ROADMAP NANOTECHNOLOGY

Introduction
Nanotechnology is generally considered to be one of the key enabling technologies which will drive innovations in the 21st century. Even at an early stage the Netherlands adopted a pro-active stance in relation to nanotechnology by initiating various national programmes. As a result, the Dutch R&D community has acquired a high level of knowledge and an excellent position in the international field of academic nanoscience and industrial commercialisation of nanotechnology.

The present Roadmap Nanotechnology is part of the Innovation contract of the top sector HTSM but, in view of its cross-topsector position, the planned activities for the period of 2013-2020 are closely connected to challenges and opportunities addressed in other roadmaps and top sectors. It therefore addresses generic nanotechnology research themes and multiple application areas which are important for the competitive position of the broader Dutch knowledge economy and the solutions for societal challenges.

The proposed innovations items have been determined in close consultation between relevant industrial partners, knowledge institutes, government, social institutions and contacts with representatives of other roadmaps and top sectors. They are therefore aligned with what is addressed in current nanotechnology programmes of NanoNextNL, NanoLabNL, NWO-NANO and TNO and what is proposed in roadmaps and innovation contracts of HTSM and other Topsectors.

1. Societal and economic relevance

Connection with the key societal themes

The European Commission has selected Nanotechnology and closely related Micro and nanoelectronics as two of it’s six “Key Enabling Technologies” (KET’s).

**Key Enabling Technologies**

- Nanotechnology
- Micro and nanoelectronics
- Biotechnology
- Photonics
- Advanced materials

**Advanced manufacturing systems**

- Climate action, resource efficiency, and raw materials
- Secure, clean and efficient energy
- Food security, sustainable agriculture,
- Marine and maritime research and the bio-economy
- Health, demographic change and wellbeing
- Inclusive, innovative and secure societies
- Smart, green and integrated transport

**Key Societal Challenges**

The KET’s form the basis of the Horizon 2020 program in which they will be deployed to make EU industries more globally competitive and provide new options to address present and future Key
Societal Challenges. The key enabling position of nanotechnology is expected to provide new opportunities for a broad scope of application areas. In view of this nanotechnology is expected to make significant contributions to solve societal challenges related to ensuring affordable healthcare, sustainable energy, healthy food and clean water for a growing and ageing population.

In the Dutch innovation landscape Nanotechnology has its home in the top sector HTSM in view of its close relation and enabling importance with the other HTSM-roadmaps. However in view of its relevance to a broad scope of societal challenges, it is also a recognised enabling technology for the top sectors ‘Life Sciences & Health’, ‘Energy’, ‘Agro & Food’, ‘Horticulture and Source Materials’, ‘Water and Chemistry’ as is depicted below.

![Fig2: Position of Nanotechnology in HTSM and connections to other topsectors](image)

For this reason nanotechnology is expected to make entrance contribution to various application areas and provide significant technological and valorisation results, as well as high-quality employment in the involved industrial sectors and scientific research communities.

In summary, nanotechnology is important for various societal themes and related application areas and top sectors. The cross connections of key topics on the nanotechnology roadmap with other HTSM-roadmaps and top sectors, will be addressed in section 2.

(Global Market size)

It is sometimes questioned by market analysts if it is possible at all to put a realistic market value on rapidly emerging technologies such as nanotechnology and the many promising - but partly still hypothetical - future products. Depending on the applied scope there are many estimates to choose from. At the upper end Lux Research projected in 2007 that by 2015 the market size in terms of "Sales of products incorporating nanotechnology" was expected to grow to a staggering $3 trillion. This is not an impossible figure if important economical sectors like semiconductor, consumer electronics and important areas of chemical industry are included. However very recently BCC Research has quantified the global market for nanotechnology based on a more focused inventory to be nearly $20.1 billion in 2011. For 2017 they expect total sales to reach $48.9 billion, which implies an annual growth rate of about 20%. Most of these figures are related to the sales value of nanomaterials, and equipment for manufacturing on nanoscale (so excluding semiconductor and consumer elec-
tronics). Compared to these established markets, the sales value of the emerging area for nanodevices (eg nanofluidic devices) is still relatively small, but double digit growth numbers are expected for these new nanotechnology market segments as well.

**Competitive position of the Dutch ecosystem**

The top 3 leading countries for commercialisation of nanotechnology are the US, Germany, and Japan. Although not comparable to these nations in terms of absolute numbers, The Netherlands is at the forefront of nanotechnology developments and is the largest player among the medium-sized economies, thanks to the proactive activities in industry as well as in academic institutes and support from science foundations.

In the field of academic nanoscience The Netherlands belongs to the top three worldwide, together with Switzerland and USA which position was achieved by investing in the best Dutch research groups in former NanoNed and MicroNed programs and simultaneously providing excellent laboratory facilities within NanoLabNL. Based on these investments, the number of Dutch publications on nanotechnology increased from 700 per year in 2005 to above 950 per year in 2010. In the same period the number of citations increased from 18,000 to 38,000 in 2010. In terms of filed patents on nanotechnology the Netherlands takes seventh place globally.

At present most of the top 20 Dutch based multinational companies perform research in the field of nanotechnology. In the growing high tech systems sector, Philips, NXP, ASML, ASM International N.V. and FEI are the biggest industrial players. In addition, DSM, Shell and Akzo Nobel are active on the market of nanomaterials & coatings in the chemistry domain. In the food area companies like FrieslandCampina, Danone and Unilever have an active interest in understanding the link between interactions on molecular scale and food microstructure. In addition to these Dutch companies, the role of the Holst Centre, uniquely bringing together multinational industries and academia with global positions and strategies in the nano-microelectronic developments has to be mentioned.

The number of nano-related projects in industry is growing by approximately 10% per year and the academic research and valorisation support in former NanoNed/MicroNed programs in the last decade, has led to the formation of more than 50 spin-off companies in the domain of nanotechnology. Examples of these such as Mapper Lithography, Micronit Microfluidics, Aquamarijn, Fluxxion Medimate LioniX and SolMateS can now be found - with 70 other SME’s - in the partner list of NanoNextNL, actively collaborating with the above mentioned multinational players in the nanotechnology field.

In spite of the above mentioned positive national developments, a 2010 international benchmark study by LUX Research ‘Ranking the Nations on Nanotech’ (2010), showed that although the volume and quality of the Dutch scientific nanotech activity is high, the Netherlands industry still scored relatively low on technology development capacity and strength on an international scale. The research agenda of the present NanoNextNL-program and the continuation of the NanolabNL program ensuring access to high quality infrastructure aim to significantly improve this situation.

**NanoNextNL**

The present NanoNextNL-program has it’s foundation in the Strategic Research Agenda of the Netherlands Nano Initiative (NNI) which was written by FOM, STW and NanoNed in 2008 at the request of the Dutch Government. The agenda identified the generic research themes and application areas which were considered of crucial importance for the global position of the Netherlands as a knowledge economy. In addition it was proposed that simultaneous attention should be given to
Risk Analysis and Technology Assessment R&D to investigate the possible impact on people, natural environment and society to ensure safe and acceptable application of new enabling nanotechnologies in the various application areas.

NanoNextNL has brought together more than 90 companies, of which 80 SMEs, which are participating together with about 30 partners from universities, knowledge institutes and medical centres. NanoNextNL has a budget of 250 M€ based on 50/50 contributions from the government and the involved partners to execute the program in the timeframe 2010-2016 and to ensure that a durable ecosystem is formed that will continue to lead national innovation in this area.

The organisation of the NanoNextNL program and its main generic and application themes is depicted below.

![Fig3: NanoNextNL research themes and application areas.](image)

**NanoLabNL**

NanoLabNL is a consortium of MESA+ NanoLab Twente (Enschede), Kavli NanoLab Delft (Delft), NanoLab@TU/e (Eindhoven) and Zernike NanoLab Groningen (Groningen), partnering with TNO and Philips. It provides a full-service and open-access infrastructure for high tech R&D in nanotechnology. The state-of-the-art facilities (cleanrooms, equipment, offices etc.) and the close proximity of research hubs in the Netherlands make NanoLabNL a unique platform for collaborative nanotechnology research. All facilities within NanoLabNL are open to all NanoNextNL partners, as well as to external users for attractive tariffs. On average 100 companies make use of the facilities each year. Each of the four NanoLabNL locations offers a range of basic infrastructure and expert techniques, unlikely to be found elsewhere in the country. The decision to make use of only a limited number of research laboratories and to make them accessible to all researchers, both public as well as private, has proven extremely effective.

The total investment in NanoLabNL sofar amounts to 150M€. An estimate of the total required investment and operating costs for the next decade is approximately 210 M€, for which a request for continuation of support has been submitted as part of the Netherlands Roadmap for Large-scale Research Facilities.
2. Application and technology challenges
State of the art for industry and science and future evolution, in present and new markets

Nanoelectronics
In the early years, the micro-electronics and semiconductor sector were the main driving force behind nanotechnology because of their need for ever increasing miniaturisation technology. Over the past thirty years it has become possible to create progressively smaller structures for the production of computer chips by means of lithographic techniques. In this time frame the density of transistors on a chip has doubled every eighteen months, known as Moore’s law. However this principle will come to an end sooner or later, increasing the need for new breakthrough ideas and technologies. This new era in electronics is identified as ‘beyond Moore’. On-going developments in the field of nanoelectronics, nanophotonics and nanofabrication will provide the HTSM top sector with new impulses to produce nanostructured chips (ASML, ASM International), microscopes to visualise and manipulate nanostructures (FEI), to be applied in the development of future electronic devices (NXP).

Bionanotechnology
In the previous decade, nanotechnology and biology have become increasingly closer bed partners. Living cells are full of ‘micromachines’ constructed of protein molecules and other nanometer-sized self-organising structures. Physicists, biologists and technicians are therefore increasingly seeking inspiration in biological systems for their research and applications based on biomimetic designs. On the other hand, nanotechnological developments can utilise new research methods, techniques and instrumentation to provide impetus to biomedical and medical research. For example, through a ‘lab-on-a-chip’ which can analyse the composition of minute quantities of bodily fluids in a fraction of the time and costs of conventional methods. Further possibilities include the development of new nanomedicines, the early detection of viruses, the control and administration of medication, and intelligent surgical equipment. For that reason, the implementation of the nanotechnology roadmap will increasingly include both public and private sector participants from the medical and healthcare sectors.

Nanomaterials
Recently, mankind has been able to control the composition of manufactured materials at an atomic scale. It is therefore becoming possible to exploit the special properties of nanomaterials, which can lead to more efficient solar cells, fuel cells and batteries. Furthermore there are environmental and chemical applications (catalytic convertors, membranes), applications in data storage (quantum dots, multiferroics) and data transport (photonic crystals). In addition the use of low-energy nanomaterials will help to resolve the major global problem of energy consumption for data processing (computers, mobile phones, internet). The Netherlands has already established an international reputation in this area and many Dutch companies (multinationals, SMEs) are active in this new field.

Relevance for other HTSM roadmaps and topsectors
The importance of the generic enabling position of nanotechnology for other enabling technologies, but especially for many application areas (inside the HTSM topsector but also related to other topsectors) is reflected in its relevance for achieving the goals of other HTSM roadmaps and top sec-
A screening of available roadmaps/TKI-contract versions with respect to connections to nanotechnology priorities (as defined in the former version of the nanotechnology roadmap) resulted in the table below.

Table 1: Relevance of Nanotechnology priorities for other HTSM roadmaps and Topsectors

<table>
<thead>
<tr>
<th>Nanotechnology Priorities</th>
<th>Enabling oriented HTSM Roadmaps</th>
<th>Application oriented HTSM Roadmaps</th>
<th>Application oriented top sectors/TKI’s</th>
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<tbody>
<tr>
<td>Nano materials / surfaces / membranes (18)</td>
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<td>Nano optics / photonics (18)</td>
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<td>Nano sensors / actuators (17)</td>
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<td>Nano electronics / components (14)</td>
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<td>Nano fabrication / patterning / assembly (13)</td>
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<td>Nanoscopy / imaging / inspection (13)</td>
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<td>Nano mechanics &amp; physics (9)</td>
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<td>Nano fluids / reactors (4)</td>
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<td>Bio-nanotechnology (3)</td>
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<td>Nano medicine / drug delivery (3)</td>
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<tr>
<td>Nano Risk Analysis / Technology Assessment (17)</td>
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</table>

Direct reference to nanotechnology in roadmap/TKI (15)

Estimated % of “nanotechnology” related activities in roadmap/TKI-contract. (To be completed)

In most of the other roadmaps and TKI-contracts a direct reference is made towards the relevance of nanotechnology, and in some cases further indications are highlighted concerning the relevance of specific nanotechnology priorities. In order to further quantify these interactions an estimate has been made what percentage of the total roadmap/top sector activities relate to nanotechnology. Together with the total R&D spending in these roadmaps, this can indicate where the best opportunities exist for expanding the cross-connections.

### 3.0 Priorities and implementation (draft)

#### Existing priorities

The list in table 1. is still regarded as the list of existing priorities for future R&D in nanotechnology. From table 1 it is clear which investments in the priorities - described in more detail in former versions of the Nanotechnology roadmap - have a broader or more specific impact for other roadmaps and top sectors. Each of the nanotechnology priorities are already part of on-going NanoNextNL and TNO-, NWO-NANO programs, but within each of the stated priorities there are novel areas which need to be explored. In particular those areas within the priorities which clearly link to the identified cross-connections in the table deserve more attention and funding.
Emerging priorities

In addition to the existing priorities listed in table 1, two new topics have been identified in the evaluation process considered suitable for allocation of additional funding for further R&D.

Nanotechnology endurance

For many envisaged large scale application areas for nanotechnology based devices such as consumer electronics, automotive/aerospace sensors, solar cells, chemical processing and water quality monitoring, it is essential that their performance and functional lifetime is understood and can be warranted over long periods and under sometimes extreme and/or varying conditions. In view of the stage of developments, not much dedicated attention has been given so far to fundamental aspects of structural and functional integrity and endurance of nanotechnology based devices. In such devices individual properties of new nanomaterials and nanostructures, in many cases processed by new nano-manufacturing methods, have to be understood and taken into account in combination with those of more conventional bonding and packaging materials and processing techniques.

Nano standardisation, inspection and regulation

For further commercial manufacturing and application of nanotechnology based products, the need for standardisation is becoming more evident to prevent non-productive diversification and ineffective and inefficient processes future manufacturers and end-users will otherwise be faced with. First examples are already found in the world of e.g. microfluidic/lab-on-chip devices and associated interchangeability of equipment and components. Also in the area of management of potential risks of “nano inside” a next step must be taken, especially in the area of engineered nano materials and nano particles.

Dedicated nanoscale oriented measurement and inspection techniques and procedures have to be developed as a basis for future (inter)nationally accepted NEN, CEN and ISO methods and procedures to certify compliance with present and future technological, health and ethical standards. In many cases a cross-over and integration of technologies developed in other roadmaps will be possible. As an example new possibilities for detection of nanoparticles can be expected from the focus on contamination control on the nanoscale in the semiconductor area, whereas similar detection methods may be also needed in fields where nanoparticles are used in (chemical) products. Furthermore a recent crowdsourcing based demonstration project in which an attempt will be made to measure “fine dust” levels by an optical add-on device on smartphones, shows what may be expected from further integration of emerging technologies.

Proposed implementation in public-private partnerships/ Transition of connected program institutes

In view of the “modus operandi” of the topsector HTSM, additional funding generated by cash investments of industrial partners will generate additional budget for existing and new NWO (FOM, STW)/TNO funded programmes in the field of nanotechnology. To ensure efficient use of resources and maximum impact of the R&D related to the above specified priorities, it is proposed to ensure a direct link to the existing NanoNextNL program which will continue well into 2016. At present NanoNextNL has already established (formal) collaborations and contacts with all other Public Private Partnership organisations with nanotechnology based activities or interests in specific applica-
tion\textsuperscript{1} or technology\textsuperscript{2} domains. Depending on their continuity in the applicable top sectors and transformation in TKI’s, these collaborations will be renewed where appropriate to ensure adequate operating space for cross-roadmap/top sector collaboration in the field of nanotechnology.

**SME activities**

In the consultation process all 80 SME-partners involved in the NanoNextNL program have been invited to provide input for the definition of the roadmap nanotechnology, many of which are expected to participate in the execution phase together with other existing SME’s enter this domain from other roadmap backgrounds. Furthermore many new start up’s and SME size spin outs from larger companies are expected to take position in this rapidly emerging technology field. For the further communication with and involvement of the SME community, existing collaborations and contacts with Dutch SME-oriented organisations and (private) consultants which are active in the nanotechnology field such as MinacNed, Syntens, Microcenter, EnablingNMT and NanoHouse will be used and extended.

**Linkage with other innovation instruments**

In addition to the proposed linkage to the on-going NanoNextNL-program the formerly mentioned NanoLabNL programme is considered highly relevant for the execution of the roadmap nanotechnology. Furthermore the EU-Horizon 2020 framework is expected to provide access to partners and networks with similar activities and facilities on a European scale.

**3.1 TKI program**

**Committed and expected R&D activities contributing to the TKI program**

**Implementation of TKI grants, connection with other roadmaps**

The committed and expected financial contributions to the nanotechnology TKI-program are specified in Section 5. In addition it must be mentioned that due to the crosscutting enabling position of the nanotechnology roadmap illustrated in table 1, industrial investments in nanotechnology, eligible for generation of the TKI-grant, are frequently connected to and registered in the related specific application area oriented HTSM roadmaps. Once the registration of the industrial contributions in these roadmaps and topsectors has been completed, a discussion in the HTSM roadmap council will be initiated to determine to what extent these can be used to provide additional funding for R&D in the identified nanotechnology priorities specified in the introduction of section 3.

**3.2 European program**

**Alignment with European strategies and policy instruments**

In the ‘Seventh Framework Programme’ (FP7) a budget of €3.5 billion was reserved for nanotechnology research by the European Union for the period 2007 to 2013. Up till now about 6% of the FP7 funding was allocated to Dutch participants. The 8th European Framework Programme - better known as Horizon 2020 - , will commence in 2014 and has a total budget of €77.6 billion for a period of 7 years. In this program nanotechnology has been identified as one of the key enabling technologies (KET’s) and specific calls will be present in the following 3 main Priorities:

\textsuperscript{1}(Wetsus, TIFN, CTMM, BMM, TIPharma, Point One, Solliance)

\textsuperscript{2}(M2i, ISPT, COAST)
In **Priority I** “Excellent Science”, no specific budget for nanotechnology proposals has been allocated which means they will have to compete with proposals in other scientific domains. 31.7 % of the total budget is allocated to this priority.

**Priority II** “Industrial Leadership”, consists of dedicated support for the “Key Enabling Technologies”. As illustrated in fig 1., “Nanotechnologies” is one of the 6 KET’s. 22 % of the total budget is allocated to this priority with a joint budget of €4 billion for nanotechnologies and 2 closely related KET’s (material and manufacturing-processing).

**Priority III** “Societal Challenges”, focuses on the 6 themes illustrated in fig 1., that have been identified as policy priorities in the Europe 2020 strategy. The emphasis will be on bringing together resources and knowledge across different fields, technologies and scientific disciplines to address these challenges. For a number of these challenges (e.g. health, food, energy), it can be expected that nanotechnologies will form the underlying basis for innovation. 39% of the total budget is allocated to these challenges.

### 4. Partners and process

**Engaged partners from industry, science, and public authorities (national and regional)**

The main national industrial/scientific partner base for execution of the roadmap nanotechnology is provided by the ecosystem in and around NanoNextNL. Once the funding allocation process described in section 3.1 has been completed, the specific involvement of partners can be specified.

**Process followed in creating this roadmap**

The selected priorities for the Roadmap Nanotechnology have been defined in a multi-step process. The first step was, working from the Strategic Research Agenda of the Netherlands Nano Initiative, to consult the directly concerned industries, knowledge institutes, governmental bodies and social institutions which in November 2011 led to the first version of the roadmap and identified priorities for further research. In this process, industrial partners known to be active in the field of nanotechnology were consulted together with representatives of industry coordinating the application themes in NanoNextNL. Furthermore scientific directors from the other top sectors have provided their input.

In a second step a summarized version of the roadmap has been sent to all known previous contributors in September 2012, to obtain their updated additional comments and contributions. In parallel the (updated) roadmaps of HTSM and TKI-contracts of other top sectors have been analysed to identify the issues for which the identified nanotechnology priorities can make a contribution, which resulted in the overview in table 1. Versions of this roadmap have been shared with many potential contributors, with special attention for the theme coordinators and program directors in the NanoNextNL program.
### Nanotechnology Roadmap

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<th>2012</th>
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### TKI Program

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### European Grants

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