures creating an urgent need for improving the understanding of the material behaviour. Novel designs incorporating multifunctional material elements will be produced by Macro 3D printing techniques for buildings. Dirt repellent coatings will ensure that buildings are maintenance free and keep looking like new for a longer period of time. Civil structures tend to get larger, e.g. bridges with a lower number of pylons requiring increased application of higher strength steels. Fiber reinforced composites are introduced to allow maintenance free operations and to reduce the total life cycle costs. A future development is the integration of additional functionalities in structures such as energy extraction and information systems.

A number of technologies for sustainable **Energy** production are being developed including solar, wind, tidal and possibly nuclear fission and fusion. A general theme in all these developments is a reduction of costs enabling cost effective competition with more traditional CO_2 emitting technologies.

Recently **Photo Voltaic** applications (PV) has gained further interest since grid parity has been achieved in many markets and cost competitiveness with traditional coal fired electricity is now a fact. This further drives the need for material developments that reduce the cost, while panel efficiency is increased. A lot of research was focused on thin films, including Perovskites, the fastest-advancing solar technology. Developments cover a wide range of topics from integration with building components for light weight modules and interconnections to advanced junctions, transparent conductive interlayers and functional coatings.

An important driver for the **Wind energy** is social acceptance of wind turbines. For this reason novel wind energy farms are often placed offshore with an additional advantage that the stronger, less turbulent winds enable higher energy production with more benign structural loads. Other highly relevant drivers like cost effectiveness and reliable energy production, result in requirements for larger blades, efficient power conversion and maintenance free operations. Larger blades have to be produced in robust production processes with reliable resins and fibers, with often unprecedented glass or carbon composite material thicknesses. Reliability must be proven for all materials under the combined influence of long-term fatigue and environmental loads (temperature, humidity, UV-radiation). Hybrid materials are required to integrate functionality in the various components, e.g. erosion-resistant water-proof coatings, materials for lightning protection and conduction, aerodynamic effectors. Tower-support structure-, and blade-hub connections are demanding hybrid connections between highly different materials. High strength steels with good joinability have to be used for the tower enabling weight and cost reduction. Tribology of gear metals needs to be optimized for the severe wear and tear conditions, and optimal material usage (copper and rare earth materials) is required for generator cost-efficiency.

As renewable energy production is often depending on the local weather conditions, **Energy-storage** plays an important role in synchronising energy demand and supply enabling continuous availability of electricity. This can be done by developing light weight batteries with a high capacity e.g. by introducing new electrode materials. Alternatively Photo Electro Chemical cells are in development that can produce electrical energy or hydrogen in a process similar to the electrolysis of water requiring electrodes for Photo Electro Chemical water splitting.

Energy efficient buildings require effective integration of **thermal storage** systems. High energy density storage materials are needed to offer long term multi-cyclic stability at tunable temperature levels. Advanced energy storage materials should be developed that are cost effective, safe and environmentally friendly with increased energy density of 4GJ/ m^3 (currently 1 GJ/ m^3).

Nuclear power production is very demanding for materials that have to survive under extreme conditions involving radiation, high temperatures and chemical attack by corrosive media. Material developments for existing **Fission** Technology are aiming to increase the reliability of operation by

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7 *http://ec.europe.eu/environment/,2015*

replacing light water reactors by more accident tolerant fuels, requiring cladding materials with improved corrosion resistance. For new generations as the very-high-temperature reactor **(**VHTR) and the supercritical water reactor (**SCWR**), that work at higher temperatures and with increased radiation levels, novel materials that are resistant to these more severe circumstances have to be developed. Molten salt reactors can become reality in 20 years from now enabling safe operations and waste minimization. The technology operates at high radiation levels, high temperatures and with chemically aggressive fluids, creating very demanding circumstances for materials.
Fusion technology will require a long development time of over 40 years involving a broad range of material developments. The first wall will exist of Reduced Activation Ferritic-Martensitic (**RAFM**) steels and Oxide dispersion-strengthened (**ODS**) steels and use multi phase alloys and (in a later stage) liquid metal walls. In the final stage of economically efficient energy production flexible high temperature superconductors and Sc coils and ceramic Sc tapes that can survive the very severe circumstances need to be available.
The core business of **professional and consumer products** (semiconductor, instruments, printing, consumer electronics and electronics) is the high tech systems and nano-electronics industry. This sector is driven by low cost, reliable performance and low energy consumption. New materials like graphene, multifunctional oxides and functional coatings have to be explored for function integration at various length scales. Nano structured multilayers will be used to produce 3D Integrated Circuits able to contain large amounts of data in small volumes. Deposition technologies like Atomic layer deposition (ALD) techniques will lead to systems on chips and wearable electronics. Improved **Packaging** concepts with improved sealing or better sensing will play an important role to reduce waste of food, which is essential to feed the world. At the same time packaging materials have to be mono-materials where possible, allowing for recycling and re-use of the materials and thus minimizing waste.
Barrier films and thin films will be used for various applications as food packaging and the production of Organic Light Emitting Diodes (OLEDs). The need for increased productivity and accuracy will lead to lighter products and fast and accurate heat exchangers requiring materials with locally controlled functional and structural properties to be arrived at using novel options that additive manufacturing offers. Combinations of materials and graded materials will be used to create components with embedded sensors. These developments will only be possible if supported by advanced research on deposition and removal technologies for new materials in dedicated processes.
In recent years increased activity in the response to **security** threats has been observed. Metamaterials can be used to make objects and materials invisible to radar, and to develop antennas that don't interfere with each other. The development of sensors will first be focused on increased sensitivity and miniaturisation, in a later stage sensors will be produced on a large scale to reduce cost and allow wider use. Additive manufacturing techniques can be used to produce materials on site in circumstances where components may be needed fast, reducing the need to keep spare parts.
Medical technology can help to tackle the major challenges of an aging population. Additive manufacturing techniques for prosthesis and in bone tissue engineering has been growing in recent years. Metamaterials producing artificial muscles have the potential to be highly disruptive. Though currently in limited use, the technology may have wide future applications in industry, medicine, robotics and many other fields.

<u>Questions and milestones for this roadmap in 2025</u>

Developments in materials production and utilisation are essential to address a broad spectrum of societal themes, meanwhile also strengthening the Dutch economy, some examples:

- **Health.** Many materials related issues have to be tackled to address the needs of an aging population at affordable cost, examples include biocompatible materials for stents and implants, low friction materials for prostheses and joint replacements, and miniaturization and function integration in electronic devices.

- **Safety.** All man-made products and structures are subject to environmental loads and aging. Continued exposure leads to a slow but consistent loss of robustness. Understanding and predicting of degradation processes enables timely repair or replacement of a component before catastrophic failure. Ultimately autonomous self-healing/ self-repairing systems should be arrived at.
- **Climate & Energy**. For increased application of sustainable energy like photovoltaics and wind energy developments in functional and structural materials are essential. A new and promising environmentally friendly development is the combustion engine based on metal fuels with potential applications in the high power density production of heat and power.
- **Mobility**. Reduction of CO_2 and NO_x emissions can be realised by increased utilisation of light weight/high strength materials, more efficient engines, and low friction surfaces. Technologies producing almost no tail pipe pollution, like electrical cars require the optimisation of batteries and fuel cells increasing efficiency and reliability and reducing costs.
- **Sustainability**. In engineering practice it is evidently desirable to reduce degradation processes of structures and devices in order to increase the durability. This is especially important when materials and functions are combined. A good example are Building Integrated Photo Voltaics (BIPV), where degradation of PV systems may not lead to the need for early replacement of the underlying roof structure. The Dutch government acknowledges the need for an accelerated transition to a circular economy[8] which is efficient (*reduce*), where alternatives are developed for scarce materials (*replace*) and materials are reused (*recycle*).

3. Priorities and implementation

Priorities in the roadmap are determined by two aspects. Firstly innovative materials have to be developed based on fundamental scientific understanding. Secondly smart manufacturing and intelligent application of materials and products are key to implementation.

Production of materials with the desired structure is only possible by applying in depth through process knowledge on materials synthesis and processing. A major scientific challenge is to understand structure –property relations at all relevant length scales of existing, modified and new materials. The current rather descriptive models should be transferred into predictive models based on physical understanding, thus enabling scientists to develop advanced and smart materials with combinations of structural and functional properties that cannot be foreseen today. The performance of improved or even completely new materials and related products in their application should be understood from basis physical principles, allowing science based materials engineering to speed up industrial development.

Important scientific developments can be expected in 6 main domains: *Materials for sustainable energy & storage,* 2) *Next-generation engineering materials,* 3) D*esigner functional metamaterials, 4) Soft and bio-inspired materials, 5) Sustainable materials and 6) Thin Films and Coatings.*

1.1 A number of technologies for **Sustainable energy** p**roduction & storage** are being developed, where a general theme lies in offering cost effective energy solutions at zero CO_2 emission. Scientific themes strongly relate to the methodology of energy production, but in all applications materials developments are key for breakthrough innovations. Examples are solar cells that need nanostructured layers and materials for light absorption and photon management, wind energy in need of increased structural performance of large blades and support structures, nanostructured materials for batteries and supercapacitors and thermochemical materials for storage of thermal energy.

[8] *Transitie -Agenda Circulaire Economie, 2018*

1.2 **Next generation engineering materials** provide load bearing capabilities and dimensional stability. Materials with improved weight to strength ratio, such as fiber reinforced polymers, advanced high strength metals, and hybrid solutions are increasingly applied to reduce energy consumption in transport applications. The potential of **hybrids and composites** is huge, important challenges remain in the application of cost effective fibers and resins, recycling and fast and cost effective processes to make the parts. **Nano structured metals** are developed to improve specific strength and formability of metals. Application of the materials requires fundamental research on joining and forming processes, including the development of stresses and the control of the final geometry. The durability and the evolution of wear and damage should be understood taking the role of structures, interfaces, soft and hard phases and coatings into account. Models need to be developed using multi-scale numerical simulations to translate physical phenomena on small scales to the actual performance on macro scale, where through process modelling and digital twinning of all phases of the materials use cycle will become the standard.

1.3 A fast growth in the understanding of how material behaviour emerges in complex materials makes it possible to **Designer functional metamaterials** with specific predetermined properties and functionalities. The metamaterials derive their functionality from their structure and offer unusual properties, examples include negative refraction of light, different magnetic properties and recently also acoustic, thermal and electronic features. Advanced processes (such as 3D printing, self-assembly, lithography and atomic scale manipulation) are being developed to make an unprecedented range of materials using control down to the atomic scale. New and unforeseen applications are expected in many domains such as data storage, photovoltaics, nanolithography and medical diagnosis. Developing successful applications of designer functional materials requires a strong fundamental understanding of material synthesis and assembly tools and theoretical and numerical (multi-scale) analysis techniques. Co-operation between engineers and scientists will be essential to bridge the engineering gap and to make the technology applicable for the industry.

1.4 **Sustainable materials** are the ideal in a circular economy where there is a balance between resource supply and demand, no waste is produced and raw materials are reused in their entirety. The challenge to achieve increased materials and energy efficiency is huge, special topics include the replacement of scarce materials and the recycling of polymeric materials and bulk materials. A specific challenge with respect to the latter is the need for technology that can be applied locally in order not to create a large transportation footprint. In order to innovate for sustainability, methods to quantify the impact of new high tech materials are being further developed.

1.5 Novel functional properties of surfaces can be obtained by the application of **Coatings and thin films.** A wide range of properties can be achieved ranging from mechanical performance (e.g. hardness, wear resistance or lubrication) to functional properties (e.g. corrosion resistance, adhesion promotors, anti-fouling or light management). Deposition technologies need to be understood on different scales to control the processes and the product properties and to allow for upscaling to the industrial practice.

1.6 **Soft and bio-inspired materials** is not included in this roadmap, but will be dealt with by the Topsector Chemistry.

1 Implementation Advanced & smart manufacturing, the fourth industrial revolution.

Sensor technology, big data and cloud computing will enable new ways of production, where reliability and predictability are combined with customization of products under the conditions of flexible mass production. The ability to collect and analyse large amounts of data online enables intelligent technical systems and will result in **Smart Factories** that can make autonomous decisions, including methods of self-optimisation and self-configuration. By connecting machines, work pieces and systems, intelligent networks are created along the entire value chain that can control each other autonomously, leading to cost effective, energy- and material efficient, and robust processes that continuously deliver high quality materials, products and processes. This is the basic principle of **Industry 4.0**, a term that was first introduced in Germany in 2017[9]. A similar initiative started in the USA and is known as the Smart Manufacturing Leadership Coalition[10]. And recently also in The Netherlands[11], This development is seen as the fourth industrial revolution.

In an Industry 4.0 factory advanced monitoring and sensoring systems combined with peer to peer comparison and fusion of information from various components provides precise prediction on materials, components and systems and will enable management to reach just in time maintenance and near zero downtime.

Implementation in public-private partnerships and ecosystems

To generate breakthrough solutions that go beyond incremental progress public private partnerships enabling scientists from academia to cooperate with engineers will be established.

Specific problems can be addressed in projects where e.g. one company co-operates with one university. To realise scientific research projects on materials for industries and at universities, relevant calls of NWO will be used.

A new trend is to create consortia, where a group of industries in the value chain, academia and research institutes cooperate in a **platform** of related activities. A concerted effort is made, aiming to address societal and economical challenges in a certain market segment or technology area. Fundamental research on new materials is combined with process know how to ensure that reliable and smart production processes are developed. Valorisation activities, with a focus on SME's, involving research institutes like BMC, ECN, NLR, TNO, and WMC, are included to enable introduction of new developments into the market in a timely and efficient manner. Examples of such platforms include:

- Materials (metals) for additive manufacturing; focusing on applications in the aerospace and high tech industry.
- Materials for constructions extreme environments, focusing on combinations of mechanical, physical and chemical challenges, mainly for transport and offshore applications.
- Materials for thin film manufacturing, focusing on new applications, materials and processes for thin film technology, coupled to the needs of the high tech industry
- Materials for composites, using a value chain approach and focusing on transport applications

It is foreseen that more platform activities will start in the future.

Linkage with other innovation instruments (e.g., public purchasing)

Not applicable

Collaboration and leverage with European and multi-national policies and programs

A transnational instrument to support cross-country cooperation on materials science and engineering is M.ERA-NET. The Horizon 2020 program attracted a number of applications involving Dutch organisations seeking support to develop new cross-sectoral industrial value chains across the EU. The INTERREG programme favours cooperation to remove disparities and foster exchange of good practices among different European regions. With strategic priorities on innovation and materials and

[9] *Industry 4.0 Working group, "recommendations for implementing the strategic initiative Industry 4.0," 2013*
[10] *https://smartmanufacturingcoalition.org/*
[11] *Smart Industry, Dutch Industry fit for the future, 2014*

resource efficiency, INTERREG is expected to play an increasing role in supporting materials innovation for the Dutch economy.

The EU Framework Programme for Research and Innovation Horizon 2020, will have a strong focus on developing European industrial capabilities in Key Enabling Technologies (KETs). Nanotechnologies, Advanced Materials and Advanced Manufacturing and Processing, have been selected as priority areas. There will be an emphasis on the contribution of Key Enabling Technologies to societal challenges.

Contractual Public-Private Partnerships (cPPPs)[12] will be used extensively for the implementation and deployment of the KET. They will allow industry to directly participate in the definition and implementation of research and innovation priorities. The three PPPs in the "Nanotechnologies, Advanced Materials, Advanced Manufacturing and Processing, and Biotechnology" part of Horizon 2020 are:

- Energy-efficient Buildings (EeB),
- Factories of the Future (FoF) and
- Sustainable Process Industries (SPIRE)

Other important programmes that foster materials development, especially relevant for metal manufacturing capabilities and related products, include the Eureka cluster "Metallurgy Europe" and the steel programme of the Research Fund for Coal and Steel **(**RFCS).

4. Partners and process [200-400 words]

Engaged partners from industry, science, and public authorities

The program will involve many innovative industries from a broad range of market segments including the energy, transport, civil and high tech sectors. Dutch industries will contribute to the delivery of the roadmap by supporting fundamental academic research on materials at universities. Research institutes like TNO, NLR, ECN and WMC will be involved to ensure that the results become available for industrial implementation. It is expected that the program will succeed to attract an increasing amount of Dutch SME's participating in platform projects growing to more than 70 industries.

Process followed in creating and maintaining this roadmap, role of SME

A recent report of the FOM Materials Foresight Committee is taken as a starting point for the HTM roadmap. It identifies four strategic research directions that built on key expertise that has been built up in the Netherlands in the past years[3]: 1) *Materials for sustainable energy*, 2) *Next-generation engineering materials,* 3) D*esigner functional metamaterials, 4) Soft and bio-inspired materials, 5) Sustainable materials and 6) Thin Films and Coatings.*

Separate roadmap sessions have been organised in March 2015 for each of the first three research directions involving ca. 60 representatives from leading academia and industry. The aim was to obtain a better insight in the drivers for the industry and society and to translate these into the future products and technologies that have to be developed. The roadmap was updated with the latest information and initiatives.

[12] *http://ec.europa.eu/research/industrial_technologies/ppp-in-research_en.html*

5. Investments (M€)

Roadmap program	2015	2016	2017	2018	2019
Industry	11	12	14	16	20
TO2 (TNO & NLR) in kind	5	6	7	8	10
NWO (STW & FOM)	5	6	7	8	10
Academia - in kind	5	6	7	8	10
Other Topsectors					
• Energy	_	3	3	4	4
• Water	_	1	1	1	1
• chemistry	_	3	3	4	4
Other Government/ EA	1,5	2,5	2,5	3,5	3,5
Grand total	**27,5**	**39,5**	**44,5**	**52,5**	**62,5**

TKI program	2015	2016	2017	2018	2019
TKI Grant	2,75	3,0	3,5	4,0	5,0
M2i-organisation	-075	-0,75	-0,75	-	-
Industry	2	2,25	2,75	4,0	5,0
TO2 (TNO & NLR) in kind	1	1	1	1,5	2
NWO (STW & FOM)	1	1,25	1,75	2,5	3
Academia - in kind	1	1,25	1,75	2,5	3
Grand total	**7**	**8**	**10**	**14,5**	**18**

European program	2015	2016	2017	2018	2019
Industry	0,05	0,1	0,2	0,2	0,3
Academia	0,05	0,1	0,1	0,2	0,2
EC	0,1	0,2	0,2	0,3	0,5
Grand total	**0,2**	**0,4**	**0,5**	**0,7**	**1,0**