Ireland's Nanotechnology Commercialisation Framework 2010 – 2014

August 2010

Forfás

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Acknowledgements

This report is based on research carried out by Lux Research and Forfás would like to fully acknowledge the quality of their work.

Many people and organisations contributed to the production of this report. Particular thanks are due to the Project Steering Group and all those, both from the public and private sector who agreed to be interviewed.

Table of Contents

Glossary of Terms

Acronym	Full Name
CAGR	Compound Annual Growth Rate
CNT	Carbon Nanotubes
DETI	Department of Enterprise, Trade and Innovation
DoD	Department of Defence
DoE	Department of Energy
EI	Enterprise Ireland
ERA	European Research Area
EU	European Union
EU15	Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the UK
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
GERD	Gross Domestic Expenditure on Research and Development
GM	General Motors
GNP	Gross National Product
HEA	Higher Education Authority
IDA	IDA Ireland
IDC	Interdepartmental Committee on Science, Technology and Innovation
INNI	Israeli National Nanotechnology Initiative
INSPIRE	Integrated NanoScience Platform for Ireland
IP	Intellectual Property
ITO	Indium Tin Oxide
LEDs	Light Emitting Diodes
MNC	Multinational Company
NanoFab	Nanotechnology Fabrication Facility
NAP	National Access Programme

NIH	National Institute of Health
NNI	National Nanotechnology Initiative
NSF	National Science Foundation
OLED	Organic Light Emitting Diode
R&D	Research and Development
SBIR	Small Business Innovation Research
SFI	Science Foundation Ireland
Si	Silicon
SME	Small to Medium Enterprise
SSTR	Small Business Technology Programme
SWOT	Strengths, Weaknesses, Opportunities and Threats
UV	Ultra Violet
VC	Venture Capital

Executive Summary

Background

This study was commissioned by Forfás as an input for the assessment of various options and strategies to support the commercialisation of Irish nanotechnology research (both private and public) as requested by the Interdepartmental Committee on Science, Technology and Innovation (IDC). Lux Research, who undertook this study with Forfás, has global experience in helping corporations and governments to strategise around nanotechnology innovation and commercialisation.

Through this study, Forfás sought to:

- Identify the options and models for the island of Ireland to leverage its existing nanotechnology research base to attract and retain Foreign Direct Investment (FDI) as well as encourage the development of indigenous enterprise. This was to be done keeping in mind the national and international innovation environment.
- Evaluate the feasibility of the various commercialisation options, including the possible establishment of a multidisciplinary Nanotechnology Fabrication (NanoFab) facility (keeping in mind the length of time to become fully operational and to yield a return on investment) that would provide researchers, enterprise and entrepreneurs with access to pre-commercialisation facilities.

Introduction

Nanotechnology is an enabling technology that can act as an anchor for Ireland's improved international competitiveness and will have a deep and lasting impact on current Irish businesses, as well as current and potential FDI in areas such as medical devices and electronics. According to Lux Research, nanotechnology impacted $254 billion worth of products in 2009 globally. This impact is forecasted to grow to $2.5 trillion by 2015. To be a competitive player in this market, Ireland must strategically position itself to be a knowledge and innovation centre for certain niche areas of nanotechnology.

Methodology

Forfás appointed a representative Project Steering Group for this study. This group was comprised of representatives from Forfás, Science Foundation Ireland (SFI), IDA Ireland, Enterprise Ireland (EI), Higher Education Authority (HEA) and the Department of Enterprise, Trade and Innovation (DETI).

To meet the study's objectives, the following three-phase methodology was implemented:

Benchmarking Ireland's nanotechnology capabilities (Phase I)

Phase I benchmarks the Irish nanotechnology research base against the best performers in a group of selected peer countries. Altogether, this benchmarking exercise assessed the relative performance of Ireland in terms of research output (publications, absolute and normalised), research quality (as measured by citation impact) and commercial emphasis (as measured by patents) against 13 countries in varying stages of nanotechnology development. As part of this process, technology areas where current Irish capabilities are strong, weak or underexposed were identified.

Global review of nanotechnology commercialisation strategies (Phase II)

Phase II evaluated the nanotechnology commercialisation strategies employed by a select group of five comparable nations to identify best practices, as well as avoidable errors. Ireland was benchmarked within this context. Also, as part of this phase, several global NanoFabs, large and small, were assessed to study their design rationale and impact.

Developing Ireland's nanotechnology vision and commercialisation options (Phase III)

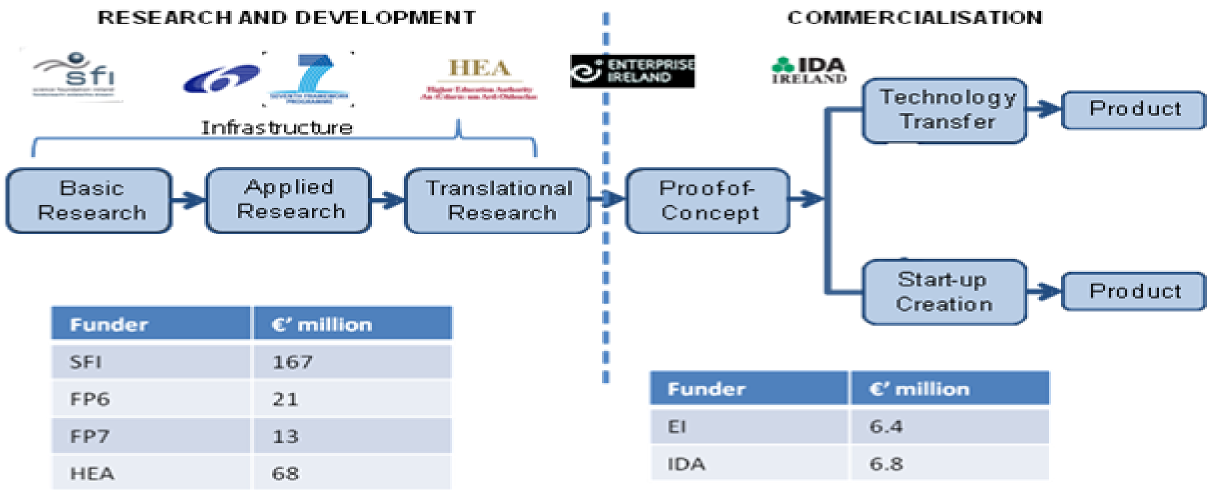
Building on the first two phases, Phase III focused on establishing Ireland's nanotechnology vision and focus areas, with the emphasis on the ability to add and create economic value and impact. With the connection between Irish focus areas and the global landscape of competition and opportunity established, options for the commercialisation of nanotechnology in Ireland were indentified.

Benchmarking Ireland's nanotechnology capabilities

Analysis found that:

- Across the nanotechnology commercialisation value chain, between 2001 and 2009, Ireland spent approximately €282 million on nanotechnology. Figure *i* summarises the breakdown of this funding across the research and development (R&D) value chain. A significant proportion of this investment has gone into investing in infrastructure and building up capabilities in this area.

Figure *i*: Nanotechnology R&D Value Chain (2001-2009) (Data Presented in Millions)



Funder	€' million
SFI	167
FP6	21
FP7	13
HEA	68

Funder	€' million
EI	6.4
IDA	6.8

Source: Provided by the respective agencies in June 2009. The "Basic Research" category here is analogous to the "Oriented Basic Research" terminology used within the Irish research establishment.

- Ireland has an excellent infrastructural base which will serve as a strong foundation as it seeks to produce high-quality nanotechnology research and leverage its commercialisation potential.
- Ireland should take a very close critical look at applications in markets traditionally considered strength areas, where quality was found to be lagging. Similarly critical attention should go to (unexpected) strength areas where research quality was found to be high and a commercial focus exists, but with low research output.
- An analytical review of the complete subset of nanotechnology areas shows that Ireland benchmarks well internationally on the basis of normalised publications, patents and quality of research; however, it does not have the critical mass to make an impact on the global stage. The lack of critical mass research output remains an Irish challenge, resulting in seemingly poor visibility to overseas peers doing research in similar areas.
- External benchmarking data suggests that there is a strong case to be made for increasing collaboration with peers in the Netherlands who have a complementary research publication and quality profile. The findings also argue a case for much closer resource and facility integration with Northern Ireland.
- Although there is strong anecdotal suggestion that the absence of technology exploitation is a strong barrier to nanotechnology commercialisation within Ireland, the findings from this report did not support these suggestions. While findings from the report showed that Ireland does lack the infrastructure to work with industrial-scale wafer sizes for university-level nanoelectronics research, the reasons for the lack of commercialisation relate more to the combination of quality, volume and the industrial relevance of the research output.
- Based on the analysis of Ireland's commercially relevant research activity in nanotechnology markets, it was concluded that research output, quality and commercial focus shows variation across markets. Even within a given market, the quality of research output, as well as commercial emphasis, varies by target application area.
- Ireland is moving broadly in the right direction on Lux Research's *Nations Ranking Grid*, with technology development being particularly strengthened in 2008; however, it needs to accelerate its efforts to focus resources in order to keep up with the progress of other nations in the coming years.
- Overall, nanotechnology is already impacting or is set to impact all sectors of Irish business and industry in a deep and meaningful way. To grow its role into becoming an innovation leader and to extract more sustainable value from its industrial activities, Ireland must strategically incentivise nanotechnology developments most relevant to its industrial base, both in the existing one and the base it desires to have in the future.

The key underlying message is Ireland's need to FOCUS.

Global review of nanotechnology commercialisation strategies

An international review of nanotechnology commercialisation strategies was conducted by Lux Research. In conjunction with the Project Steering Group, five countries were selected. The selected countries either shared a number of characteristics with Ireland (Singapore, Israel, the Netherlands) or are clear global leaders (U.S. and Germany). Ireland was benchmarked with these five countries and the main findings are:

- Across all countries there has been an emphasis on setting up and maintaining the necessary infrastructure and therefore Ireland's investment in world-class infrastructure is in line with international best practice. The critical factor going forward will be Ireland's ability to maintain and use this infrastructure efficiently.
- In an ideally functioning science commercialisation context, the market acts as a guiding mechanism for technology development and innovation, defining needs and demanding solutions for those needs, thereby setting a research agenda. Most of the five countries have what is referred to as a "*super-customer*", which is an organisation or group of organisations which, through funding leverage and application focus, significantly contribute to the commercialisation of nanotechnology research (e.g. the Department of Defence (DoD) and Department of Energy (DoE) in the US or the small and medium enterprise (SME) sector in Germany). In Ireland, there is no market-driven demand pull for research or "*super-customer*" to perform this role, and as a result, researchers tend to choose their own areas to work in.
- The challenges in Ireland are not unique; other nations face challenges with nanotechnology commercialisation. However, a particular challenge in Ireland is the variation in quality across the research base and the lack of critical mass.
- The peer group of nations (Germany, US, Netherlands, Israel and Singapore) has learnt that it is all about focus and that in a resource-constrained environment, broad thematic investments can have limited impact.
- In all countries, the government plays a prominent role in supporting the commercialisation of nanotechnology and it is appropriate that the Irish government continues to play a significant role in incentivising and promoting Irish nanotechnology R&D.
- Programmes elsewhere have clearly defined success metrics and rigorous periodic evaluation.
- The programmes required for commercialisation of nanotechnology in Ireland are in place but remain as yet untested. When compared to peer nations, Ireland's levels of funding (based on 2009 figures) appear adequate and all the necessary programmes and business culture are in place for technology transfer and start-up creation. However, any commercialisation strategy will have to drive technology exploitation more proactively and devise programmes to make the research more commercially relevant through dialogue with "end-customers" to understand and define their needs and let those needs inform the research.

Review of NanoFabrication Facilities

A key part of this study was to explore the feasibility of developing a NanoFabrication Facility (NanoFab) in Ireland. Findings from this study show that Ireland's infrastructure is on par with the best available elsewhere and will serve it well for the foreseeable future. The current standard of infrastructure should not limit an ambitious nanotechnology vision for Ireland. This finding, combined with the output of the benchmarking and international review, means that Ireland's current and forecasted research output does not require investment in a significant NanoFab facility. Such a facility would require a financial commitment in the hundreds of millions of euro range, with a sustained annual government funding well in excess of Ireland's current total annual nanotechnology spend. But above all, for the foreseeable future, such a facility would most likely become a contract research and fabrication location for foreign researchers and therefore should not be the focus of resources and strategy at this critical juncture in the development of Ireland's nanotechnology commercialisation strategy. The cost benefit outcome for such an investment is not persuasive.

The current Irish nanotechnology infrastructure is however missing a discrete translational research element, especially when it comes to nanoelectronics research. Supporting the access to facilities such as IMEC[1] or collaboration with the University of Cambridge to avail of their facilities can overcome this gap and also has the additional advantage of promoting international exposure and collaboration.

Developing Ireland's nanotechnology vision and commercialisation options

To formulate Ireland's nanotechnology commercialisation options, national objectives have been developed by the Project Steering Group. These objectives were informed by the following considerations:

- A strong consensus exists within the policy and funding establishment to simultaneously service the needs of indigenous enterprise and multinationals;
- There is a strong divergence of opinion between the business and the academic sector regarding the commercial readiness and industrial relevance of existing research;
- A strong consensus exists around putting industry first to create a situation of demand pull instead of science push;
- There is a need to stimulate maximum overlap between existing infrastructure and research capabilities, thereby optimising existing and any additional investment; and
- Ireland has both near-term goals (retain existing FDI; producing high quality, high impact research in Ireland; attracting private/corporate investment in research) as well as longer-term ones (attain international competitiveness in identified niche areas; develop technologically-sophisticated indigenous enterprise; upgrade existing FDI and attract new mobile R&D) and the strategy needs to cater for both.

Ireland's nanotechnology objectives were established by the Project Steering Group as follows:

- To utilise nanotechnology as a catalyst for creating economic value and establishing an entrepreneurial innovation culture;
- To provide a vibrant and collaborative innovation infrastructure that effectively incentivises companies currently operating in Ireland to engage in high-impact R&D as well as attract new multinational mobile R&D investment;
- To develop the multidisciplinary workforce necessary to successfully commercialise nanotechnology innovations, both local and foreign, make the existing industrial base more technologically sophisticated and promote the establishment of new indigenous high-technology businesses; and
- To promote industrially-relevant, high-impact research in Irish universities while better leveraging existing infrastructure and encouraging national and international collaborations.

The Project Steering Group concluded that Ireland's nanotechnology objectives are achievable, but only if a focused and proactive strategy is implemented.

[1] Nanotechnology Research Centre in Belgium.

Recommendations

In order to meet the above objectives, Forfás recommends the following:

Recommendation 1: Focus Irish nanotechnology research

The primary difference between Ireland and the nations reviewed in Phase II is *focus*. To ensure economic impact from public investment, Ireland needs to maintain current funding levels but focus this funding into fewer, more strategic technology-application combinations. This report recommends[2] that Ireland should focus its nanotechnology efforts across three technology domains – Advanced materials, More than Moore[3] and Nanobiotechnology – as they apply across four application domains – Next-generation electronics, Medical devices and diagnostics, Environmental applications, and Industrial process improvements (Table *i*).

Table *i*: Proposed Focus Areas for Irish Nanotechnology Research

Application focus areas → / **Technology focus areas ↓**	**Next-gen electronics**	**Medical devices and diagnostics**	**Environmental applications**	**Industrial process improvements**
Advanced Materials (Functional nanomaterials and nanostructures, Composites, Coatings, Catalysts)	Post-Silicon (Si) materials, Beyond CMOS, printed electronics	Coatings, delivery and diagnostics systems, imaging	Nanostructured membranes, Pollution abatement and treatment, LEDs, coatings	Insulation, coatings, catalysts
More than Moore	System-on-chip, radio, sensors, actuators, cooling element	Bio-logic, sensors, personal health monitors	Sensors Intelligent system control	Sensors, Intelligent system control
Nanobiotech - (Red, Green and White)[4]	-	Encapsulation	Waste treatment	Green chemistry

[2] In order to select the focus areas for Ireland, the following selection principles were agreed by the Project Steering Group: Build on areas where existing research is of high quality (citations/publications) and output (publications/NP); Maximise overlap with existing industrial base – local and foreign; Prioritise areas with substantial pre-existing infrastructure/resourcing investment; Shortlist areas with opportunity for resource sharing and collaboration with Northern Ireland and those that offer unique collaboration potential across the ERA; and Identify themes which resonate with national priorities (e.g. smart economy, green agenda).

[3] **More than Moore:** Focusing on system integration instead of transistor density.

[4] **Green nanobiotechnology:** Biotechnology applied to agricultural processes; some overlap with the energy universe (biofuels). **Red nanobiotechnology:** Use of biological systems or derivatives as applied to medical processes, like engineering organisms to produce antibiotics or genomic manipulation for personalised medicine or advanced imaging technologies. **White nanobiotechnology:** Industrial biotechnology as a component of green chemistry or biotechnology applied to industrial processes, to engineer greener materials, processes or products.

The recommended focus areas should be evaluated and updated on a predetermined schedule (every 3-5 years). This approach represents global best practice and helps keep research priorities relevant and has a selection bias towards areas that meet/exceed expectations. A coordinating group comprising representatives of industry, academia and government, both Irish and foreign, should be set up (Recommendation 2) and tasked with monitoring and evaluating the focus areas and identifying new ones as appropriate. With such a focused approach (and using the implementation strategy recommended in this report), Ireland can derive significant economic value from continued nanotechnology investments.

Specific metrics and targets for the five year commercialisation strategy were proposed by Lux Research[5] (Table *ii*). Using similar funding as today, only focused better, these input and output targets should produce higher impact research and involve collaboration with nations facing similar considerations.

Table *ii*: Proposed Metrics and Targets

In the Period 2010-2014	Advanced Materials	More than Moore	Nanobiotech	Total
Publications	165	165	200	530
Patents	30	30	10	70
Start-ups	10	10	10	30
PhDs	40	40	40	120
Engineers	250	250	250	750
International Promotion	Conferences and workshops as a forum to showcase Irish innovation and expose global community to nanotechnology in Ireland (~5 international conferences per year)			
Public Outreach	Public awareness programmes to educate the population on nanotechnology's promise, risks, and to expose students and entrepreneurs to opportunities in nanotechnology (~12 seminars/lectures per year)			

[5] The desired outcomes of the nanotechnology investment (how many patents, publications, start-ups etc.) for the 2010-2014 period that would (on a relative basis) position Ireland on par or ahead of similar nations were estimated by Lux Research using the following guiding principles:

Produce higher impact research (without a spike in investment);

Using similar funding as today, only focused better;

Collaborate with nations facing similar considerations; and

Strive to improve international profile of Irish nanotechnology.

To implement the recommendation on focus and to meet the target outputs, Forfás proposes a number of strategic implementation measures which include:

- Strategy development;
- Funding;
- Self-sustainability;
- Industry involvement in research;
- Infrastructure;
- Workforce development and academia; and
- Collaboration.

Actions related to these strategic measures are in some cases already being implemented across the system; however, it is important that they are targeted with respect to nanotechnology. This will present significant challenges to implementation, specifically in ensuring an appropriate balance between focus and research excellence in competitive funding. However, without this proactive, focused and coordinated strategy industry engagement is unlikely.

Recommendation 2: Establish a nanotechnology coordinating group

Nanotechnology strategy development, monitoring and review should be centralised under one coordinating group. This coordinating group would comprise multiple stakeholders from government departments, the development agencies, industry and academia.

Using the findings and recommendations in this report as a basis, the group would be tasked with the following:

- Coordinate and oversee the implementation of the nanotechnology strategy as agreed by the Minister for Science, Technology and Innovation based on the findings and recommendations in this report;
- Advise on the necessary supports to be put in place to:
  - Promote the development of innovative local nanotechnology industries which will strongly impact Irish economic growth and benefit investors;
  - Represent the Irish nanotechnology efforts (nationally and internationally);
  - Promote collaboration (nationally and internationally);
  - Provide national accountability for public funds by monitoring progress towards achievement of defined goals; and
- Identify appropriate public and private funding sources for selected projects.

This group would have a charter of at least five years to provide continuity, align with time scales of academic research and commercial development and provide enough time to gauge results.

Recommendation 3: Align funding to focus areas and coordinate funding management

This nanotechnology strategy implies a funding stream for the theme "nanotechnology" in the annual Science Technology and Innovation budget. This nanotechnology commercialisation strategy is likely to require a minimum total funding requirement of €114 million[6] (Table *iii)* over the next five years (or €22.8 million annually), split fairly equally across the three technology focus areas. The nanotechnology coordination group will be responsible for coordinating and overseeing the cohesiveness of the implementation of this funding strategy and will report to the Department of Enterprise, Trade and Innovation (DETI).

Recommendation 4: Ensure diverse funding sources and increased industrial funding

Table *iii* shows the proposed allocation of the required funding between R&D (predominantly applied research), commercialisation, environmental health and safety initiatives and also between government funds and non government funds (money raised by academia and that contributed by industry).

Table *iii*: Sources, Usage of Funds and Performance Ratios

	In the Period 2010-14	Total Investment €114 million
Funding breakdown by source	Government	€114 million*
Government funding breakdown by use	R&D	70%
	Commercialisation and Environment Health and Safety	30%
Performance Ratios	Publications (per million euro)	4.65
	Patents (per million euro)	0.61
	Start-ups (per million euro)	0.22
	PhDs (per million euro)	1.05

*Ideally an increasing proportion of this funding would come from non government sources and this is something Ireland should aspire to.

[6] Using the metrics and targets in Table *ii*, the investment required to produce a single unit of each (1 PhD, 1 start-up, 1 patent, etc.) was estimated based on Lux Research's knowledge of the area.

As Ireland is in the early stages of nanotechnology research commercialisation, the funding will have to largely come from public sources for at least the next three years. Corporate investment will come on the back of quality academic research that is targeted at current and future market needs. Such research should be the near-term Irish priority and should underpin the proposed nanotechnology focus areas. Ireland needs to introduce structured programmes (aligned to the focus areas) to attract and significantly increase industry involvement, commitment and investment in nanotechnology R&D activities. The inclusion of industry on the coordinating group will be important in this context.

Recommendation 5: Establish a self sustainable strategy

Government has a role in supporting emerging and potentially (economically) important technology areas. Once research, technology and development programmes are established the government must be in a position to focus its attention on the next emerging area. The coordinating group should be tasked to develop a self-sustainable plan that secures future required investment with reduced government contribution. As nanotechnology moves into the true commercialisation arena where private enterprise best operates, the need for government funding will reduce.

Recommendation 6: Develop Infrastructure to support Ireland's nanotechnology vision

The central focus of the public research investment in nanotechnology research is not at this point about more new infrastructure. The near term focus should be to maximise use of existing infrastructure; the INSPIRE[7] network and the National Access Programme (NAP) are steps in the right direction as they develop infrastructure sharing agreements with selected international partners over the subsequent months. The medium term focus should be to upgrade existing infrastructure, e.g. adding capabilities to work with biological media to institutions with More Moore[8] clean rooms. In the long term a review of the performance resulting from the near and medium term foci should be carried out to identify critical infrastructure augmentation needs.

Recommendation 7: Develop an entrepreneurial workforce to enable the effective translation of relevant research into commercially viable opportunities

To effectively commercialise nanotechnology, Ireland must develop an entrepreneurial workforce to enable effective translation of relevant research into commercially viable opportunities. With a specific focus on nanotechnology over the next 12 to 18 months, Ireland should deploy all of the below options:

- Develop structured nanotechnology PhD programmes;
- Attract foreign researchers to work in Ireland;
- Develop business curricula within graduate and undergraduate programmes;
- Promote internships and retraining programmes;
- Review academic performance assessment; and
- Initiate business plan competitions.

[7] Integrated Nanoscience platform for Ireland

[8] More Moore: Alternative technologies to scale devices along Moore's law once the physical limits of silicon-based transistors have been reached.

Recommendation 8: Encourage and foster intensive collaboration at a national and international level

Given nanotechnology's multidisciplinary nature, Ireland must continue to encourage and foster intensive collaboration (both inter academia and industry-academia) at both national and international level as an important means of sourcing ideas, resources and opportunities. The chosen focus areas lend themselves to such engagements. Although such collaborations exist today, they have not been directed at the multi-lateral level and have yet to significantly raise the profile of Irish nanotechnology research globally. This approach also fits in with the overarching goal of improving Ireland's international profile as a nanotechnology player.

To achieve this, steps should be taken to:

- Initiate meaningful collaborative agreements with the following countries: Netherlands, Denmark, Germany, Finland, US, Singapore and Israel;
- Initiate the process of cross border collaboration with Northern Ireland.
- Leverage Ireland's position in the Environment, Health and Safety area of nanotechnology to increase participation in EU-level discussions and consortia;
- Continue to institute sabbatical programmes for leading foreign researchers to come to Ireland and for Irish researchers to spend time in research centres abroad; and
- Organise nanotechnology-themed executive events, within Ireland, focused at international corporate attendees.

1 Project Objectives and Rationale

This study was commissioned by Forfás as an input for the assessment of various options and strategies to support the commercialisation of Irish nanotechnology research (both private and public) as requested by the Interdepartmental Committee on Science, Technology and Innovation (IDC). Lux Research, who undertook this study with Forfás, have global experience in helping corporations and governments to assess and strategise around nanotechnology innovation and commercialisation.

Through this study, Forfás sought to:

- Identify the options and models for the island of Ireland to leverage its existing nanotechnology research base to attract and retain Foreign Direct Investment (FDI) as well as encourage the development of indigenous enterprise. This was to be done keeping in mind the national and international innovation environment.
- Evaluate the feasibility of the various commercialisation options, including the possible establishment of a multidisciplinary Nanotechnology Fabrication facility (NanoFab) (keeping in mind the length of time to become fully operational and to yield a return on investment) that would provide researchers, enterprise and entrepreneurs with access to pre-commercialisation facilities.

1.1 Project approach and work plan

Forfás appointed a representative Project Steering Group for this study. This group was comprised of representatives from Forfás, Science Foundation Ireland (SFI), IDA Ireland, Enterprise Ireland (EI), Higher Education Authority (HEA) and the Department of Enterprise, Trade and Innovation (DETI).

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Phase II evaluated the nanotechnology commercialisation strategies employed by a select group of five comparable nations to identify best practices, as well as avoidable errors. Ireland was benchmarked within this context. Also, as part of this phase, several global NanoFabs, large and small, were assessed to study their design rationale and impact.

Developing Ireland's nanotechnology vision and commercialisation options (Phase III)

Building on the first two phases, Phase III focused on establishing Ireland's nanotechnology vision and focus areas, with the emphasis on the ability to add and create economic value and impact. With the connection between Irish focus areas and the global landscape of competition and opportunity established, options for the commercialisation of nanotechnology in Ireland were indentified. Lux Research reported the findings from Phase I and II to the Project Steering Group Based on this analysis, Forfás presents proposed actions for the island of Ireland to develop a commercialisation framework for nanotechnology.

Extensive consultation was carried out throughout the course of this study which included regular engagements with representatives from the NanoFab Consortium[9], Department of Enterprise Trade and Investment in Northern Ireland, Invest Northern Ireland and industry. During Phase I, Forfás also conducted site visits to numerous Irish companies and research institutes and interviewed professors, students, policy makers and industry participants.

[9] The Nanofab Consortium is an industry led grouping which developed a proposal for a nanofab facility in Ireland (*Report from the Nanofab Consortium, 2008*)

2 Introduction: Why Nanotechnology Matters

Nanotechnology is an enabling technology affecting a wide range of industries. It impacted $254 billion worth of products globally in 2009 and this impact is forecasted to grow to $2.5 trillion in 2015.

Nanotechnology has increasingly become a fact of life and business. Nanotechnology follows the evolutionary trend of other world-changing technologies like plastics, biotechnology and information technology. For emerging technologies, everything starts with the discovery phase, a period of basic research and application development. This phase has a characteristic time span in the region of about 20 years. After this is the commercialisation phase. For example: plastics had their discovery phase in the 1920s with the first blockbuster product, nylon stockings, in 1939. In biotechnology, DNA was characterised in 1953 and the first biotech start-up, Genentech, was founded in 1976. Similarly, in information technology, the internet protocol was proposed in 1974 and Netscape's blockbuster browser was released in 1994.

Nanotechnology's discovery phase started in the mid-1980s with the invention of scanning probe microscopes. This enabled scientists to visualise matter at the nanoscale for the first time. Innovations have reached the market in electronics (A123 Systems' nanostructured battery electrodes appeared in Black & Decker's Dewalt line of power tools), in healthcare, (nanoparticulate drug reformulations like Abbott's cholesterol drug) and in materials and manufacturing (Nanogate's tribological coatings).

2.1 What Is Nanotechnology?

Many definitions of nanotechnology exist. The working definition of "nanotechnology", which was agreed by the Project Steering Group for the purpose of this report, is as follows:

Nanotechnology - The <u>purposeful engineering</u> of matter at <u>scales of less than 100 nanometres (nm)</u> to achieve <u>size-dependent</u> properties and functions.

The three components of this definition (purposeful engineering, scales of less than 100 nm and size-dependent properties and functions) serve as qualifiers for whether or not a given innovation constitutes "nanotechnology"[10] (See Figure 1). These components are discussed below.

- **Purposeful engineering**

  To eliminate materials and devices that have nanoscale dimensions but were not purposefully designed to.

- **Scales of less than 100 nm**

  This boundary condition is by no means a hard-and-fast rule; it simply serves as effective shorthand for the point at which the properties of matter change in size-dependent ways due

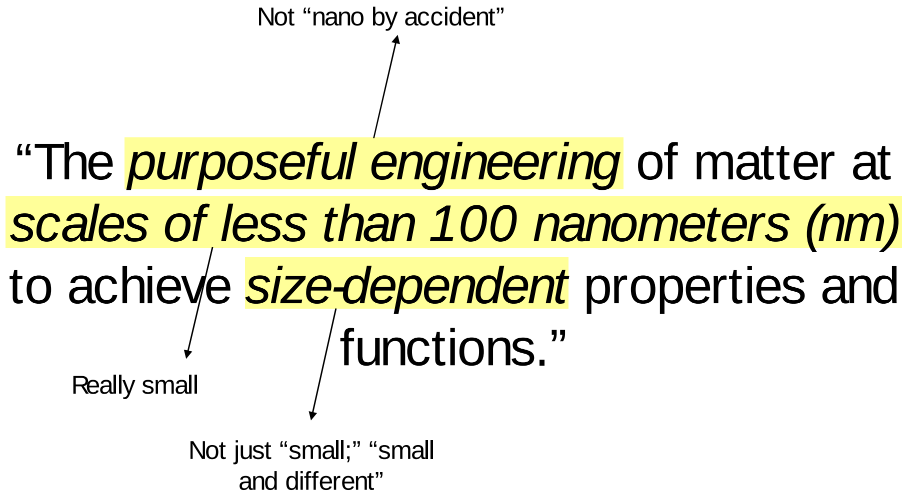
[10] See Appendix A for a detailed explanation of these three components and some commonly-held, inaccurate conventional wisdom regarding nanotechnology.

to quantum mechanical influences, dramatic increases in surface area, or other effects that manifest themselves only at the nanoscale.

- **Size-dependent properties and functions**

  This is the most critical qualifier in the definition. Nanotechnology applications involve materials and structures that are not only *small*, but are *small and different.*

Figure 1: Definition of Nanotechnology



To assist with the understanding of scale, 10 hydrogen atoms side by side measure about one nanometre in width. A strand of DNA is about two nanometres wide.

Source: Lux Research

2.2 The Nanotechnology Value Chain

Nanotechnology is an enabling technology with a broad impact across multiple sectors. In essence, there is no "nanotechnology industry" but instead nanotechnology developers supplying new products and knowhow that add value to a wide set of existing industries. A value chain structure can be used to visualise the role that nanotechnology applications play from raw materials through to the final goods (Figure 2). The value chain is divided into four categories, three of these categories form a linear value chain and the fourth spans the whole value chain.

The categories are:

- **Nanomaterials**

  Nanomaterials are purposefully engineered structures of matter, with at least one dimension of less than 100 nm. These structures exhibit size-dependent properties that have been minimally processed. Commercially significant types of nanomaterials include carbon nanotubes, nanoclays, fullerenes, metal and metal oxide nanoparticles, dendrimers and nanoporous materials. For example, the nanotechnology value chain leading to General Motors' (GM) Chevrolet Impala starts with a nanomaterial: nano-sized clay particles from Southern Clay Products, sold under the Cloisite brand, which have been chemically modified to be compatible with polymers.

- **Nanointermediates**

  Nanointermediates are intermediate products, neither the first nor the last step in the value chain. Returning to the Chevrolet Impala value chain, Southern Clay provides its clay nanoparticles to plastic manufacturer LyondellBasell, which incorporates them into a polypropylene composite that GM will later use to mould parts of the car's body.

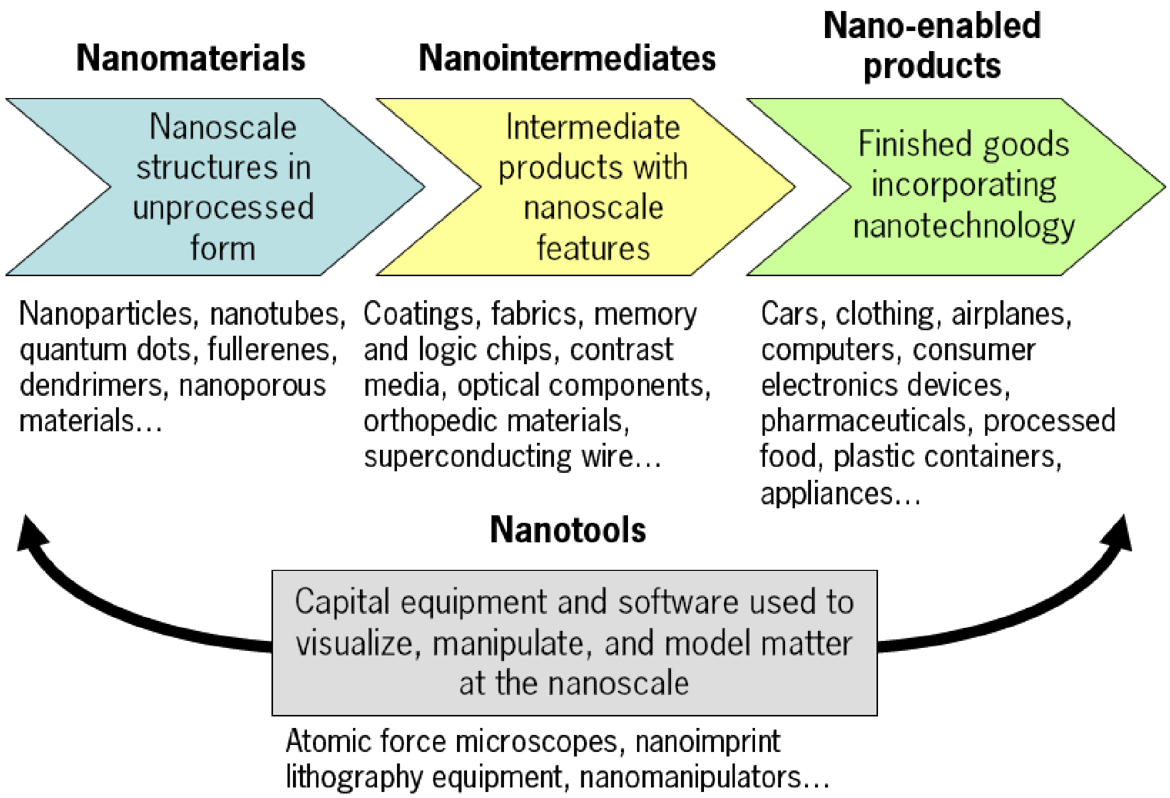
- **Nanotechnology-enabled products**

  Nanotechnology-enabled products are finished goods at the end of the value chain that incorporate nanomaterials or nanointermediates. In the case of GM's Chevrolet Impala, the nanotechnology-enabled product is the car.

- **Nanotools**

  The previous three value chain stages flow into one another. Nanomaterials are used in nanointermediates which are incorporated into nano-enabled products. Researchers and manufacturers working at all three of those stages make use of the fourth value chain category in their R&D and production activities, namely nanotools. Nanotools represent the capital equipment and software used to visualise, manipulate and model matter at the nanoscale.

Figure 2: The Nanotechnology Value Chain



Source: Lux Research

Over the past decade, nanotechnology developers have slowly transitioned from being pure nanomaterials manufacturers (companies that focused on their ability to make a new and different kind of entity) to nanointermediates developers (companies which work on harnessing nanotechnology to solve specific market needs).The *nanomaterials* segment of the value chain is getting commoditised and being dominated by large companies and smaller developers (companies and nations) that are largely focused on the *nanointermediates* segment of the value chain. This is where a majority of the profit margin is captured. The *nano-enabled products* segment is the demand centre made up of the large and small manufacturing and service companies of the world, but it largely functions as an adopter of nanotechnology rather than a frontline developer.

2.3 Nanotechnology's Market Penetration

Over the last decade, nanotechnology has witnessed unprecedented excitement on the parts of researchers, policymakers and investors. Often times, the limits imposed by the pace of the aforementioned discovery phase were ignored and unrealistic promises were made about everything from cancer cures and aging reversal to quantum computing and revolutionary next-generation memory devices. Instead, nanotechnology has slowly worked its way into being an important, yet lower profile enabler (applications like coatings and encapsulants). To a large extent, nanotechnology has been a victim of its own hype – no real-world technology could be expected to live up to the claims made for nanotechnology in some of the early excitement about the field. Despite this nanotechnology is evolving into a useful enabler for a diverse array of products. Nanotechnology's fundamentals are strong.

Nanotechnology R&D funding has been growing at a steady pace, up 15 percent in 2008, to reach $18.2 billion globally[11] [12]. This has resulted in steadily increasing numbers of publications and patent filings. Publications have grown at a 19 percent compound annual growth rate (CAGR) since 2006 to reach 48,426 in 2008[13]. Patent filings are up 12 percent CAGR over the same period to hit 12,391 filings in 2008. On the commercialisation front, Lux Research calculate that nanotechnology will be incorporated into $254 billion worth of products globally in 2009 and is forecasted to be incorporated into $2.5 trillion worth of products globally by 2015[14].

Nanomaterials are already, or soon will be, making a difference in eight main commercial markets: aerospace, automotive, construction, electronics, energy and environment, manufacturing, medical and pharmaceutical and oil and gas[15]. Figure 3 shows Lux Research's expectations of nanotechnology's global deployment in different application areas.

[11] See the December 2008 Lux Research Report "Cleantech's Dollar Investments, Penny Returns".

[12] See Appendix B for a breakdown of funding sources by government, corporate and venture capital (VC), and by geography.

[13] Science Citation Index and Delphion searches. Search string: TS = (quantum dot OR nanostruc* OR nanopartic* OR nanotub* OR fulleren* OR nanomaterial* OR nanofib* OR nanotech* OR nanocryst* OR nanocomposit* OR nanohorn* OR nanowir* OR nanobel* OR nanopor* OR dendrimer* OR nanolith* OR nanoimp* OR nano-imp* OR dip-pen).

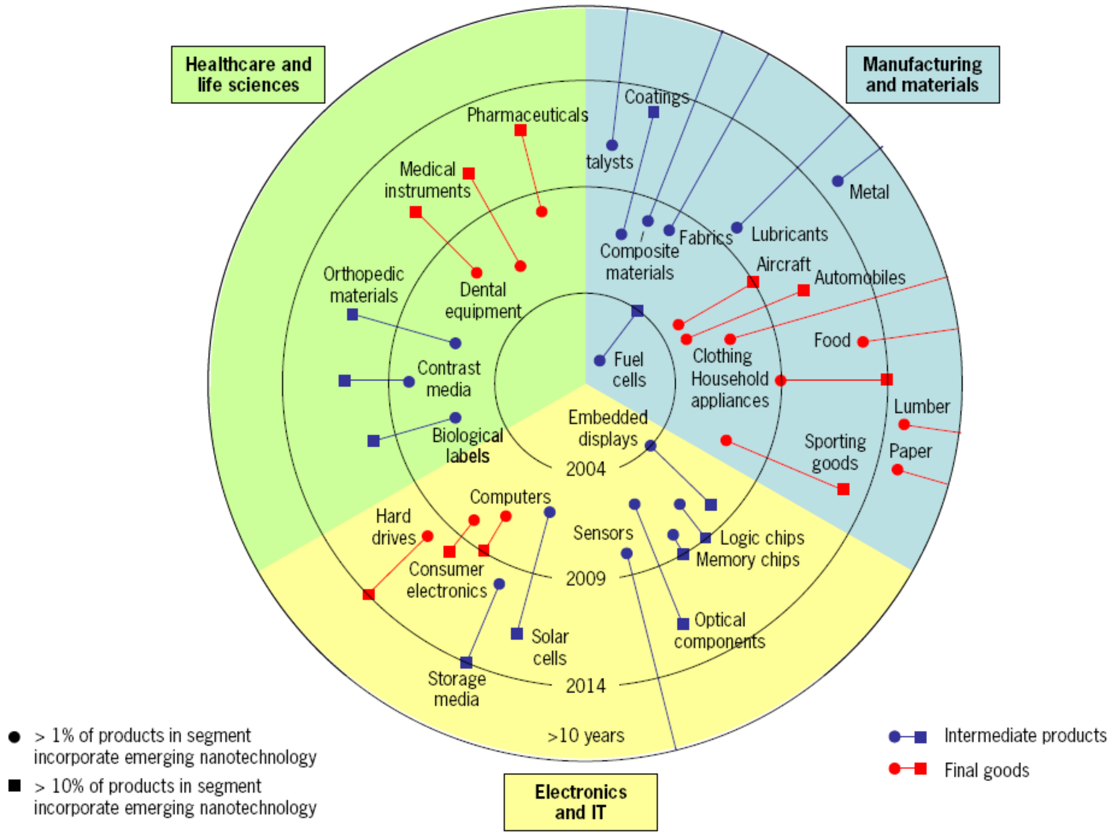
[14] See the June 2009 Lux Research Report "The Recession's Ripple Effect on Nanotech".

[15] See Appendix C for the specific applications within these markets where, Lux Research believe, using nanomaterials could help in gaining competitive advantage.

2.4 Nanotechnology and Ireland

If one superimposes Figure 3 onto the list of the largest Irish business sectors, nanotechnology's potential impact on Ireland's economy becomes apparent (Table 1). Each of these sectors is either already, or soon will be, impacted by nanotechnology. The greatest impact will be in the 2009 to 2014 period, with technologies that are currently at *development* stage (proof-of-concept type work), making the transition to the *introduction* stage (with first products entering the market) and then to commercial scale (with product revenues in the tens and hundreds of millions). Equally important is the fact that a significant portion of all innovation in these sectors is likely to be driven by nanotechnology.

Figure 3: Expectations on Nanotechnology's Global Deployment by Sector



Source: Lux Research

Ireland is faced with a choice - it can back away from nanotechnology or it can make focused, deliberate efforts to generate a pipeline of world-class, high-impact nanotechnology innovations. A strategy of funding everything (that can be typical of government efforts to fund early-stage technologies) is no longer practicable in a field that is about to move into the commercialisation phase.

Table 1: Nanotechnology's Impact on Irish Business Sectors with High Sales/Employment Share

Sector	Examples	Deployment Status (year of mass deployment)
Manufacturing	▪ Anti-wear coatings ▪ Electrical infrastructure ▪ Antimicrobial materials ▪ Processing aids ▪ Catalysts ▪ Antifouling and anti-corrosion coatings ▪ Filtration ▪ Sensors to monitor water and air ▪ Anti-adhesion coatings/lubricants ▪ Insulation	Introduction or Commercial Scale (Ongoing)
Food	▪ Biosensors that detect contaminants and pathogens ▪ Encapsulation systems ▪ Design of flavours and antioxidants to improve functionality ▪ Nanodispersions and nanocapsules for delivery of functional ingredients ▪ Packaging technologies ▪ Coatings – antimicrobial, wear-resistant, barrier, thermal	Development (2012 and beyond)

Sector	Examples	Deployment Status (year of mass deployment)
Electronics and IT	▪ Transparent conductors ▪ Thermal management ▪ Displays ▪ Memory technologies ▪ Printed electronics ▪ LEDs and optical components ▪ Energy storage ▪ Narrier coatings ▪ Packaging ▪ Lithography	Development or Introduction (2012 and beyond)
Chemicals and Pharmaceuticals	▪ Nanomaterials ▪ Coatings ▪ Polymer dispersions ▪ Micronized drugs ▪ Drug delivery ▪ Catalysts ▪ Theranostics ▪ Imaging ▪ Composites	Development or Introduction (2015 and beyond)

Source: Lux Research

2.5 Ranking International Nanotechnology Activity

Nanotechnology has become increasingly global in scale in recent years, with cooperative efforts involving multiple countries becoming more the norm than the exception. Lux Research have developed a framework (called the *Nations Ranking Grid*) for analysing nanotechnology globally. Using this framework, analysis of countries is carried out along two axes: *nanotechnology activity*, an absolute measure of the raw material for nanotechnology development and *technology development strength*, a relative measure of a nation's technology commercialisation. Nanotechnology activity is on the vertical axis and technology development strength is on the horizontal axis. Analysing the data underpinning the metrics in Table 2 and 3, countries can be plotted onto the nations ranking grid. Therefore, Lux Research's *Nations Ranking Grid* provides an assessment of each nation's overall nanotechnology performance and capabilities (Figure 4)[16].

Table 2: Nanotechnology Activity Criteria

Criterion	Weight	Description	Why It Matters
Nanotech initiatives	15%	Qualitative assessment of the operational status, effectiveness, and coordination of nanotechnology initiatives at the national, regional and local levels	Indicator of level of planning and foresight brought to nanotechnology development
Nanotech centres	15%	Number of dedicated government and university nanotechnology facilities in country with a focus on either R&D or commercialisation	Magnets for academics, breeding grounds for start-ups and collaboration centres for corporations
Government spending	10%	Amount of funding at regional and national levels specifically allocated to nanotechnology in 2008	Clearest indication of a country's willingness and ability to develop nanotech innovations
Risk capital	10%	Qualitative assessment of availability of risk capital to fund new ventures, taking into account institutional venture capital, government grants and subsidised loans	Bridge across the "valley of death" for entrepreneurs commercialising nanotechnology
Corporate nanotech funding	10%	Estimated spending by established corporations on nanotechnology R&D in 2008, at purchasing power parity	In countries with little history of start-up ventures, large corporations drive nanotechnology development
Nanotechnology publications	15%	Number of articles in scientific journals on nanoscale science and engineering topics from 1995 through 2008	Best available indicator of nanotechnology research activity
Issued international patents	15%	Number of international patents on nanotechnology-enabled inventions issued from 1995 to 2008 to entities based in country	Indicator of intent to commercialise nanotechnology innovations globally
Active companies	10%	Qualitative score; considering both number and quality of companies active in nano, including large corporations, small and midsize companies and start-ups	Measurement of business, not academic, nanotechnology activity

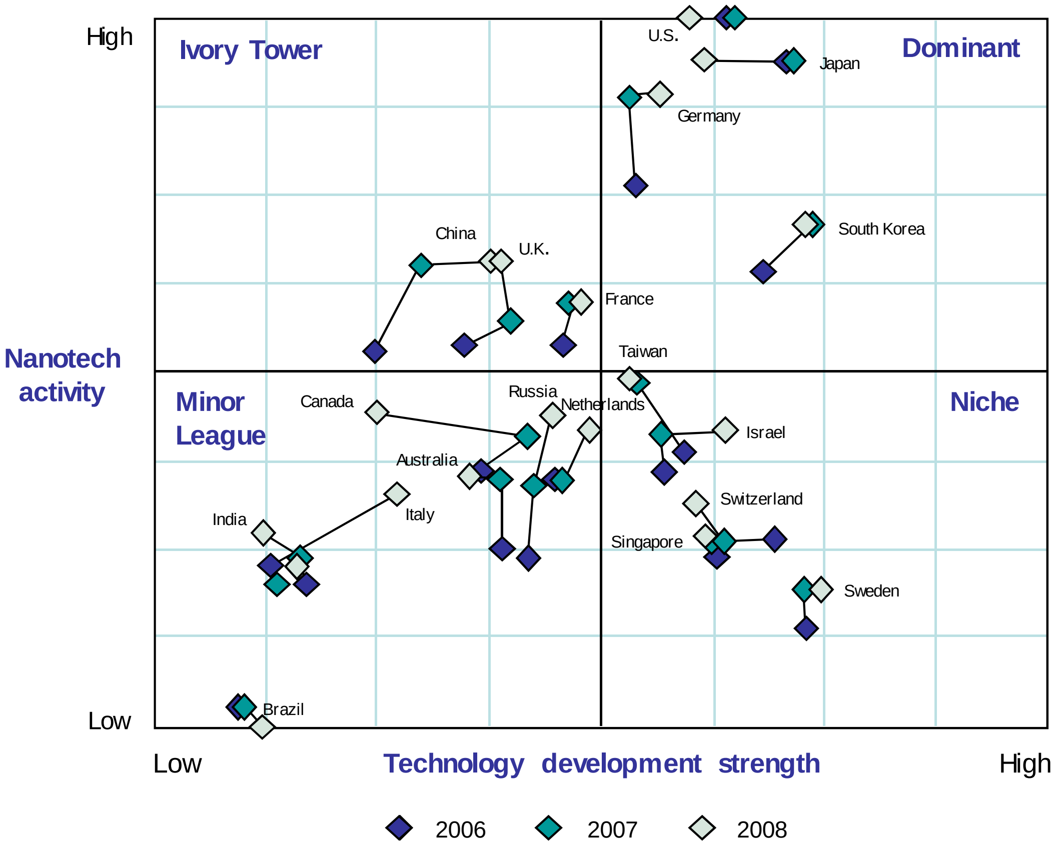
[16] See Appendix D for a more detailed discussion on the Nations Ranking Grid.

Table 3: *Nations Ranking Grid* **- Technology Development Strength Criteria**

Criterion	Weight	Description	Why It Matters
High-tech manufacturing as percent of GDP	20%	Value of domestic output for high-tech chemicals, information technology products, pharmaceuticals, and life sciences products for most recent year available divided by GDP in that year	Indicator of how much a country has developed an economy that exploits high technology
R&D spending as percent of GDP	25%	Gross domestic R&D spending from both government and private-sector sources divided by GDP, for most recent year available	Demonstrates a country's private- and public-sector commitments to technology commercialisation
Technology and science workforce	20%	Number of R&D personnel per $1,000 of GDP at purchasing power parity, for most recent year available	Required to convert scientific innovations into commercially viable products and services
Science and engineering PhDs	15%	Number of science and engineering Ph.D. graduates as a percent of total population, most recent year available	Required to generate scientific innovations that feed commercialisation efforts
Expatriation of highly educated	10%	Percent of highly educated leaving country in 2008	When the highly educated expatriate, technology commercialisation suffers
Infrastructure	10%	Composite metric composed of electricity availability (2%), mobile phones per capita (2%), Internet hosts per capita (2%), Internet users per capita (2%), and abundance of roads (2%), for 2008	Basic infrastructure is required for effective technology commercialisation

Source: Lux Research

Figure 4: *Nations Ranking Grid*



Source: Lux Research

Based on the *Nations Ranking Grid* (Figure 4) in 2008 the US and Japan continued to hold the leadership positions. China improved its technology development capability through increases in its R&D workforce and number of earned science and engineering degrees. Russia improved its nanotechnology with the introduction of Rusnanotech ($780 million nanotechnology funding programme).

As part of this study, Ireland will be mapped onto the *Nations Ranking Grid* (Chapter 3). There are two key points to note from an Irish perspective: 1) several countries will continue to significantly fund nanotechnology and 2) very few small nations have mounted a serious threat to break into the dominant tier, too small to really compete with larger nations on nanotechnology activity metrics. These small nations are now looking to exploit expertise in particular sectors; for example, electronics for Taiwan and life sciences for Singapore. Based on the information above, it is expected that more small nations will adopt this approach.

2.6 Nanotechnology's Outlook

Market analysis by Lux Research states that: In the 2009 to 2011 period, nanotechnology development will be characterised by nanotechnology entering new industries and focusing on near-term applications. From 2012 to 2014, nanotechnology will start to affect the industries it has penetrated in new ways, simplifying supply chains and impacting on industries, like pharma and oil and gas. Beyond 2015, nanotechnology will become routine enough that the "nano" term will largely fade from view in many industries, while overall funding finally levels off and high-profile applications like flexible organic solar cells finally approach commercial readiness. Lux Research expects the following trends:

Nanomaterials manufacturing becomes the province of large companies

- During the next two years, nanomaterials manufacturing will increasingly shift from start-ups to large corporations.

Electronic materials increase in importance

- Two nanomaterial applications with the greatest corporate R&D interest are 1) new transparent conductors, based on carbon nanotubes (CNTs) or silver nanowires, to replace indium tin oxide (ITO) in displays and 2) barrier films to keep oxygen and water away from sensitive electronic components in uses like organic light emitting diodes (OLED) displays and flexible solar cells. It is expected that through to 2011, speculative actions will make this market space crowded.

More corporations adopt explicit nanomaterials safety policies

- Companies will see openness about their own safety efforts as a way to gain competitive advantage in a sceptical marketplace.

New industry clusters emerge

- For years, the chemical and electronics industries have dominated nanotechnology applications development; however, between 2012 and 2014, Lux Research expect to see other clusters emerge, such as oil and gas. The King Abdullah University of Science and Technology donated $25 million to Cornell University to study oil, gas and other energy and environmental applications. Shell invested $10.6 million in a joint venture it formed with NanoDynamics for a similar purpose.

Developing countries increase their involvement in the development of nanotechnology

- Developing countries continue to commit a growing number of resources to nanotechnology development, as nations like India, Brazil and Iran increase nanotechnology priorities. With strong science and technology work forces, these countries have great potential for nanotechnology work.

Food and personal care applications

- Because of costs, long testing cycles and the fear of perceptual risks, uses of nanotechnology in or on the body have lagged, but the use of the technology in those fields is expected beyond 2015, driven by the developments in technologies in the previous time period. A key driver will be nanoencapsulants for preservatives, flavouring and nutrients in food. In addition to the more established food packaging, active ingredient delivery in "cosmeceuticals" will supplement existing uses of metal oxide ultra violet (UV) absorbers.

Nanotechnology funding reaches its peak

- As government-funded facilities and initiatives mature, government funding specifically for nanotechnology is likely to level off. Also, given the range of other emerging technologies diversified firms need to explore, nanotechnology will never command more than a certain percentage of their R&D budgets, perhaps as high as 50 percent in the semiconductor industry, but rarely more than 10 to 20 percent otherwise. As a result, corporate funding will hit a natural limit. Similarly, venture capital (VC) funding can not grow forever and will soon level off or drop. All told, sometime past 2015, total funding for nanotechnology R&D will reach its peak, staying flat or slightly declining thereafter.

2.7 Key Messages

Based on the above, the Project Steering Group were advised of the following:

- Nanotechnology is an enabling technology that has the potential to impact the minutest aspect of human life;
- Although the road thus far has been fraught with slower than promised development and adoption, nanotechnology's fundamentals are strong; and
- Every significant aspect of Ireland's economy is set to be greatly impacted by nanotechnology.

3 Benchmarking Ireland's Nanotechnology Capabilities

3.1 Methodology

A benchmarking exercise was carried out to formulate a detailed picture of Ireland's existing nanotechnology research capabilities, potential nanotechnology opportunities and the required future research capabilities that would have to be developed to address these opportunities. In order to perform the benchmarking, primary data (obtained through site visits, surveys and interviews) and secondary data (focused on patent and publication analysis) was collected and analysed. Further details are provided below.

- **Site visits[17] and interviews**

  A number of site visits were conducted at academic and research institutions on the island of Ireland. These site visits, combined with interviews with key personnel, yielded important qualitative and quantitative insights to complement the secondary data analysis. Additionally, the interviews provided valuable personal observations that enabled a better understanding of the context of academic research and nanotechnology commercialisation in Ireland.

- **Surveys[18]**

  For input into this study, a nanotechnology survey was undertaken by Forfás. The results of the survey were used to complement the primary data obtained via site visits and interviews.

- **Secondary research analysis**

  Thirteen nations were chosen as the peer group for the benchmarking on the basis of the following attributes:

  - Countries similar to Ireland in their global nanotechnology standing: Brazil, India, Italy, Australia, Canada, Russia and the Netherlands;
  - Global nanotechnology leaders (Figure 4): U.K., US, Japan and Taiwan; and
  - Other comparable nations within the European Union: Denmark and Finland.

  In order to compare and rank Ireland within the peer group, the following three key metrics were chosen (Table 4):

Table 4: Benchmarking Parameters and Proxies

Parameters for Comparison	Proxy Used
Research Output	Publications/GDP and Publications/GERD
Quality of research produced	Citations/Publications
Commercial emphasis	Patents/GDP and Patents/GERD

[17] See Appendix E for a detailed list of the visited sites and the interviewees.

[18] See Appendix L for the survey template mailed out to all the respondents.

- Research output (number of publications);
- Research quality (using citations divided by publications as a proxy indicator); and
- Commercial emphasis (using patent numbers as a proxy indicator).

Secondary data[19] for 2006, 2007 and 2008 was sourced from databases such as Delphion and ISI Web of Knowledge. The rationale behind going no further back than 2006 was that most nations have only been significantly funding nanotechnology research since 2001. Therefore analysing results after five years of investment (2006 onwards) allows for sufficient time for set-up and development.

- **Lux Research's** ***Nations Ranking Grid***

  Lux Research's proprietary *Nations Ranking Grid* (Figure 4) provides a standardised framework for assessing nanotechnology internationally. This provides a framework to assess nanotechnology performance and research capabilities of a given country. Using the metrics outlined in Figures 6 and 7, Ireland can be mapped onto the *Nations Ranking Grid.*

3.2 Findings

Nanotechnology Funding in Ireland

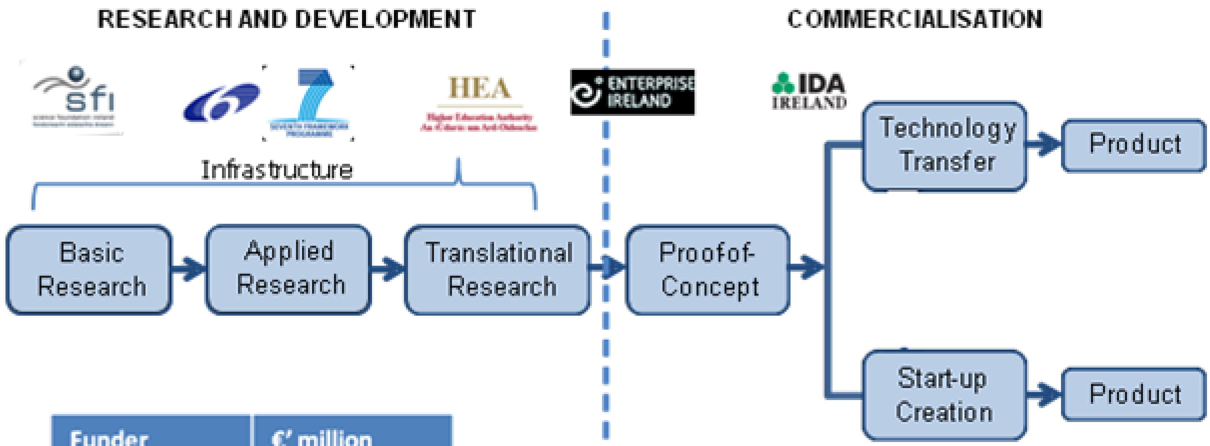
Nanotechnology funding figures were collected based on the definition of nanotechnology employed for this study (Section 2.1). Results indicated that over the period January 2001 to June 2009, Ireland has invested €282 million in nanotechnology R&D (or an investment of approximately €35.3 million per annum). A significant proportion of this funding was used to invest in research infrastructure and capability building in this area. Data from Forfás' nanotechnology survey reported that over 50 percent of the Principle Investigators surveyed received in excess of €500,000 in research funding in 2008. Based on international analysis by Lux Research, the annual funding figure compares favourably with investments made by several countries looking to break into the group of dominant nanotechnology nations on their *Nations Ranking Grid* (Figure 4). The annual funding figures put Ireland's annualised funding as a percentage of 2008 Gross National Product (GNP) at 0.0261percent. Contrasting this with 0.0098 percent for the US, or 0.0089 percent for the Netherlands and it can be seen that Ireland has made a significant investment in nanotechnology. Only Germany in the peer group, with 0.0311percent, reports a higher figure than Ireland.

A large part of the funding to date, especially from agencies like the HEA and SFI, has gone towards establishing research infrastructure and research capabilities in Ireland. The leading nanotechnology research institutes all have quality equipment for inspection, fabrication and modelling. This infrastructure is comparable to (and often better than) a number of academic institutions and national and corporate laboratories visited by Lux Research in the US and Asia over the years. This fact was also acknowledged by several of the interviewees. In the near future, if maintained, the availability of infrastructure and equipment will not be a barrier to the creation of high impact research in Ireland.

Figure 5 presents a schematic representation of the nanotechnology commercialisation value chain and also breaks down the Irish nanotechnology funding across the funding agencies.

[19] See Appendix F for the sources employed to collect the secondary data

Figure 5: The Irish Commercialisation Value Chain (2001-June 2009)



Funder	€' million
SFI	167
FP6	21
FP7	13
HEA	68

Funder	€' million
EI	6.4
IDA	6.8

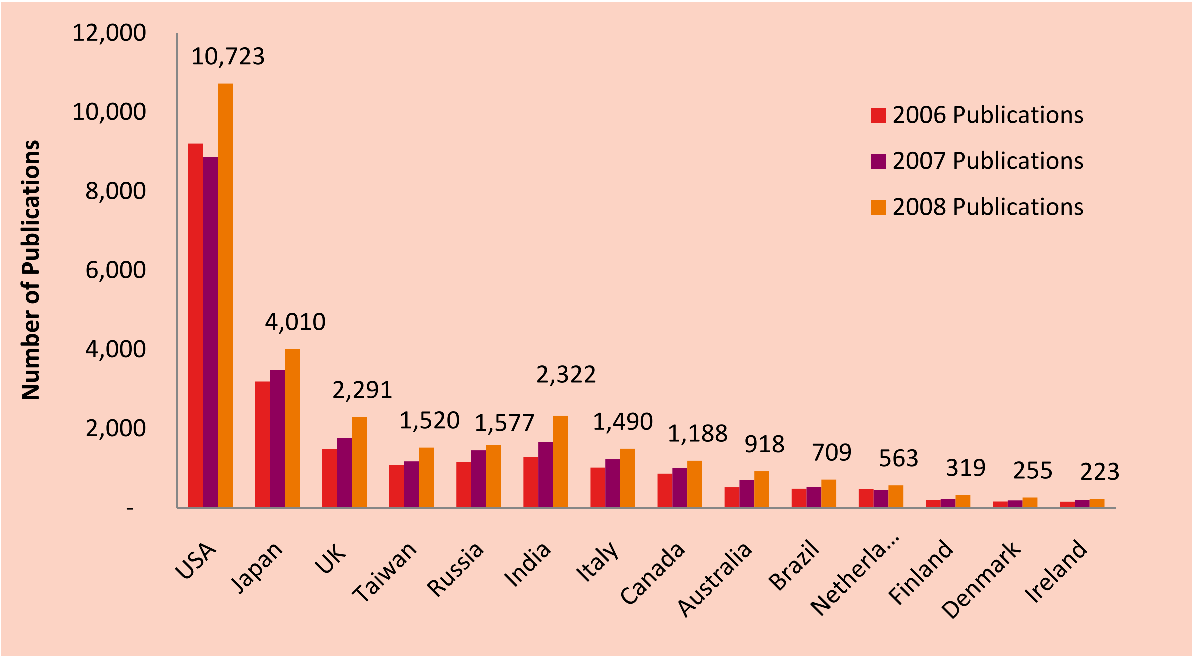
Source: Provided by the respective agencies in June 2009. The "Basic Research" category here is analogous to the "Oriented Basic Research" terminology used within the Irish research establishment.

On the commercialisation side of the value chain, EI has programmes in place to support technology transfer, proof-of-concept and early-stage incubation. While the overall funding allocated to these programmes can certainly be augmented (to be more in line with international numbers), the funding available to individual projects are on par with global norms. Results from Forfás' nanotechnology survey on the availability of funding indicated that respondents see this as a barrier to commercialisation. However, Lux Research's findings did not reflect that viewpoint and indicated that for the current pipeline of projects moving from R&D to commercialisation, the funding allocated via EI is adequate.

Ireland's Productivity and Absolute Research Output

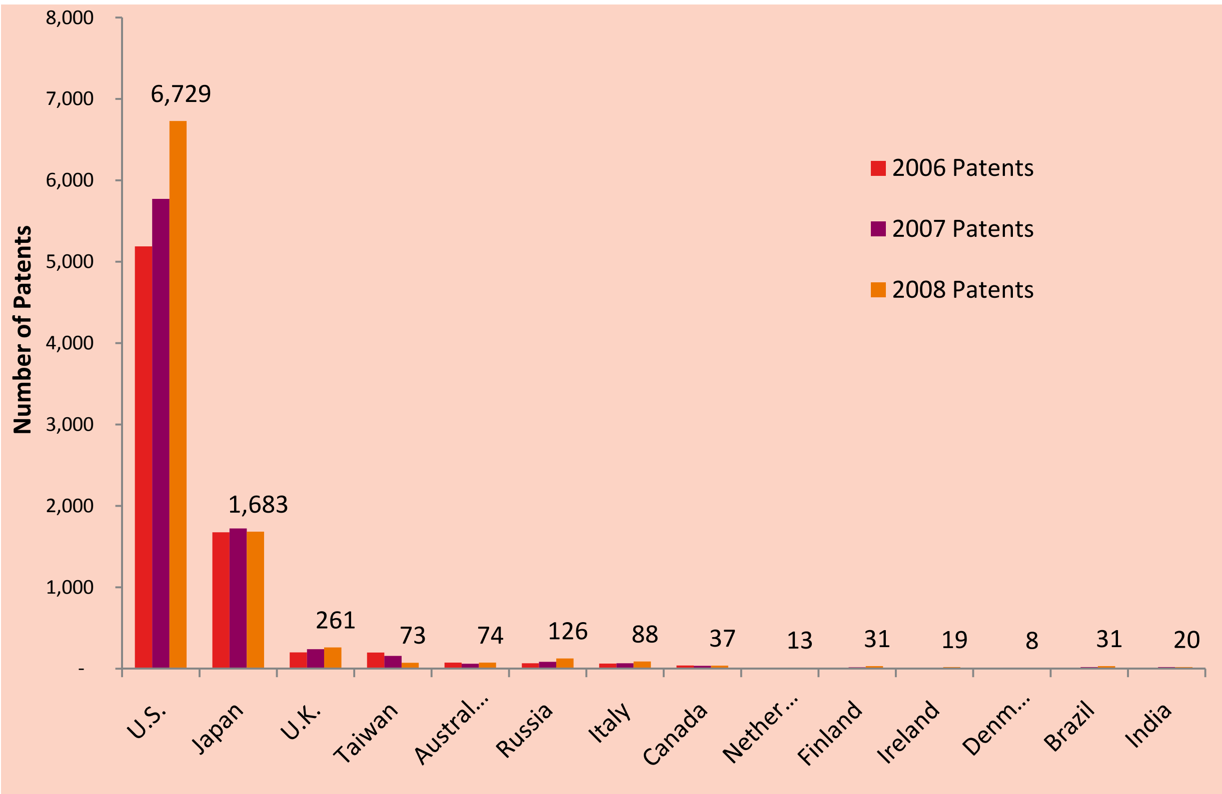
Analysing productivity, patents or publications produced per unit GERD, Ireland consistently features in the top 2-3 nations of the peer group. However, in absolute terms the output is very small as shown in Figures 6 and 7. In absolute terms, analyses indicate that Ireland is in the last position in number of publications but fares better in terms of patent filings. Therefore, the lack of a critical mass presents a challenge for Ireland.

Figure 6: Absolute Number of Nanotechnology Publications Compared to the Peer Group (2006-2008)



Data labels represent the 2008 research output for each country.

Figure 7: Absolute Number of Nanotechnology Patents Compared to the Peer Group (2006-2008)



Data labels represent the 2008 research output for each country.

Market Analysis of Nanotechnology Activity in Ireland Relative to the Peer Group

Lux Research assessed Ireland's and the peer group's nanotechnology activity across 80 market-application combinations (8 markets each with 10 target applications, examples of which are shown in Table 5)[20].

Table 5: Nanotechnology Markets and Target Applications

Market	Sample Target Applications	2008 Market Size (USD billion)	2012 Market Size (USD billion)
Manufacturing and Materials	▪ Processing aids ▪ Sensors ▪ Coatings ▪ Insulation	158	779
Automotive	▪ Fuel-based additives ▪ Catalysts ▪ Lubricants	121	537
Electronics and IT	▪ Displays ▪ Memory technologies ▪ Heat management	56	286
Healthcare and Life Sciences	▪ Wound care ▪ Targeted delivery ▪ Controlled release	24	118
Construction	▪ Insulation, temperature/light control materials ▪ interior/exterior coatings	10	96
Energy & Environment	▪ Energy storage ▪ Sustainable materials ▪ Remediation, conservation	2	17

[20] See Appendix C for a detailed breakdown of the 80 market-application combinations.

Market	Sample Target Applications	2008 Market Size (USD billion)	2012 Market Size (USD billion)
Aerospace	▪ Structural materials ▪ Avionics ▪ Electrical infrastructure ▪ flame-retardants	1	8
Oil & Gas	▪ Sensors ▪ Downhole power ▪ Proppants and binders	0.01	0.8

Source: Lux Research Analysis

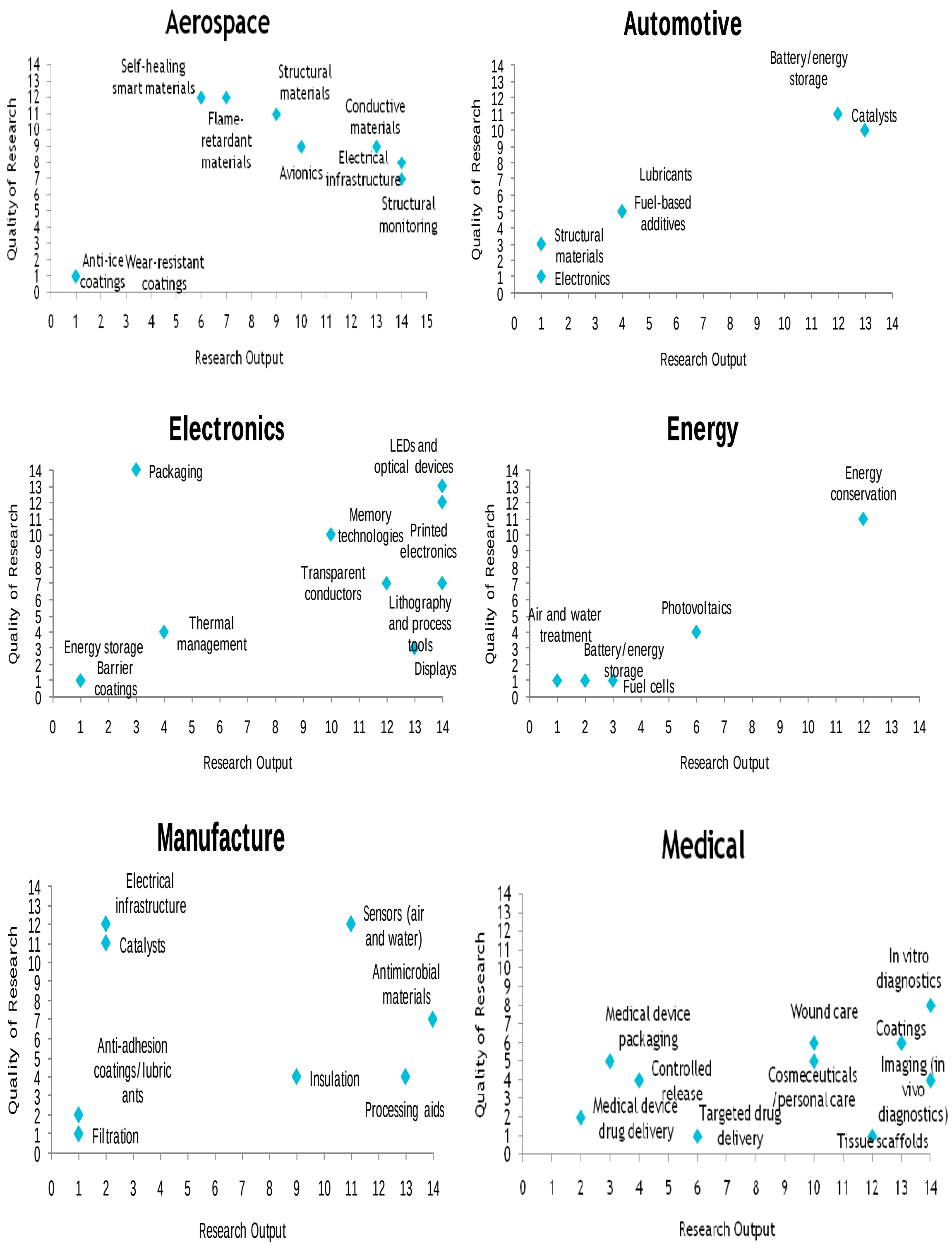
After screening the 80 market-application combinations, results indicated that Ireland has commercially relevant research activity in 49 of the 80 nanotechnology market-application areas. For each of these 49 market-application areas, the comparison metrics (see Table 4 for an explanation of the metrics and proxies used) were analysed. A score for all countries in the peer group rated on a 1 - 14 scale was given (with 14 = highest and 1 = lowest). From this, conclusions were drawn regarding Ireland's research output and productivity, the quality of research produced and the commercial emphasis. The key results are presented below (see appendix G for all the key findings).

Ireland's Research Quality

Figure 8 shows the distribution of the quality of Ireland's commercially relevant nanotechnology research for each market application area relative to the peer group. Key messages from this analysis suggest that:

- Ireland has relatively high research output overall as well as in most individual areas;
- The quality of the research produced varies greatly from application to application;
- All medical and pharmaceutical applications rank at or below average on research quality;
- Energy and environment applications mostly score below average in both quantity and quality of research output, except for energy conservation; and
- Other markets generally split between high and low quality research applications.

Figure 8: The Quality of Ireland's Commercially Relevant Research across the Six Nanotechnology Markets Relative to the Peer Group



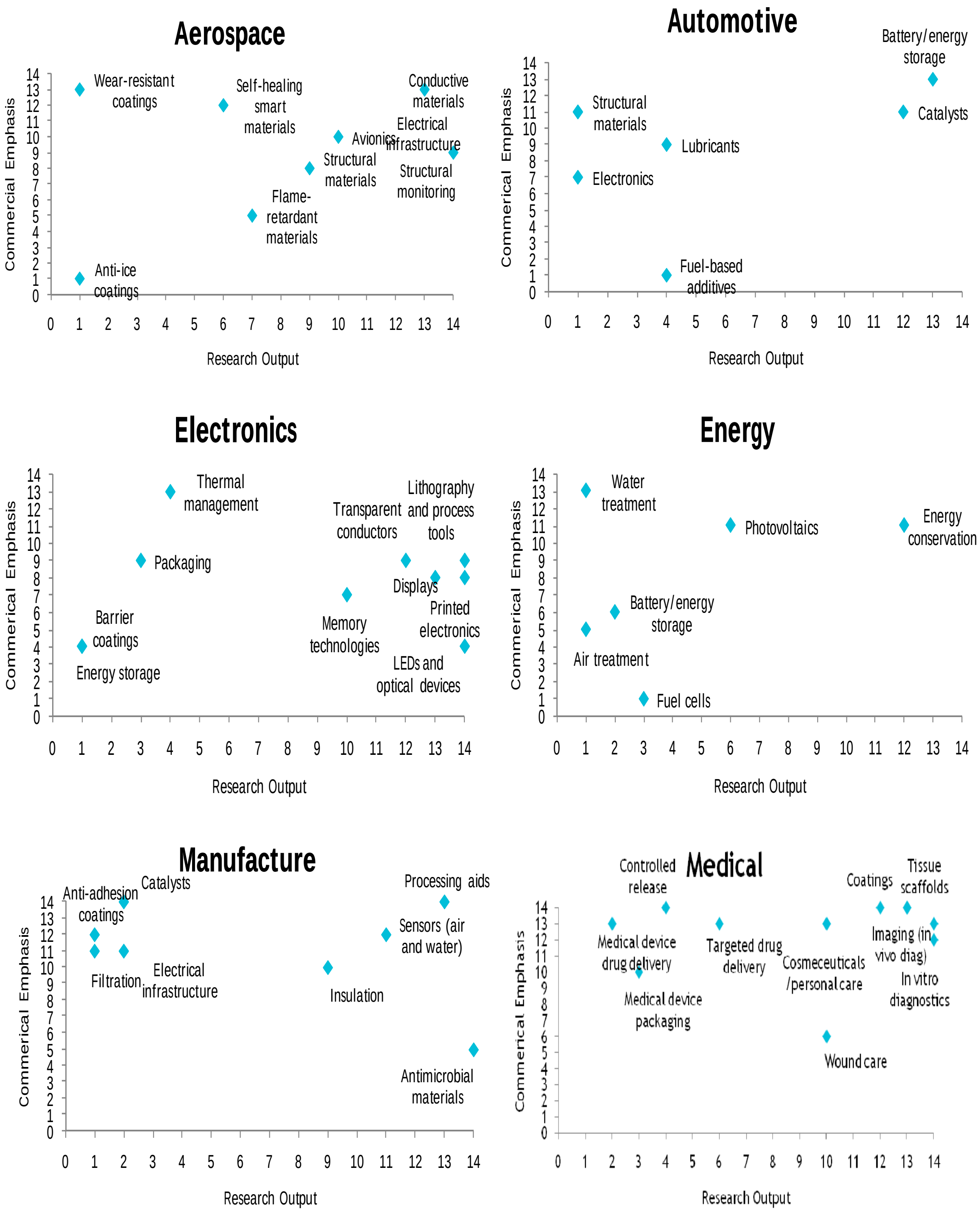
Ireland's Research Commercial Focus

Figure 9 shows the commercial emphasis of Ireland's research output relative to the peer group. Key messages from this analysis suggest that:

- Ireland generally ranks above average in commercial focus;

- Electronics ranks above average on commercial focus;
- Medical and pharmaceuticals ranks highly, though research output varies greatly by application; and
- Most energy and environment market applications lagging in both research output and commercial emphasis.

Figure 9: The Commercial Emphasis of Ireland's research in the 49 market-application areas across the Six Nanotechnology Markets Relative to the Peer Group



From Figures 8 and 9, the key message emerging is the wide variance in the distribution of the data, overall and within each individual sector type.

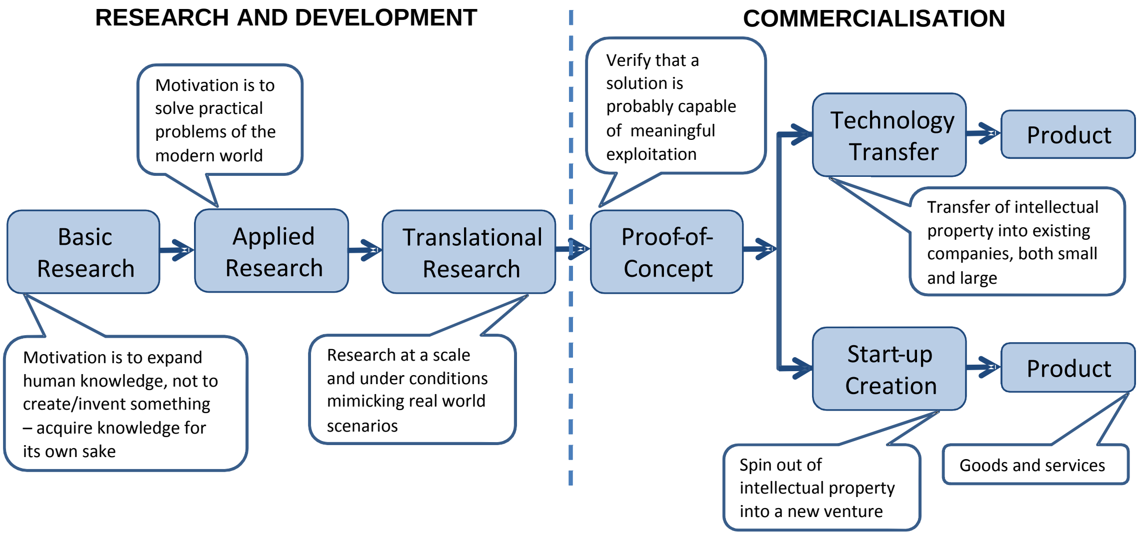
Focus of Nanotechnology Activity

Whether by design or chance, it was found that there is already an element of focus in Ireland's nanotechnology effort. A vast majority of the Principle Investigators interviewed and surveyed worked in the broad thematic areas of electronics and medical device technologies. This is understandable given Ireland's unique FDI situation where the leading companies in these domains all have existing manufacturing operations in the country. However, as shown above, this granularity of focus is not nearly enough.

Technology Exploitation Element

All interviewees and survey respondents indentified an absence of technology exploitation as a key barrier to commercialisation of nanotechnology. Figure 10 presents a linear depiction of the nanotechnology invention-innovation-commercialisation process, called *the commercialisation value chain*. Figure 10 allows one to visualise who the stakeholders in the process are and the different motivations at each stage. To date, the majority of the Irish investment in nanotechnology has supported the early R&D side of the commercialisation value chain. The commercialisation value chain is explained in more detail below.

Figure 10: The Nanotechnology Commercialisation Value Chain



Source: Lux Research

- *Basic Research:* This process typically carried out in universities and national laboratories. The motivation is to expand human knowledge. Such research, by definition, does not have commercial potential as a primary goal.
- *Applied Research*: The goal is to address a specific, real-world challenge. This involves applying the knowhow generated through basic research in a very deliberate fashion.
- *Technology Transfer / Start-up Creation:* Downstream in the chain is where one finds the commercial outcomes of the research, either through transfer of knowhow into existing enterprise (*technology transfer*) or through the creation of new entities (*start-up creation*).

> These sections of the commercialisation value chain are well understood, with clear infrastructure and funding mechanisms. It is the two segments that link the upstream segments to the downstream ones, i.e. the *translational research* and *proof-of-concept* stages that most nanotechnology commercialisation struggles.

The distinction between *translational research* and *proof-of-concept* can be understood as follows. For a project looking at deploying nanoscale zinc oxide for UV protection coating applications basic and applied research will look into the properties of zinc oxide and methods to formulate nanoparticles of a defined size, but two major challenges have still to be overcome before this material can be considered commercially ready. The first challenge is to create a stable dispersion of these nanoparticles which can be applied to surfaces while maintaining clarity and transparency (*translational research*). The second challenge is to analyse the effect of UV on surfaces coated with nano zinc oxide dispersion relative to the control case to prove that there is a net increase in UV protection (*proof-of-concept*). In particular, the activities that fall under translational research require significant application development expertise which is well outside the reach of academia from a resources perspective. Often times, corporations seek proof-of-concept to be established before investing. This creates a significant barrier to commercialisation which most technologies and innovators must seek to overcome.

Findings from this report show that Ireland experiences this problem, especially in the area of electronics where it was found that the translational research piece is absent. Very little of the research is carried out at the industrially-relevant 8” and 12” wafer sizes and there is a knowledge gap that must be bridged before relevant Irish innovation can be translated to the commercial arena for these applications. This problem is far less pronounced in other nanotechnology research areas where the necessary infrastructure is either already in place or could be created with minor additions to existing facilities.

Addressing the Missing Translational Element

Having concluded that the translational element is missing, work was undertaken to assess whether this presents a barrier to commercialisation, as claimed by interviewees. Findings from this report suggest not. The reason for this is that, as pointed out by several interviewees, a very small portion of the ongoing research is commercially relevant over the next five years. Based on the analysis and consultation, Lux Research concluded that unless Ireland picks a fundamentally different way of planning, conducting and evaluating research, the near term commercial impact of ongoing work will be minimal, even with a translational research mechanism in place.

Findings from Lux Research’s assessment of the translational element indicated that, firstly, not only is the existing infrastructure adequate for Ireland’s current needs, but it is also sufficient for any reasonable research initiative that Ireland might choose to undertake in the near future. Ireland has a world class infrastructure but needs to be interconnected differently. The INSPIRE[21] network and the NAP Programme have been positive initiatives to achieve a better connected infrastructure. Secondly, collaborative agreements should be supported to access the required facilities such as with Imec in Belgium.

[21] Integrated NanoScience Platform for Ireland, a consortium of all Irish third level institutions, eight from the South and two from the North.

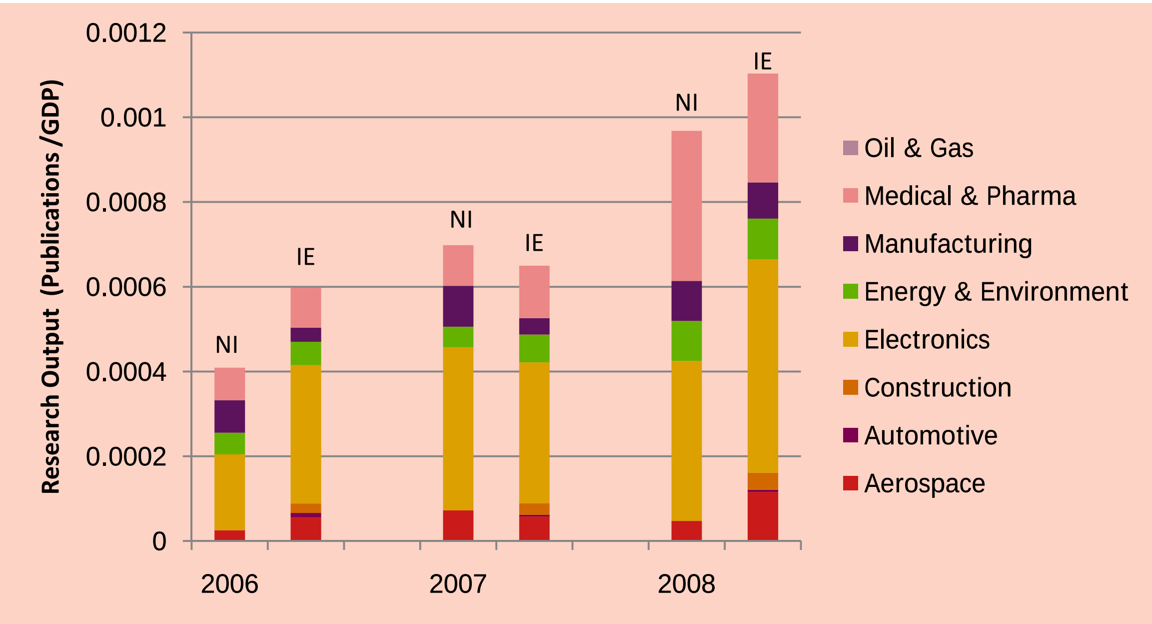
Potential Collaboration Opportunities Abound

Ireland has a low international profile. Although Ireland does have some international research collaborations, further collaboration (both inter academia and industry-academia) should be used as an important means of sourcing ideas, resources and opportunities. This also would have the added advantage of improving Ireland's visibility in the international nanotechnology community. Based on the detailed international benchmarking presented in Appendix H, the Netherlands, Denmark, UK and the US are excellent collaborators for Ireland.

Potential Collaboration with Northern Ireland

Northern Ireland and Ireland have initiatives in place to share infrastructure. During the course of this study, Lux Research visited several institutions and researchers in Northern Ireland and carried out an analysis on patents and publications. Figures 11 and 12 present the results from this analysis.

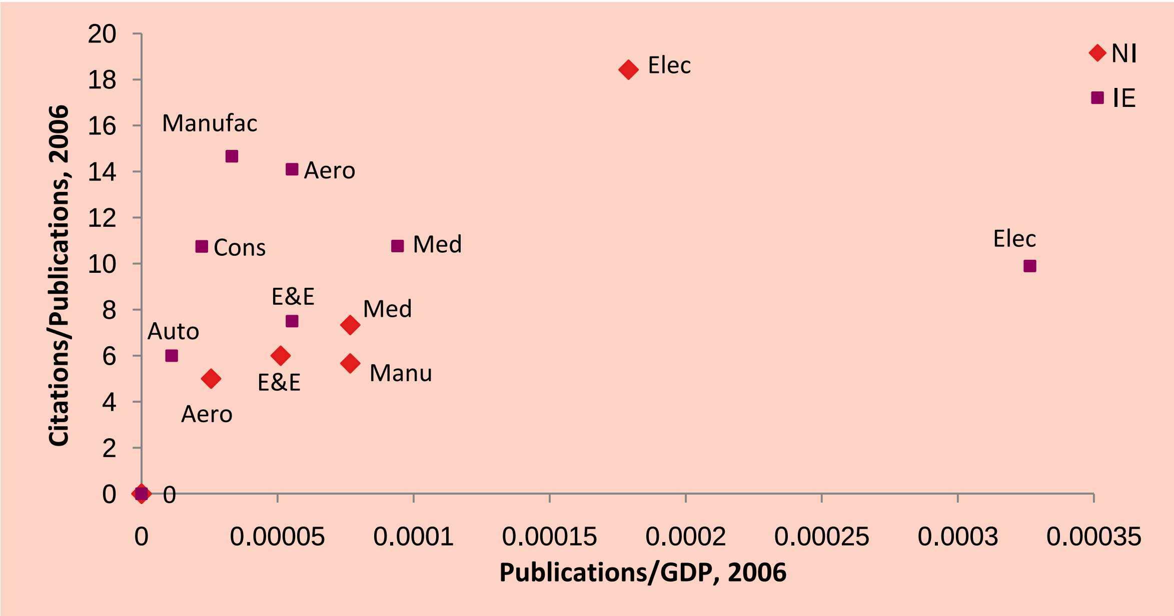
Figure 11: Ireland's and Northern Ireland's Research Output (2006-2008)



Ireland and Northern Ireland produce a similar share of applied research. Northern Ireland has done well in proposing and establishing several market focused initiatives in the form of cross-sector industry-driven innovation communities. There was also considerable industry- academia collaboration between researchers in Northern Ireland and corporations and start-ups in the UK and US and it therefore appears that research topics being pursued by researchers in Northern Ireland are more attuned to market realities than those in Ireland and the commercialisation infrastructure is well laid out.

That said however, there are a lot of synergies between Ireland and Northern Ireland, with respect to the current state of research, ambitions and challenges and increased collaboration between the two regions is therefore recommended. In particular, More Moore Information and Communication Technology (ICT) and Advanced Materials for Energy/Environmental applications would be suitable collaborative opportunity areas.

Figure 12: Ireland's and Northern Ireland's Research Output and Quality (2006)



Ireland's Strengths, Weaknesses, Opportunities and Treats (SWOT) Analysis

Based on the interview findings, survey and secondary data analysis, Ireland's SWOT analysis is presented in Table 6.

Table 6: Ireland's SWOT Analysis

STRENGTHS	WEAKNESSES
o Infrastructure is commendable and fit for purpose to meet research and commercialisation needs for the near future o Adequate levels of highly-qualified research staff o Some research areas of relative high quality o High commercial emphasis of research o High normalised research output o Established base of multinationals in potential key focus areas	▪ Insufficient focus ▪ Some established research areas are of inconsistent quality ▪ Absolute research output short of critical mass ▪ No formal coordinated nanotechnology vision ▪ No strong market pull for existing research ▪ Untested commercialisation mechanism ▪ Low international visibility as an attractive base for nanotechnology research ▪ Lack of sufficient numbers of qualified engineers to drive research scale-up and productisation[22]
OPPORTUNITIES	**THREATS**
▪ Leverage resources via collaboration ▪ Leverage the existing MNC[23] base to jump start growth in key focus areas ▪ Utilise nanotechnology innovation as a catalyst to attract more global mobile R&D ▪ Take advantage of the inherent cross-disciplinary nature of nanotechnology to foster much closer collaboration within academia and between academia and industry ▪ Leverage nanotechnology to generate new economic opportunities for Irish SMEs ▪ Tap more deeply into the expanding EU research funds and facilities channelled into nanotechnology ▪ Closer resource and facility integration with Northern Ireland	o Continued uncertain economic climate, possibly leading to a premature withdrawal from funding nanotechnology as a theme o Global mobile R&D investments are becoming ever more difficult to attract and retain o Ireland is competing against an increasing number of other nations with similar ambitions o Nanotechnology is moving beyond early scientific research with the emphasis shifting to applications o As with other nations, lack of structured information and awareness regarding the possible health and environmental impact of nanotechnology could lead to public mistrust

Source: Lux Research

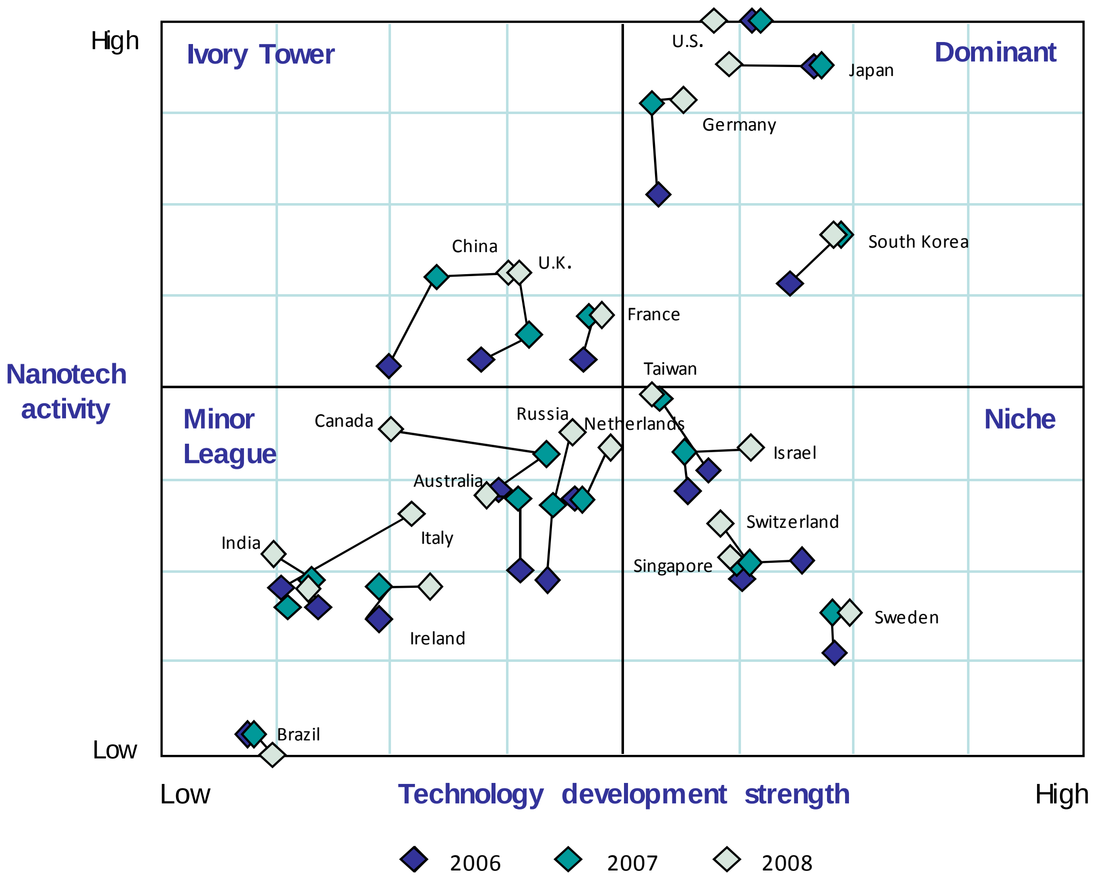
[22] Modifying a product to make it suitable for commercial production

[23] Multinational Company

Positioning of Ireland on the *Nations Ranking Grid*

Although nanotechnology is still in its early stage of development in Ireland, it can be seen from Figure 13 that Ireland has been making moves in the right directions, increasing its nanotechnology activity score over 2006-2007 and its technology development strength over 2007-2008. The next steps must be carefully engineered to carry Ireland into the "correct" quadrant. While the ultimate goal would be to get into the dominant quadrant, Ireland can get there via either the "niche" or the "ivory tower" quadrant.

Figure 13: Ireland Shows Slow Movement in the Right Direction



Source: Lux Research

A pragmatic strategy to adopt would focus on Ireland improving its technology development strength (which would have the welcome side-effect of helping it commercialise non-nanotechnologies too and hence yielding a greater return on investment). This strategy would propel Ireland into a peer group consisting of Singapore, Israel and Taiwan. Here, Ireland would be ideally developing a limited set of nanotechnologies, but doing an excellent job of extracting commercial value out of them.

3.3 Key Findings from Benchmarking Ireland's nanotechnology capabilities (Phase I)

To summarise the key messages regarding Ireland's strengths, weaknesses, opportunities and threats and based on the analyses performed during the benchmarking process, the conclusions are:

- Across the nanotechnology commercialisation value chain, between 2001 and 2009, Ireland spent approximately €282 million on nanotechnology. A significant proportion of this investment has gone into investing in infrastructure and building up capabilities in this area.
- Ireland should take a very close critical look at applications in markets traditionally considered strength areas, where quality was found to be lagging. Similarly critical attention should go to (unexpected) strength areas where high quality was found to be high and a commercial focus exists, but with low research output.
- An analytical review of the complete subset of nanotechnology areas shows that Ireland benchmarks well internationally on the basis of normalised publications, patents and quality of research; however, it does not have the critical mass to make an impact on the global stage. The lack of critical mass research output remains an Irish challenge, resulting in seemingly poor visibility to overseas peers doing research in similar areas.
- External benchmarking data suggests that there is a strong case to be made for increasing collaboration with peers in the Netherlands who have a complementary research publication quality profile and similar scale issues. The findings also argue for much closer resource and facility integration with Northern Ireland.
- Although there is strong anecdotal suggestion that the absence of technology exploitation is a strong barrier to nanotechnology commercialisation within Ireland, the findings from this report did not support these suggestions. While findings from the report showed that Ireland does lack the infrastructure to work with industrial-scale wafer sizes for university-level nanoelectronics research, the reasons for the lack of commercialisation relate more to the combination of quality, volume and the industrial relevance of the research output.
- Based on the analysis of Ireland's commercially relevant research activity in nanotechnology markets, it was concluded that research output, quality and commercial focus shows variation across markets. Even within a given market, the quality of research output, as well as commercial emphasis, varies by target application area.
- Ireland is moving broadly in the right direction on Lux Research's Nations Ranking Grid, with technology development being particularly strengthened in 2008; however, it needs to accelerate its efforts to focus resources in order to keep up with the progress of other nations in the coming years.
- Overall, nanotechnology is already impacting or is set to impact all sectors of Irish business and industry in a deep and meaningful way. To grow its role into becoming an innovation leader and to extract more sustainable value from its industrial activities, Ireland must strategically incentivise nanotechnology developments most relevant to its industrial base, both in the existing base and the one it desires to have in the future.

The key underlying message is Ireland's need to FOCUS.

4 International Review of Nanotechnology Commercialisation Strategies

Different countries have different models for nanotechnology commercialisation and research translation; however, all successful government nanotechnology programmes have focus, carefully planned infrastructure and emphasis on workforce development as common themes.

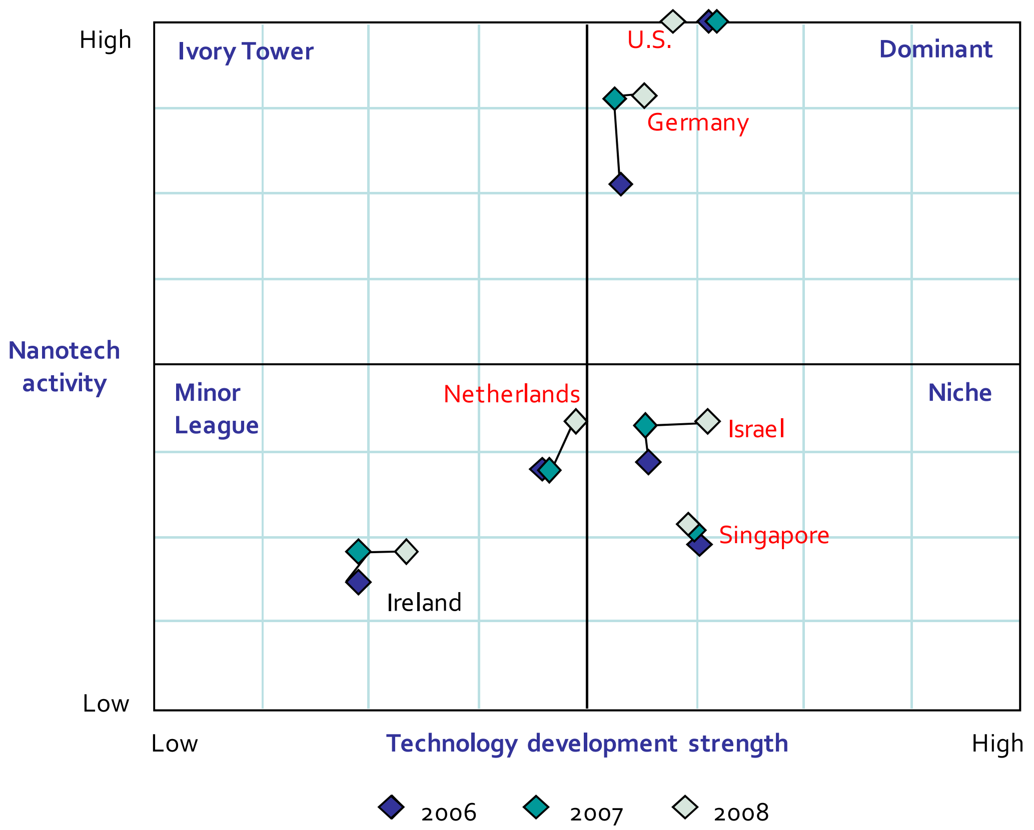
4.1 Why a Global Review Is Important

This global review assesses the nanotechnology commercialisation strategies adopted by a select group of countries to identify best practices that could be adapted to an Irish setting. Ireland is then positioned within this context.

4.2 Selection of Countries for International Review

For the global review, the Project Steering Group decided to focus on a select group of nations from different quadrants of the *Nations Ranking Grid* (Figure 14).

Figure 14: Countries Selected For the Global Review on the ***Nations Ranking Grid***



Source: Lux Research

The five countries selected (and the reasons for their selection) were:

- **US**: The clear global leader in nanotechnology innovation with several best practice policy instruments and strategies;
- **Germany**: European nanotechnology commercialisation leader. Its strong, innovative, indigenous SME base could be a model for Ireland's SME agenda;
- **Singapore**: A small nation with an FDI focus;
- **Israel**: A small country that has had great success in developing its national nanotechnology efforts in a very short span of time; and
- **The Netherlands**: A European country which provides an unique model to provide the translational research element.

For each of the selected countries, key stakeholders were interviewed. The interviews were supplemented with extensive secondary research into the history and current state of nanotechnology funding, research, infrastructure, policies, patents and publications. Profiles on each country were highlighted and features of its nanotechnology commercialisation reviewed to identify best practices to adopt. The findings are set out in Figure 15 and Table 7. A more detailed analysis is available in appendices J and I[24] [25].

Based on the information presented in Figure 15 and Table 7 and the country profiles this generated (see Appendix I), the following are the findings:

No One Single Successful Model

A great diversity in approaches to commercialisation exists across nations. Table 7 summarises the key attributes and performance indicators for each of the five selected countries and compares them to those of Ireland. From this Table it can be seen that Ireland has the lowest percentage of industry-academia collaboration of the group, as measured using shared publications as a proxy. However, it is important to note here that industry-academia collaboration can take many different forms and does not necessarily result in a joint publication. Therefore, this table does not present a complete representation of industry-academia collaboration and must be treated with caution.

Nanotechnology Commercialisation

Figure 15 compares the nanotechnology commercialisation efforts of Ireland to the selected nations on five broad attributes:

- Research focus;
- Presence of super-customers[26];
- Nature of the entity coordinating the national nanotechnology efforts;
- Nanotechnology R&D funding sources; and
- Commercialisation focus.

[24] See Appendix J for the country profiles

[25] See Appendix I for key takeaways by country

[26] A super-customer is an organisation which, through funding leverage and application focus, significantly contributes to the commercialisation of nanotechnology research (e.g. the Department of Defence (DoD) and Department of Energy (DoE) in the US).

Table 7: Comparing the Selected Countries to Ireland

	US	Germany	Singapore	Israel	Netherlands	Ireland
GNP per capita (€) for 2008	32,042	28,584	22,725	16,941	32,305	35,953
National nano initiative	National Nano Initiative	High Tech Strategy for Germany	Agency for Science, Technology and Research	Israel National Nano Initiative (INNI)	NanoNed	Nano funded under the SSTI (2006-2013) -
Year established	2001	2006	2001	2001	2004	*2001*
Total funding since inception	€ 6.74 billion (2001 – 2008)	€ 1.47 billion (2006 - 2008)	€ 111 million (2001 - 2008)	€ 100 million (2001 - 2011)	€ 235 million (2004 – 2009)	€282 million
Annualised funding as % of 2008 GNP (in billions of €)	0.0098 %	0.0311 %	0.0157%	0.0085%	0.0089 %	0.0261%
Publications ((Pubs) 2006-2008)						
% Corporate	1.0%	6.7%	0.0%	0.9%	8.0%	0.0%
% Academic	94.0%	73.3%	96%	87.4%	81.0%	97.0%
% Shared	5.0%	20.0%	4.0%	11.7%	11.0%	3.0%
2006-2008 Pubs/GNP (in billions of €)	2.07	1.62	0.58	4.05	1.96	3.68
Patents (2006-2008)						
% Corporate	70.0%	91.6%	91.7%	55.4%	75.0%	98.0%
% Academic	30.0%	7.7%	8.3%	38.3%	25.0%	2.0%
% Shared	0.0%	0.7%	0.0%	6.3%	0.0%	0.0%
2006-08 Patents/ GNP (in billions of €)	0.03	0.07	0.15	0.32	0.04	0.08

Source: Lux Research

From Figure 15 below it can be seen that Irish research is very technology centric, on average, without strong tie-ins to particular applications. The nanotechnology commercialisation funding-vision-strategy is not clarified and coordinated by one clear authority. To an extent, SFI (being the largest funder of nanotechnology research) acts as an informal guiding force.

Figure 15: Different Models of National Nanotechnology Commercialisation

Successful Nano-commercialisation Strategies Share Some Key Traits

In developing its nanotechnology strategy there are many strategic measures across the spectrum of commercialisation strategies that Ireland can employ. The key question is: "*what does a good nano-commercialisation strategy look like and how do you know when you have succeeded*?"

4.3 Defining Success

A successful nanotechnology commercialisation strategy includes:

- **Sharp, multidisciplinary focus**: pick a small number of strategic areas of emphasis (market-technology combinations) which embody nanotechnology's multidisciplinary nature and yet provide a mechanism to extract the most value out of a nation's investment.
- **Efficient use of funds**: avoid redundancies in staff, instrumentation and facilities, creating distinct centres of excellence and networking them together in a meaningful fashion.
- **Fewer commercial obstacles** (infrastructure, funding and technology transfer): set up mechanisms and processes which provide the best people with everything they need to develop and commercialise nanotechnology.
- **Prototyping and testing provisions**: recognise that a large part of nanotechnology's commercialisation challenge has to do with standardisation and characterisation of materials and institute programmes to address this question.
- **High quality and environmental standards**: the nanotechnology that can act as a springboard for sustainable economic impact will be both of the highest quality and environmental stewardship and incorporate metrics to measure both.

In the case of Ireland, the *successful* outcome of Ireland's nano-commercialisation strategy, as agreed by the Project Steering Group, will be measured by:

- High scientific productivity (publications and patents) and quality;
- Better trained workforce (science and engineering graduates);
- Increased number of start-ups;
- Greater technology transfer to existing industrial base;
- Significant proportion of the GDP from nano-enabled goods and services; and
- Attracting appropriate FDI involvement.

Taking the above on board and reviewing Ireland within this context, the findings show that:

Ireland's Investment in Infrastructure Has Been in Line with International Best Practice

A key commonality between the five reviewed nations has been the emphasis on setting up and maintaining the necessary infrastructure. For example, the US allocates 10 percent of the total National Nanotechnology Initiative (NNI) budget to infrastructure investments in user centre facilities and instrumentation. Israel deployed a bulk of its $45 million National Nanotechnology Initiative (INNI) investment from 2001 to 2005 towards building state-of-the-art research facilities. The Netherlands devoted 34 percent of the five-year €235 million NanoNed programme resources towards creating a coherent and accessible infrastructure (NanoLab NL). In this context, Ireland's investments in setting up world-class laboratories and research facilities with top-of-the-line equipment were in line with international best practice. The critical factor will be Ireland's ability to maximise the use of and maintain these facilities.

Absence of a Super-Customer is a Challenge that Ireland Needs to Address

In an ideally functioning science commercialisation economy, the market acts as a guiding mechanism for technology development and innovation by defining its needs and demanding solutions (thereby setting a research agenda). In the case of Ireland, there is no market-driven demand pull for research. This is where public sector agencies have to step in.

In the case of the US (although a parallel market mechanism exists), the nanotechnology research agenda is largely set by what one could call *super-customers* viz. the Departments of Energy, Defence etc. In Israel, the military establishment serves in this role and in the early days of the INNI, it was the only demand centre. In essence, a super-customer is a large funding agency which, through programmes like Small Business Innovation Research (SBIR) grants, helps provide early-stage sustenance to emerging technology companies, while at the same time ensuring that focused research (to serve its priorities and needs) is carried out. Ireland does not a super-customer to act as a demand centre for emerging nanotechnologies and this can be a significant barrier to commercialisation.

Taking this onboard, Ireland must guard against having a sole super-customer. A model worth considering is the US NNI. The NNI is made up of 25 federal agencies with their own priorities and agendas. Technology-centric agendas of the National Science Foundation (NSF) and the National Institute of Health (NIH) are counterbalanced by more application-driven agendas of the DoD and the DoE. This results in a more diverse portfolio of technology development priorities.

Peer Group Nations Have Learnt That it's All about Focus

The peer group of nations have learnt that it is all about focus. In a resource-constrained environment, broad thematic investments are unsuccessful in having a meaningful impact; even good research goes unnoticed due to scale. The reviewed countries have gone beyond broad themes to more clearly defined technology-application maps. Ireland should look to transition from discovery-based science and product development to application-driven problem solving.

Government's Role in Nanocommercialisation

Nanotechnology in Ireland is in its infancy, with research at the early stage. At such a stage of development, R&D is typically conducted using public funds. Private investment will come in time on the back of high impact research. Thus, it is imperative that the government continues to play a supportive role in incentivising and promoting Irish nanotechnology R&D. Israel is a good example of a country which focused and attracted industry. There the government provides significant matching funds across the board augmented by vibrant VC funds. Over a three year period, the matching funds programme managed to attract significant corporate partnerships. In Germany, the government proactively participates in commercialisation by acting as an angel investor, as well as through Small Business Innovation Research (SBIR)-type programmes. In the US there is the Small Business Technology Programme (STTR) and SBIR grants programmes. In the case of Singapore, public funds also go towards proactive programmes for technology transfer and start-up creation.

Approaches to Innovation

A decade ago Israel was in a similar position to Ireland. From that point, Israel is now a technology leader in niche areas of nanotechnology. To support this transition, the government placed the bulk of its nanotechnology research towards infrastructure build up. Focus areas were established with the help of an international advisory board. It developed bilateral agreements with the likes of US, UK, South Korea, etc. which helped raise the profile of its researchers. Singapore does its own version of this via its GET-UP initiative which uses favourable tax laws and unique resource sharing agreements with various types of facilities to boost international competitiveness of its local businesses.

Defined Success Metrics and Rigorous Periodic Evaluation

It is hard to be successful if you don't know what success looks like. This statement is true for nanotechnology strategies as well. It is critical to not only clearly define what the end goals are, but also to periodically evaluate the progress to estimate how close a country is to attaining these goals. This is critical in order to maximise the chances of sustainable success.

In several steps of the commercialisation value chain, the role of engineers is critical. Ireland's ranks well below EU15[27] average in tertiary graduates in engineering, manufacturing and construction as a percentage of total tertiary graduates[28]. Sustained meaningful commercialisation will be harder (if not unlikely) without a vibrant cohort of engineers and countries like Israel are formally stating this as a key success metric.

[27] Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the UK

[28] Main Trends in Science and Innovation. OECD, 2007.

A Large Nanofabrication Facility (NanoFab) is Not a Pre-requisite for Successful Nanotechnology Commercialisation

As discussed earlier, the Irish nanotechnology infrastructure is missing a discrete translational research element, especially when it comes to nanoelectronics research. However, during the course of this study no evidence was found to suggest that nanotechnology commercialisation in Ireland is being held up specifically due to this missing translational piece. As shown in Figures 16(a + b), there are different models globally of providing the translational research component.

Figure 16 (a): Different Models for Providing the Translational Element

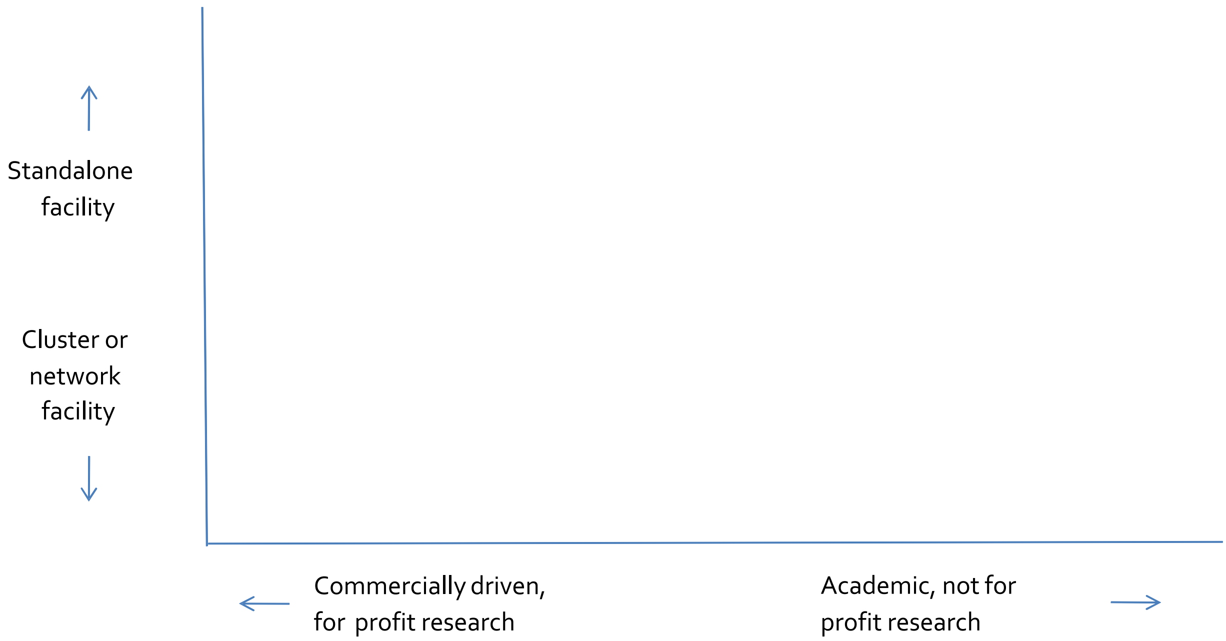


Figure 16 (b): Different Models for Providing the Translational Element

	Capital cost to build	Ongoing operating costs	Risk of obsolescence	Potential attraction for foreign MNCs	Suitability to SMEs	Maximum leverage of existing research infrastructure
IMEC			Yellow	Green	Yellow	
Cambridge Nanoscience Centre	Green	Green	Yellow			
CNST			Green	Green	Yellow	
Nanolab NL	Yellow	Yellow	Green	Yellow	Green	Green
Current situation, utilize nanofabs abroad	Green	Green	Green			Yellow

Green ← Better — Yellow

Source: Lux Research

Ireland's current situation would require its researchers to conduct research beyond the 8" wafer size at a facility abroad. Collaboration with IMEC in Belgium or University of Cambridge would enable this. Given the fraction of the overall nanotechnology research within Ireland that is at a scale and in the technology domain which would require work at this level, such a strategy is feasible. Researchers all over the world use some derivative of this approach. This has the additional advantage of promoting international exposure and collaboration.

While Ireland has excellent infrastructure the Netherlands, specifically its NanoLab NL initiative, is worth reviewing. This initiative aims to provide a coherent and accessible infrastructure for nanotechnology research and innovation in the country. The primary philosophy behind the programme is that infrastructure is only built to meet a well-characterised need that is otherwise unmet i.e. a facility-first approach is not supported. The NanoLab NL initiative takes state-of-the-art facilities at local universities and networks them together in a fashion. To that end, all the activities of the nanofab are split into basic and expert functions. The basic functions provide a general infrastructure suitable for common fabrication activities and are replicated at most locations. The expert functions (ion beam etching, e-beam induced deposition, interferometry, etc.) are unique to a facility. Researchers requiring the expert functions can use them at the nearest facility. Such an approach is feasible in Ireland. The NanoLab NL initiative also ensures that existing infrastructure is first upgraded and fully utilised before new infrastructure is built.

The findings from this study mean that Ireland's current and forecasted research output does not require investment in a significant NanoFab facility. Such a facility would require a financial commitment in the hundreds of millions of euro range, with a sustained annual government funding well in excess of Ireland's current total annual nanotechnology spend. The research shows that there is not a case to support such a new significant facility in Ireland. Firstly, it would require a monetary commitment of hundreds of millions of euros, with a sustained annual government funding well in excess of Ireland's current total annual nanotech spend. Secondly, it risks making the excellent facilities that exist redundant. For the foreseeable future such a facility would end up becoming merely a contract research and fabrication location for foreign researchers. But above all, Ireland's current and forecasted research output simply could not justify such a facility and this nanofab would end up having a very poor cost-benefit outcome. Lux Research, in common with the Project Steering Group, does not believe that this should be the focus of Ireland's resources and strategy at this critical juncture in its nanotechnology journey.

Ireland's Nanocommercialisation Programmes Are In Place, But Remain As Yet Untested

When compared to its peer nations, Ireland's current level of funding for proof-of-concept stage research appears fit for purpose. Similarly, all the necessary programmes and the business culture are in place for technology transfer, start-up creation and productisation. Despite this, it was found that the mechanism remains as yet untested. As one of the interviewees stated, this could mean that either the research is irrelevant for the existing industrial base or that it is too early stage for start-up creation.

Ireland could better utilise its technology transfer network to proactively drive technology exploitation by mapping Intellectual Property (IP) onto market needs and seeking out partners in relevant market-application combinations to transfer the technologies into. Similarly, Ireland could use matchmakers to link market needs to individual professors to inform research activities to make them more commercially relevant. It is critical that Ireland drive the nanotechnology commercialisation process at least to the point where clear commercial outputs are seen. The recent IP review[29] and the recommendations from the Innovation Task Force Report will enable this to happen.

4.4 Key Findings from global review of nanotechnology commercialisation strategies (Phase II)

Based on the analyses conducted during the global review, the conclusions are as follows:

- Across all countries there has been an emphasis on setting up and maintaining the necessary infrastructure and therefore Ireland's investment in world-class infrastructure is in line with international best practice. The critical factor going forward will be Ireland's ability to maintain and use this infrastructure efficiently.
- In an ideally functioning science commercialisation context, the market acts as a guiding mechanism for technology development and innovation, defining needs and demanding solutions for those needs, thereby setting a research agenda. Most of the five countries have what is referred to as a "*super-customer*", which is an organisation or group of organisations which, through funding leverage and application focus, significantly contribute to the commercialisation of nanotechnology research (e.g. the DoD and DoE in the US or the SME sector in Germany). In Ireland, there is no market-driven demand pull for research or "*super-customer*" to perform this role, and as a result, researchers tend to choose their own areas to work in.
- The challenges in Ireland are not unique; other nations face challenges with nanotechnology commercialisation. However, a particular challenge in Ireland is the variation in quality across the research base and the lack of critical mass.
- The peer group of nations (Germany, US, Netherlands, Israel and Singapore) has learnt that it is all about focus and that in a resource-constrained environment, broad thematic investments can have limited impact.
- In all countries, the government plays a prominent role in supporting the commercialisation of nanotechnology and it is appropriate that the Irish government continue to play a significant role in incentivising and promoting Irish nanotechnology R&D.
- Programmes elsewhere have clearly defined success metrics and rigorous periodic evaluation.
- The programmes required for commercialisation of nanotechnology in Ireland are in place but remain as yet untested. When compared to peer nations, Ireland's level of funding (based on 2009 figures) appear adequate and all the necessary programmes and business culture are in place for technology transfer, start-up creation and productisation. However, any commercialisation strategy will have to drive technology exploitation more proactively and devise programmes to make the research more commercially relevant through dialogue with "end-customers" to understand and define their needs and let those needs inform the research.

[29] Review of the supports for the exploitation of Intellectual Property from Higher Education Research

5 Ireland's Nanotechnology Vision, Focus and Outputs

5.1 Key Issues for Nanotechnology in Ireland

Despite the positive developments in nanotechnology in Ireland over the last decade, there are a number of critical issues requiring attention. These include:

Ireland risks being left behind

- Global nanotechnology efforts have moved beyond early stage scientific research to applications development. Most countries around the world are investing significant funds into nanotechnology R&D, which include new entrants like Bulgaria and Albania. Ireland needs to at least maintain its existing level of funding to stay competitive.

Focus is critical for Ireland's effective use of resources

- Nanotechnology's cross-disciplinary nature tempts spreading resources across multiple areas. Ireland should ensure that resource allocation should focus on a few strategically-significant applications, instead of a non-discriminating funding model. Such a strategy will maximise Ireland's chances of generating increased economic impact.

Ireland needs a national policy of resource allocation in nanotechnology

- Given the absence of a defined "super-customer" capable of driving priorities in research and development towards viable applications, resource allocation should be explicitly channelled to commercially viable opportunities until a working "market mechanism" for prioritisation evolves. Identifying these opportunities is a critical step and should be undertaken in a consultative fashion.

Nanotechnology can be a natural enabler for innovation

- The cross-disciplinary nature of nanotechnology can foster increased collaboration and create added value. As discussed, nanotechnology will impact every core Irish business sector deeply and will be a strong driver for technology upgrade of existing enterprise.

Small can be good

- Ireland's small size can, and should, be turned into an advantage through sharper focus, more efficient use of funds, fewer commercial obstacles, rapid prototyping and testing and higher quality standards.

Ireland should be an intelligent follower

- The governance and commercial exploitation of nanotechnology in Ireland can benefit from starting with a relatively clean slate but at the same time being able to learn from best practices of other nations.

5.2 Developing Ireland's Nanotechnology Objectives

To formulate Ireland's nanotechnology commercialisation options, national objectives have been developed by the Project Steering Group. These objectives were informed by the following considerations:

- A strong consensus exists within the policy and funding establishment to simultaneously service the needs of indigenous enterprise and multinationals;

- There is a strong divergence of opinion between the business and the academic sector regarding the commercial readiness and industrial relevance of existing research;
- A strong consensus exists around putting industry first to create a situation of demand pull instead of science push;
- There is a need to stimulate maximum overlap between existing infrastructure and research capabilities, thereby optimising existing and any additional investment; and
- Ireland has both near-term goals (retain existing FDI; producing high quality, high impact research in Ireland; attracting private/corporate investment in research) as well as longer-term ones (attain international competitiveness in identified niche areas; develop technologically-sophisticated indigenous enterprise; upgrade existing FDI and attract new mobile R&D) and the strategy needs to cater for both.

Ireland's nanotechnology objectives were established by the Project Steering Group as follows:

- To utilise nanotechnology as a catalyst for creating economic value and establishing an entrepreneurial innovation culture;
- To provide a vibrant and collaborative innovation infrastructure that effectively incentivises companies currently operating in Ireland to engage in high-impact R&D as well as attracting new multinational mobile R&D investment;
- To develop the multidisciplinary workforce necessary to successfully commercialise nanotechnology innovations, both local and foreign, make the existing industrial base more technologically sophisticated and promote the establishment of new indigenous high-technology businesses; and
- To promote industrially-relevant, high-impact research in Irish universities while better leveraging existing infrastructure and encouraging national and international collaborations.

The Project Steering Group concluded that Ireland's nanotechnology objectives are achievable, but only if a focused and proactive strategy is implemented.

5.3 Identifying Ireland's Nanotechnology Focus Areas

With Ireland's nanotechnology objectives defined, the selection criteria for the focus areas were defined as follows:

- Build on areas where existing research is of high quality and output (Table 8);
- Maximise overlap with existing industrial base, local and foreign;
- Prioritise areas with substantial pre-existing infrastructure/resourcing investment;
- Shortlist areas with opportunity for resource sharing and collaboration with Northern Ireland and those that offer unique collaboration potential across the European Research Area (ERA) (Table 9); and
- Identify themes which resonate with national priorities (e.g. smart economy, green agenda).

Table 8: Irish Research Areas with High Quality and Output Compared to the Comparator Group

Aerospace	Automotive	Electronics	Energy & Environment	Manufacturing	Medical & Pharma
Structural Materials Avionics Conductive materials Electrical infrastructure Structural monitoring	Catalysts Battery/Energy storage	Printed electronics Memory technologies Transparent conductors Lithography and process tools	Energy conservation	Sensors (air & water)	In vitro diagnostics

Table 9: Potential Countries and Topics for Collaboration.

Country	Potential Collaboration Topics
Northern Ireland (and the U.K. broadly)	Nanostructured materials, nanocomposites, nanocoatings, nanomaterials for environmental applications, LEDs, printed electronics, packaging, theranostics, delivery systems
Netherlands	LEDs, printed electronics, packaging, theranostics, delivery systems, nanostructured materials, nanocomposites, nanocoatings
Denmark	Theranostics, delivery systems, nanostructured materials, nanocomposites, nanocoatings
Germany	Nanotechnology for energy and environmental applications, nanostructured materials, nanocomposites, nanocoatings
Finland	LEDs, printed electronics, packaging
US, Singapore, Israel	Countries outside the ERA/EU with whom a broad partnership to share resources and researchers in several areas makes sense

Using this selection criteria, several potential technology focus areas (i.e. relating to the field of science being pursued) (Table 10) and market focus areas (i.e. relating to the end user of technology) (Table 11) for Ireland were identified.

Table 10: Ireland's Technology Focus Area Options

Technology Area*	What	Why	Why not
Advanced materials	Nanocomposites, alloys, ceramics etc. tailored for a wide range of applications, including novel materials for post-silicon (posy-Si) electronics	Large addressable markets, gives researchers lot of playing room, broad potential applicability across existing and new Irish business sectors	Need strong focusing presence of a super-customer to appropriately channel resources
More than Moore	Goes beyond conventional semiconductor to focus on system integration rather than transistor density	System-on-package approach has applicability in sensors – environment, medical, food; leverages existing capabilities (LEDs, sensors, etc.) and infrastructure	Unlikely to have significant "SME agenda" (technology upgrade of existing SMEs) applicability in the near-term
Nanoelectronics	Si-alternative route to transistors, including use of materials like CNTs, graphene, III-V compound semiconductors, and novel architectures	Strong pre-existing industrial base, electronics is already a key national focus	Co-design – collaboration between designers and technologists – is a must; long commercialisation timelines; commercial impact impossible without strong semiconductor industry patronage – [this is probably a good mid-term alternative]
Red nanobiotech	Use of biological systems or derivatives as applied to medical processes, like engineering organisms to produce antibiotics or genomic manipulation for personalised medicine or advanced imaging technologies	Cutting edge, constantly moving landscape means Ireland is not too far behind; global IP space has several holes which Ireland could target	Commercialisation unlikely without heavy VC backing, Ireland will have to get over a significant knowledge hump; already well-funded through other means

Technology Area*	What	Why	Why not
Green nanobiotech	Biotechnology applied to agricultural processes; some overlap with the energy universe (biofuels) – design of transgenic crops	Most FDI investment will likely involve R&D; can have direct positive impact on indigenous food sector, strong synergies with Ireland's other biotech investments	Ireland has too much distance to make up; strong global monopolies make this a hard market to penetrate
White nanobiotech	Industrial biotech as a component of green chemistry or biotechnology applied to industrial processes, to engineer greener materials, processes, or products	Strong unmet global need, several European start-ups are key global players and might show willingness to collaborate or relocate to Ireland, strong synergies with Ireland's other biotech investments	No significant existing research base/capability

*The technology focus areas relate to the field of science being pursued

Table 11: Ireland's Market Focus Area Options

Market*	Comment
Semiconductors	Strong industrial base but global power centre for Si-semiconductor is migrating to Asia; Existing public infrastructure can be readily utilised for market-driven research, possibly with minor upgrades in the mid-term
Medical devices and diagnostics	Several tech focus area options have deep applicability in this market; Industrial base more likely to engage in co-development
Pharma	Requisite level of commitment is too expensive to make; global landscape is cluttered and nanotechnology-driven solutions are largely unproven
Manufacturing	Makes up a large share of total Irish industry with strong applicability of all technology focus area options; broad definition will require strong focusing influence of super-customers
Food	Large component of Irish GNP, mostly indigenous enterprise; nanotechnology research in this sector requires significant application development which companies might not have an appetite for
Energy and Environment	Environmental applications is a better fit with technology focus areas; energy is complex and Irish opportunity is very constrained

*The market focus areas are the applications and end uses for which these technologies will be developed

Examining the pros and cons of the areas presented in Tables 10 and 11, Ireland's nanotechnology focus areas as agreed by the Project Steering Group are presented in Table 12.

Table 12: Proposed Focus Areas for Irish Nanotechnology Research

Application focus areas → **Technology focus areas** ↓	**Next-gen electronics**	**Medical devices and diagnostics**	**Environmental applications**	**Industrial process improvements**
Advanced Materials **(Functional nanomaterials and nanostructures, Composites, Coatings, Catalysts)**	Post-Silicon materials, beyond CMOS, Printed electronics	Coatings, delivery and diagnostics systems, imaging	Nanostructured membranes, Pollution abatement and treatment, LEDs, coatings	Insulation, coatings, catalysts
More than Moore	System-on-chip, radio, sensors, actuators, cooling element	Bio-logic, sensors, personal health monitors	Sensors Intelligent system control	Sensors, Intelligent system control
Nanobiotech **(Red, Green and White)**		Encapsulation	Waste treatment	Green chemistry

The following points regarding these focus area recommendations are as follows:

- Focus areas should be evaluated and updated on a predetermined schedule (every 3-5 years). This approach represents best practice and it helps keep research priorities relevant and has a selection bias towards areas that meet/exceed expectations;
- An advisory group comprising representatives of industry, academia and government, both Irish and foreign, should be tasked with monitoring and evaluating the focus areas and identifying new ones as appropriate; and
- The focus areas should be underpinned by responsible development of nanotechnology

Table 13 identifies the pros, cons and relevant market sizes for Ireland's agreed focus areas. These are strong factors to consider as Ireland starts to put together its funding strategy.

Table 13: Ireland's Focus Areas - Pros, Cons, Market Sizes

Application focus areas → / Technology focus areas ↓	Next-gen electronics $56 billion (2008)	Medical devices and diagnostics $20 billion (2008)	Environmental applications $2 billion (2008)	Industrial process improvements $158 billion (2008)
Advanced Materials **(Functional nanomaterials and nanostructures, Composites, Coatings, Catalysts)**	▪ Good existing research base in post-Si materials ▪ Application development is lacking and is non-trivial	▪ Relevant industrial base is an asset ▪ Current research not a good starting point	▪ In line with national priority and cross-border agenda ▪ Very little immediately relevant existing IP	▪ Strong existing research base in catalysts, coatings ▪ Risk-averseness makes this a hard market to penetrate
More than Moore	▪ The "next frontier" for the ICT industrial base ▪ Existing IP here is not commercially relevant	▪ Strong potential for collaborations between ICT and Medtech MNCs ▪ No history of systems engineering	▪ Easy extension of work in the other markets ▪ Market opportunity is small	▪ Easy extension of work in the other markets ▪ Market opportunity is small
Nanobiotech **(Red, Green and White)**		▪ Very large market opportunity ▪ Almost no existing research base	▪ Potential to emerge as a market leader ▪ Intense global activity makes rapid action imperative	▪ Potential to attract a wholly new kind of FDI ▪ Slow global growth despite significant interest implies strong tech issues

5.4 Collaboration with Northern Ireland

Results from Phase I indicate that several of the focus areas yield themselves to cross-border resource sharing, facility clustering and to better positioning a North-South proposal to attract EU funding. These are:

- Advanced materials;
- More than Moore;
- Environmental applications; and
- Next-gen electronics.

5.5 Ireland's nanotechnology investment and targeted outputs

Lux Research estimated the desired outcomes of the nanotechnology investment (how many patents, publications, start-ups etc.) for the 2010-2014 period that would (on a relative basis) position Ireland on par or ahead of similar nations. To calculate Ireland's projected outputs, the following guiding principles were used:

- Produce higher impact research (without a spike in investment);
  - Using similar (or lesser) funding as today, only focused better;
  - Collaborate with nations facing similar considerations e.g. Netherlands in electronics to bring a multiplier into play; and
- Strive to improve international profile of Irish nanotechnology.

Table 14 summarises Ireland's projected outcomes.

Table 14: Ireland's Projected Outcomes

In the Period 2010-2014	Advanced Materials	More than Moore	Nanobiotech	Total
Publications	165	165	200	530
Patents	30	30	10	70
Start-ups	10	10	10	30
PhDs	40	40	40	120
Engineers	250	250	250	750
International Promotion	Conferences and workshops as a forum to showcase Irish innovation and expose global community to nanotechnology in Ireland (~5 international conferences per year)			
Public Outreach	Public awareness programmes to educate the population on nanotechnology's promise, risks, and to expose students and entrepreneurs to opportunities in nanotechnology (~12 seminars/lectures per year)			

Source: Delphion, ISI Web of Knowledge, Lux Research analysis; PhDs refer to science PhDs and the engineers are graduate level

A preliminary estimation of the cost metrics was undertaken, noting that this is a purely scientific exercise, using comparables, proxies and assumptions and should be interpreted with caution. This analysis is only meant to serve as a starting point, since the final cost of the options is closely tied to goals set and implementation strategy choices made.

Using the data in Table 14, the investment required to produce a single unit of each (1 PhD, 1 start-up, 1 patent, etc.) was estimated based on Lux Research's knowledge of the area. A combination of these factors, adjusted for Ireland's current position, gives the overall investment required for that particular focus area. Table 15 presents the total required investment for the focus areas for the period 2010-2014.

Table 15: Sources, Usage of Funds and Performance Ratios

	In the Period 2010-14	Total Investment €114 million
Funding source	Government	€114 million*
Government funding breakdown by use	R&D	70%
	Commercialisation and Environment Health and Safety	30%
Performance Ratios	Publications (per million euro)	4.65
	Patents (per million euro)	0.61
	Start-ups (per million euro)	0.22
	PhDs (per million euro)	1.05

*Ideally an increasing proportion of this funding would come from non government sources over the medium to long term and this is something Ireland should aspire to.

There are a few significant points to note about this funding plan:

- Over the past three years Ireland's nanotechnology publications have grown at a CAGR of 22 percent. Extending the same rate forward would lead to 2,525 additional publications in the 2010 to 2014 period. This strategy instead assumes a fundamental reset of the innovation process (which will have a start-up time associated with it), leading to a fewer number of publications (approximately 530) but of much higher average quality.
- Similarly, Ireland would file 485 new patents between now and 2014. In this proposed strategy, 70 new patents would be targeted, but each with a high likelihood of a clear commercial outcome.
- Maintaining the evaluation criteria of research excellence, in the near term, a bulk of the funding will be for oriented basic, applied and translational research that has a clear expected commercial application and outcome. While this research is being progressed, the funding directed towards commercialisation activity will make up a lower share of the overall investment. In the midterm, after the initial five year plan has been implemented and its results studied, Ireland should review its strategy of investing in oriented basic research periodically to ensure alignment with commercialisation priorities. The immediate goal is to produce high quality nanotechnology research with commercial applicability and also to increase public-private partnerships.

This nanotechnology commercialisation strategy leads to a total funding requirement of €114 million over the next five years (or €22.8 million annually), split fairly equally across the three technology focus areas. As Ireland is in the early stages of nanotechnology commercialisation, the funding will have to largely come from public sources for at least the next three years before private investment comes on stream. Another point to note is that in the Irish context, government and academic funding is one and the same, with public funds driving both. However, globally, an increasing dichotomy between the two is observed, with governments providing a steady base funding for education and research and academic institutions raising incremental variable funds through private donations and endowments. This divergence is a natural artefact of a system's maturity and the national culture and no special efforts are needed at this time to artificially create it in Ireland.

5.6 Key Finding from Developing Ireland's Nanotechnology Objectives and Focus

Based on the above, the study concluded that:

- Despite some significant challenges and a late start, Ireland can still derive significant economic value from continued nanotechnology investments;
- Any nanotechnology strategy should adhere to the established overarching national priorities of retaining FDI and growth of indigenous industry;
- Ireland should focus on three technology areas (advanced materials, More than Moore and Nanobiotech) and four application areas (next gen electronics, medical devices & diagnostics, environmental applications, and industrial process improvements);
- In the medium to long term, spending realignment, sharp focus and funding source diversification will enable Ireland to continue investing in nanotechnology at a reduced burden to the government;
- Ireland must formally and proactively include industry in setting priorities and identifying focus areas; and
- Significant industry involvement in a short timeframe is unlikely without a proactive and focused implementation strategy.

6 Developing Ireland's nanotechnology vision and commercialisation options

In order to meet the above objectives, Forfás recommends the following:

Recommendation 1: Focus Irish nanotechnology research

The primary difference between Ireland and the nations reviewed in Phase II is *focus*. To ensure economic impact from public investment, Ireland needs to maintain current funding levels but focus this funding into fewer, more strategic technology-application combinations. This report recommends[30] that Ireland should focus its nanotechnology efforts across three technology domains – Advanced materials, More than Moore[31] and Nanobiotechnology – as they apply across four application domains – Next-generation electronics, Medical devices and diagnostics, Environmental applications, and Industrial process improvements (see Table 12).

The recommended focus areas should be evaluated and updated on a predetermined schedule (every 3-5 years). This approach represents global best practice and helps keep research priorities relevant and has a selection bias towards areas that meet/exceed expectations. A coordinating group comprising representatives of industry, academia and government, both Irish and foreign, should be set up (Recommendation 2) and tasked with monitoring and evaluating the focus areas and indentifying new ones as appropriate. With such a focused approach (and using the implementation strategy recommended in this report), Ireland can derive significant economic value from continued nanotechnology investments.

Specific metrics and targets for the five year commercialisation strategy were proposed by Lux Research (see Table 14). Using similar funding as today, only focused better, these input and output targets should produce higher impact research and involve collaboration with nations facing similar considerations.

To implement the recommendation on focus and to meet the target outputs, Forfás proposes a number of strategic implementation measures which include:

- Strategy Development;
- Funding;
- Self-sustainability;
- Industry involvement in research;
- Infrastructure;
- Workforce development and academia; and
- Collaboration.

[30] In order to select the focus areas for Ireland, the following selection principles were agreed by the Project Steering Group: Build on areas where existing research is of high quality (citations/publications) and output (publications/GNP); Maximise overlap with existing industrial base – local and foreign; Prioritise areas with substantial pre-existing infrastructure/resourcing investment; Shortlist areas with opportunity for resource sharing and collaboration with Northern Ireland and those that offer unique collaboration potential across the ERA; and Identify themes which resonate with national priorities (e.g. smart economy, green agenda).

[31] **More than Moore:** Focusing on system integration instead of transistor density.

Actions related to these strategic measures are in some cases already being implemented across the system; however, it is important that they are targeted with respect to nanotechnology. This will present significant challenges to implementation, specifically in ensuring an appropriate balance between focus and research excellence in competitive funding. However, without this proactive, focused and coordinated strategy industry engagement is unlikely.

Recommendation 2: Establish a nanotechnology coordinating group

Nanotechnology strategy development, monitoring and review should be centralised under one coordinating group. This coordinating group would comprise multiple stakeholders from government departments, the developmental agencies, industry and academia.

Using the findings and recommendations in this report as a basis, the group would be tasked with the following:

- Coordinate and oversee the implementation of the nanotechnology strategy as agreed by the Minister for Science, Technology and Innovation based on the findings and recommendations in this report;
- Advise on the necessary supports to be put in place to:
  - Promote the development of innovative local nanotechnology industries which will strongly impact Irish economic growth and benefit investors;
  - Represent the Irish nanotechnology efforts (nationally and internationally);
  - Promote collaboration (nationally and internationally);
  - Provide national accountability for public funds by monitoring progress towards achievement of defined goals; and
- Identify appropriate public and private funding sources for selected projects.

This group would have a charter of at least five years to provide continuity, align with time scales of academic research and commercial development and provide enough time to gauge results.

Recommendation 3: Align funding to focus areas and coordinate funding management

This nanotechnology strategy implies a funding stream for the theme "nanotechnology" in the annual Science Technology and Innovation budget. This nanotechnology commercialisation strategy is likely to require a minimum total funding requirement of €114 million[32] (see Table 15*)* over the next five years (or €22.8 million annually), split fairly equally across the three technology focus areas*.* The nanotechnology coordination group will be responsible for coordinating and overseeing the cohesiveness of the implementation of this funding strategy and will report to the Department of Enterprise, Trade and Innovation (DETI).

[32] Using the metrics and targets in Table *ii*, the investment required to produce a single unit of each (1 PhD, 1 start-up, 1 patent, etc.) was estimated based on Lux Research's knowledge of the area.

Recommendation 4: Ensure diverse funding sources and increased industrial funding

Table 15 shows the proposed allocation of the required funding between R&D (predominantly applied research), commercialisation, environmental health and safety initiatives and also between government funds and non government funds (money raised by academia and that contributed by industry). As Ireland is in the early stages of nanotechnology research commercialisation, the funding will have to largely come from public sources for at least the next three years. Corporate investment will come on the back of quality academic research that is targeted at current and future market needs. Such research should be the near-term Irish priority and should underpin the proposed nanotechnology focus areas. Ireland needs to introduce structured programmes (aligned to the focus areas) to attract and significantly increase industry involvement, commitment and investment in nanotechnology R&D activities. The inclusion of industry on the coordinating group will be important in this context.

Recommendation 5: Establish a self sustainable strategy

Government has a role in supporting emerging and potentially (economically) important technology areas. Once research, technology and development programmes are established the government must be in a position to focus its attention on the next emerging area. The coordinating group should be tasked to develop a self-sustainable plan that secures future required investment with reduced government contribution. As nanotechnology moves into the true commercialisation arena where private enterprises operate best, the need for government funding will reduce.

Recommendation 6: Develop Infrastructure to support Ireland's nanotechnology vision

The central focus of the public research investment in nanotechnology research is not at this point about more new infrastructure. The near term focus should be to maximise use of existing infrastructure; the INSPIRE network and the NAP programme are steps in the right direction as they develop infrastructure sharing agreements with select international partners over the subsequent months. The medium term focus should be to upgrade existing infrastructure, e.g. adding capabilities to work with biological media to institutions with More Moore[33] clean rooms. In the long term a review of the performance resulting from the near and medium term foci should be carried out to identify critical infrastructure augmentation needs.

Recommendation 7: Develop an entrepreneurial workforce to enable the effective translation of relevant research into commercially viable opportunities

To effectively commercialise nanotechnology, Ireland must develop an entrepreneurial workforce to enable effective translation of relevant research into commercially viable opportunities. With a specific focus on nanotechnology over the next 12 to 18 months, Ireland should deploy all of the below options:

- Develop structured nanotechnology PhD programmes;
- Attract foreign researchers to work in Ireland;
- Develop business curricula within graduate and undergraduate programmes;

[33] More Moore: Alternative technologies to scale devices along Moore'e law once the physical limits of silicon-based transistors have been reached.

- Promote internships and retraining programmes;
- Review academic performance assessment; and
- Initiate business plan competitions.

Recommendation 8: Encourage and foster intensive collaboration at a national and international level

Given nanotechnology's multidisciplinary nature, Ireland must continue to encourage and foster intensive collaboration (both inter academia and academia-industry) at both national and international level as an important means of sourcing ideas, resources and opportunities. The chosen focus areas lend themselves to such engagements. Although such collaborations exist today, they have not been directed at the multi-lateral level and have yet to significantly raise the profile of Irish nanotechnology research globally. This approach also fits in with the overarching goal of improving Ireland's international profile as a nanotechnology player.

To achieve this, steps should be taken to:

- Initiate meaningful collaborative agreements with the following countries: Netherlands, Denmark, Germany, Finland, US, Singapore and Israel;
- Initiate the process of cross border collaboration with Northern Ireland.
- Leverage Ireland's position in the area of Environment, Health and Safety in nanotechnology to increase participation in EU-level discussions and consortia;
- Continue to institute sabbatical programmes for leading foreign researchers to come to Ireland and for Irish researchers to spend time in research centres abroad; and
- Organise nanotechnology-themed executive events within Ireland focused at international corporate attendees.

Appendices

Appendix A

Three components of nanotechnology's definition serve as qualifiers for whether or not a given innovation constitutes "nanotechnology". These components are as follows[34]:

Purposeful engineering

This qualifier is intended to eliminate materials and devices that have nanoscale dimensions but were not purposefully designed to, representing "happy accidents". Many materials exist with nanoscale dimensions that were not knowingly designed to have them and which were found to have a critical dimension (i.e., length, width, or height) of less than 100 nm only decades or centuries later with the advent of powerful microscopes. For example, synthetic zeolites, crystalline structures with pore sizes as small as one nanometre across primarily used to make detergents and serve as desiccants, have been manufactured synthetically since the 1930s and several tons of these materials are sold annually by companies like Süd-Chemie and Toray Industries. But most synthetic zeolites were not purposefully engineered for their properties and scientists did not learn about their nanoscale pore sizes until many decades after their manufacturing processes had been refined.

Scales of less than 100 nm

This boundary condition is by no means a hard-and-fast rule; it simply serves as effective shorthand for the point at which the properties of matter change in size-dependent ways due to quantum mechanical influences, dramatic increases in surface area, or other effects that manifest themselves only at the nanoscale. This component of the definition is primarily intended to eliminate micromechanical systems (MEMS), such as the micromirror systems used in Texas Instruments' Digital Light Processing (DLP) display technology and microsystems such as microfluidics devices from companies like Nanogen that serve as "labs-on-a-chip." MEMS and microsystems are thriving areas of technology innovation, but they involve devices with critical dimensions orders of magnitude larger than the nanoscale, they do not exhibit size-dependent properties other than marginally more massive integration and they can more appropriately be thought of as a niche of the semiconductor industry rather than as cousins to nanotechnology applications.

Size-dependent properties and functions

This is the most critical qualifier in the definition: nanotechnology applications involve materials and structures that are not only *small*, but are *small and different.* This qualifier is intended to eliminate technologies that exhibit feats of miniaturisation that lead to nanoscale features, but without any discontinuous changes in properties due to size. For instance, many processes in the semiconductor industry deposit very thin films of material, with thicknesses well less than 100 nm, but without resulting in any new properties, they simply allow the manufacturing to use less material.

[34] Source Lux Research

Inaccurate Conventional Wisdom about Nanotechnology

To make sense of nanotechnology's commercial applications, one first must dispense with three points of commonly held conventional wisdom[35]:

Inaccurate conventional wisdom #1: "*There is a nanotechnology industry*".

Many observers of nanotechnology commercialisation believe that there is a nanotechnology industry or sector emerging, comprising like-minded "nanotechnology companies" with similar business drivers and challenges, all selling "nanotechnology products." These terms are both inaccurate and unconstructive because nanotechnology applications span so many sectors. Look at a historical analogy from another broad-reaching horizontal technology: Electricity – the purposeful manipulation of electrons. Electricity enabled applications as diverse as lighting, telephony and semiconductors, but all of these applications were extremely broad-ranging and spawned businesses that had little or nothing to do with one another outside of shared fundamental technologies employed. The same is true in nanotechnology.

Inaccurate conventional wisdom #2: "*If it's nano, it's new*".

Hopefully the earlier discussion of materials with nanoscale dimensions that were not purposefully designed put an end to this point of view. For another example, consider the Lycurgus cup, a Roman drinking vessel made of glass, constructed 1,600 years ago and now at the British Museum in London. When viewed in ambient light, the Lycurgus cup appears green, but when white light is shone directly through it, it appears brilliant red. This is because of gold and silver nanoparticles unwittingly baked into the glass by the ancient Romans. They were employing nanostructures centuries ago, but they weren't purposefully engineering anything (and in fact, archaeological finds of failed attempts to recreate the Lycurgus cup lend weight to the thesis that it was a "happy accident"). What's new in nanotechnology is purposeful engineering expressly to achieve size-dependent properties.

Inaccurate conventional wisdom #3: "If it's nano, it has the potential for huge profit margins".

Nanotechnology applications are already appearing today in very diverse products, many of which are commodities purchased on the basis of price and availability with thin profit margins that are likely to stay thin forever. In almost all cases, customer attitudes and product specification needs won't change simply because nanotechnology is incorporated. While buyers will initially pay a slight premium for a stain-resistant toilet, a denser memory chip, or a higher-throughput medical diagnostic tool, these gains won't last. Once rivals can replicate the advance, they will compete away the fat profit that the first-mover enjoyed and drive margins to industry averages. In the long run, this means that margins for products incorporating nanotechnology will trend toward product category averages. If so, does anyone stand to benefit from incorporating nanotechnology into products? Absolutely, the first movers that use a period of exclusivity to either lift margins or capture share.

[35] Source Lux Research

Appendix B

Nanotechnology Funding Reaches $18.2 as Government Spending Booms and VC Rebounds[36]

Spending on nanotechnology R&D around the world maintained its growth in 2008, as the breadth of nanotechnology's influence continued to expand. Global spending on nanotechnology from governments, corporations and venture capitalists (VCs) totalled $18.2 billion in 2008, up 15 percent from the $15.8 billion spent in 2007.

Government funding totalled $8.4 billion in 2008, 46 percent of total[37]

Government spending constitutes almost half of overall nanotechnology funding and plays a fundamental role in promoting basic research. In 2008, government funding for nanotechnology grew dramatically, nations around the world spent $8.4 billion on nanotechnology, a 16 percent growth from the $7.2 billion spent in 2007. Asian nations lead spending by region, allocating a total of $2.8 billion, a sum that swells to $3.4 billion when the funding figures are expressed at purchasing power parity (PPP), correcting for the varying amount of goods and services a dollar can acquire in different nations. By section, the largest share – $3.1 billion, or 38 percent of the total went to materials and manufacturing, followed by energy and environment at $2.5 billion.

Corporate funding amounted to $8.6 billion in 2008, 47 percent of total[38]

Corporate funding became the largest source of nanotechnology R&D funding in 2007, surpassing government spending and the trend continues in 2008, though its growth was more modest due to a the global economic downturn. Corporate funding was also largest in Asia, with $3.8 billion in 2008 and $4.0 billion at PPP. By sector, electronics and IT accounts for the greatest share of nanotechnology corporate funding, marshalling $4.2 billion, or 49 percent of the total.

Venture capitalists invested $1.2 billion in 2008, 7 percent of total[39]

After a flat 2007, total investment in nanotechnology by VCs rocketed up in 2008, reaching $1.2 billion by December 1, 2008, already up 60 percent from the $773 million invested in 2007. Companies in the energy and environment sector attracted the most funding for the second year in a row after receiving $502 million in 2008, equivalent to 41percent of the year's total on the strength of big investments in Nanosolar and A123 Systems.

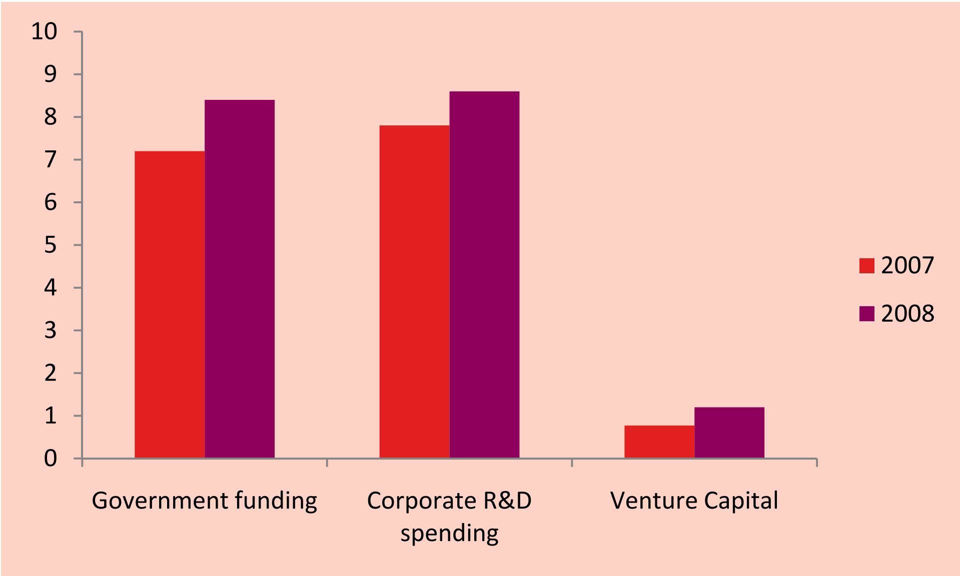
[36] Source: Lux Research.

[37] Source: Lux Research.

[38] Source: Lux Research.

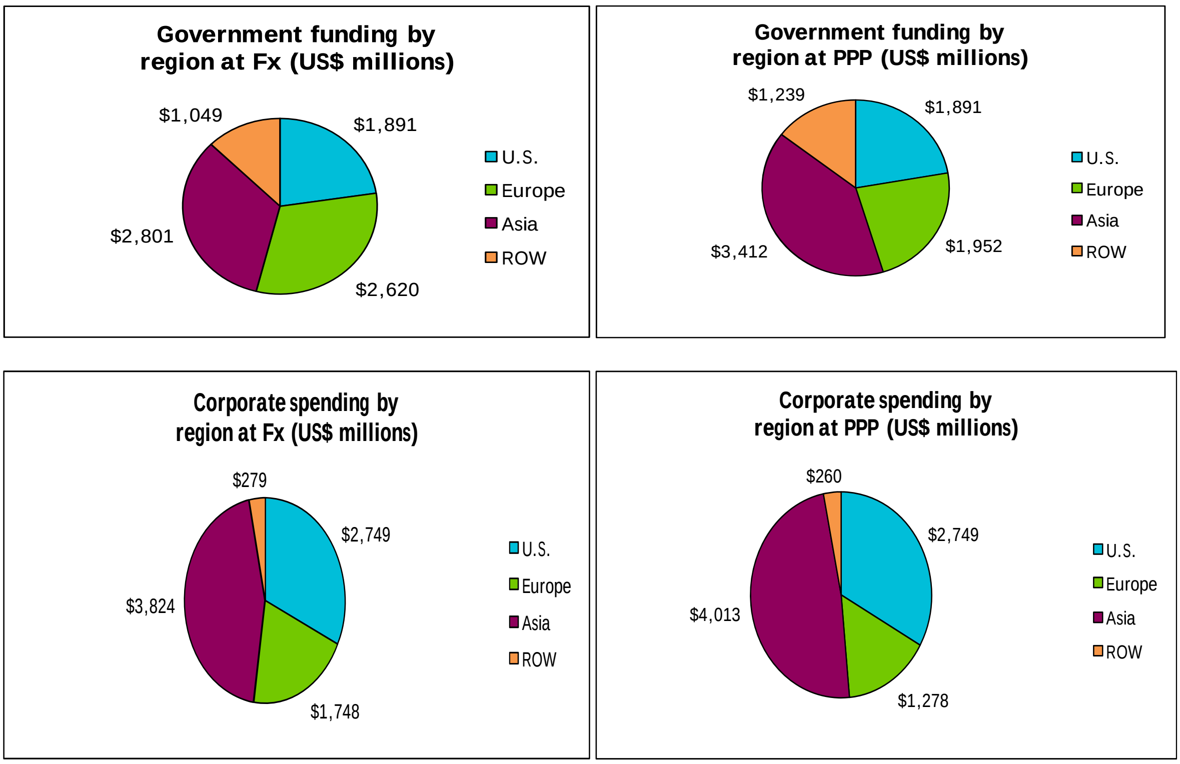
[39] Source: Lux Research.

Figure 17: Global Funding for Nanotechnology Comes from Three Major Source (USD in millions)



Source: Lux Research

Figure 18: Government and Corporate Nanotechnology Funding by Region



Source: Lux Research

Appendix C

The Eight Different Commercial Markets and the Applications within Those Markets with High Potential Nanotechnology Impact

C-1: Aerospace (Key Nanotechnology Solutions)

Application	Description	Readiness	Key companies
Avionics	Several nano-enabled memory technologies may achieve the radiation hardness required for use in aircraft systems	Development	Nantero, Cavendish Kinetics, Micromem Technologies
Structural monitoring	Continuous monitoring of structures may reduce downtime for aircraft maintenance by detecting problems early	Lab	PEL Associates, Rensselaer Polytechnic Institute, Lumedyne Technologies
Self-healing smart materials	Future aircraft may leverage morphing materials that can adapt to different stages of a flight and repair damage	Lab	PEL, Max Planck Institute of Colloids and Interfaces, University of Bristol
Structural materials	Nanostructured metallic alloys and nanoporous materials make aircraft strong but light to cut fuel consumption	Introduction	Modumetal, Integran, Applied Sciences, The NanoSteel Company
Antimicrobial materials	Nanoparticles of silver embedded in various supports and polymers help keep interior surfaces free of microbes	Scale	Millidyne, NanoHorizons, Agion Technologies, Bio-Gate, HeiQ Materials

Application	Description	Readiness	Key companies
Flame-retardant materials	Many materials for interiors today use high-heat thermoplastics that may also incorporate nanoclays	Introduction	Starfire Systems, Applied NanoWorks, Nanocor, Pyrograf Products, Nanocor
Conductive materials	EMI shielding and lightning strike protection can benefit from CNTs and graphene to make composites conductive	Development	NanoTechLabs, Nanoledge, Raymor Industries, XG Sciences, Pyrograf
Anti-icing coatings	Functionalised ceramic nanoparticles embedded in coatings make surfaces ultrahydrophobic to resist ice adhesion	Development	CG2 NanoCoatings, Luna Innovations, Nanovere
Electrical infrastructure	Nanostructured alternatives to standard copper wiring can increase electrical conductivity while reducing weight	Introduction	NanoComp Technologies, Aegis Technologies, Integran, 3M
Wear-resistant coatings	Metal and composite coatings enabled with ceramic nanoparticles help preserve external aerodynamic surface integrity	Introduction	Integran Technologies, Mayaterials, Hyperion Technologies, Nanogate

Source: Lux Research

C-2: Automotive (Key Nanotechnology Solutions)

Application	Description	Readiness	Key companies
Fuel-based additives	Cerium oxide nanoparticles are a key part of fuel additives that claim to increase diesel engine fuel efficiency	Introduction	Oxonica, Antaria, Cerion Technologies, Energenics
Catalysts	Nano-enabled catalysts combat air pollution in automotive catalytic converters while reducing precious metal usage	Introduction	Nanostellar, Catalytic Solutions, Namos, SDCmaterials, QID Nano
Wear-resistant coatings	Nanoparticle-coated interior parts withstand extreme heat and pressure better than conventional materials	Introduction	Ecology Coatings , nCoat, Starfire Systems, Nanovere, Mayaterials
Aesthetic coatings	Clear coats and chrome replacements use nanoparticles to enhance appearance and protect exterior	Scale	PPG, Xtalic, Nanocyl, Nanofilm
Tribological coatings	Ceramic NP coatings that prevent deposits from forming in engines can enhance fuel efficiency	Introduction	Nanogate Technologies, Beneq, NanoMech
Structural materials	Nanoclays and nanostructured metals help to make lightweight and strong moulded net shape auto parts	Introduction	NanoScience Engineering, Southern Clay Products, Nanocor, Modumetal
Anti-static materials	CNTs already are commonly used to prevent static build-up on fuel lines and graphene may offer a cheaper	Scale	Hyperion Catalysis, Nanocyl, Vorbeck, XG Sciences, Mitsui, Bayer,
Electronics	Memory technologies, electric wiring, and interconnects rely on nanoscale features for their properties	Introduction	APowerCap Technologies, NVE, Nantero, Aegis Technologies
Lubricants	Ceramic metal sulphide NPs and biologically derived molecules provide alternatives to lubricants from oil	Development	Green Earth Technologies, ApNano Materials
Battery/energy storage	Electrodes engineered at the nanoscale enable higher-performance rechargeable batteries for electric vehicles	Development	A123 Systems, Evonik, Ionova, Anzode, High Power Lithium

Source: Lux Research

C-3: Construction (Key Nanotechnology Solutions)

Application	Description	Readiness	Key companies
Self-cleaning coatings	Titanium dioxide (TiO_2) NPs and other materials embedded in other materials react with or repel dirt and contaminants	Introduction	Millennium Inorganic, Nanogate, Green Earth Nano Sciences, BASF
Exterior coatings	Paints and window treatments use NPs to make these UV-resistant, dirt- and water-repellent, non-stick and stable	Introduction	Nanovations, Nanophase, Nanogate, nGimat, Luna Innovations
Interior coatings	NPs are used in protective coatings for wood and floors and could potentially add flame retardance	Introduction	Green Earth Nano Sciences, Bühler Partec, Bayer
Antimicrobial coatings	Silver NPs on ceramic substrates or embedded in polymers make fabrics and fixtures antimicrobial	Scale	Millidyne, Agion, NanoHorizons, Nanogate, Nanux,
Air filtration	Odour remediation and nanoporous filters can get air cleaner than ever before	Scale	NanoScale, eSpin Technologies
Structural materials	Nanostructured alloys of materials already render steel much stronger and CNT additives could also add strength	Scale	MMFX Technologies, The NanoSteel Alcan
Temperature-control materials	Coatings on windows and buildings based on organic NPs could retain energy from the sun to release later	Development	TAG Technology, Nanofilm, QuarTek, BASF
Insulation	Nanoporous aerogels offer insulation in a much thinner form factor, enabling better usage of tight spaces	Scale	Aspen Aerogels, Va-Q-Tec, NanoPore,
Photovoltaics (PV)	Nano-enabled thin-film PV technologies begin to improve the economic case for more widespread adoption of solar	Development	XeroCoat, Cyrium Technologies, Stion, Innovalight,
Light-control materials	By responding to the amount of sunlight, light-control materials can keep indoor light more constant	Introduction	Huper Optik, TAG Technology

Source: Lux Research

C-4: Electronics (Key Nanotechnology Solutions)

Application	Description	Readiness	Key companies
Transparent conductors	CNTs and metal NPs in a polymer matrix can replace costly indium tin oxide (ITO) in displays and solar PV panels	Development	Eikos, Unidym, Cambrios, Cima Nanotech, Nanofilm, Canatu, Nano-C
Thermal management	Nanostructured devices can provide active cooling, while highly conductive features can provide thermal contact	Introduction	Nextreme, Applied Sciences, Nanolab, NovaCentrix, IMEC, NanoComp
Displays	CNTs, quantum dots, and nanoscale layers of polymers can improve the properties of displays, including flexibility	Development	Motorola, Samsung, Cambridge Display, QD Vision, Evident, Ntera
Memory technologies	As optical lithography hits its limits of resolution, emerging technologies offer the promise of extending Moore's law	Development	Nantero, EverSpin, NVE Corp., Samsung, Molecular Imprints, IMEC, HP
Printed electronics	RFID and flexible displays will drive the growth in electronics made by printing processes rather than lithography	Development	Kovio, NanoMas, Nano-C, Polyera, Nanoident, Five Star, Bayer, Cima
LEDs and optical components	Nanoscale engineering and NPs like QDs and dendrimers boost LED output and enable precision optical elements	Introduction	API Nanotronics, Nanocs, NanoGram, PPG, Lightwave Logic, NeoPhotonics
Energy storage	Nanostructured electrodes and NP electrode coatings can greatly improve performance for consumer devices	Introduction	Enable IPC, Cap-XX, Primet, Ionova, APowerCap Technologies, ZPower

Application	Description	Readiness	Key companies
Barrier coatings	Several efforts use NPs in attempts to create gas barrier coatings impermeable enough for OLED applications	Development	Nova-Plasma, Hybrid Plastics, IMRE (Singapore)
Packaging	Soldering and bonding at lower temperatures protects nearby components, plus other packaging improvements	Introduction	NovaCentrix, Ormecon, Nanodynamics, Reactive Nanotechnologies, Mayaterials
Lithography and process tools	Fullerenes target improved resists, anti-static packaging for semiconductor wafers and nanoimprint lithography	Scale	Hybrid Plastics, Frontier Carbon, IMEC, Hyperion Catalysis, Nanocyl, Obducat

Source: Lux Research

C-5: Energy and Environment (Key Nanotechnology Solutions)

Application	Description	Readiness	Key companies
Environmental remediation	Various types of ceramic or metal NPs can react with pollutants or toxins in soil, water and air	Development	Lehigh Nanotech Network, NanoScale, NanoChemonics, SiGNa Chemistry
Sustainable and bio-based materials	New processes enable bio-based packaging materials to be made from waste or strengthened for longer usage	Introduction	Novomer, EcoSynthetix, Topchim, NanoBioMatters, OrganoClick
Batteries/energy storage	Electrodes engineered at the nanoscale enable higher performance rechargeable batteries	Introduction	Altair Nanotechnologies, Cap-XX, Anzode,
Wind	Blades made of stronger composite materials with anti-icing coatings can enhance the performance of wind turbines	Development	CG2 NanoCoatings, Nanoledge, Enable IPC, Amroy, Vestas
Photovoltaics (PV)	PV systems based on newer, less costly technologies can offset part of energy consumption derived from fossil fuels	Development	NanoGram, Bloo Solar, XeroCoat, Nanologica, Stion,
Water treatment	Novel approaches improve anti-fouling properties of systems to lower total system operating cost	Development	Lehigh Nanotech Network, NanoH_2O, IBU-tec, Argonide,
Air treatment	Catalysts combat air pollution in automotive catalytic converters and soon in smog-cleaning paints	Introduction	Catalytic Solutions, Nanostellar, Cerion Technologies, Millennium Inorganic
Fuel cells	Improvements to membranes may bring fuel cells closer to feasibility in stationary power and other applications	Development	Catalyx Nanotech, QuantumSphere, Ener1, Nano-Tek
Waste	Waste materials and waste energy can be converted into better uses through applying new processes and materials	Lab	Exilica, GMZ Energy, Headwaters
Energy conservation	Light-controlling and heat-controlling films and insulation enable more resourceful use of energy commonly lost	Development	Huper Optik, QuarTek, Nanofilm, TAG Technology

Source: Lux Research

C-6: Manufacturing (Key Nanotechnology Solutions)

Application	Description	Readiness	Key companies
Anti-wear coatings	Diamond nanocrystals and nanostructured metal composites make various industrial parts more durable	Scale	Starfire Systems, Integran, Advanced Diamond, Carbide Derivative, Sub-One
Electrical infrastructure	Nanoclays in electrical cable claddings make them flame-retardant; metal nanocomposite provide stronger cables	Introduction	Nanocor, Kabelwerk Eupen, Beijing ChamGo Nano-Tech, 3M, Integran
Antimicrobial materials	Nanoparticles of silver embedded in various supports and polymers help keep surfaces free of microbes	Scale	Agion Technologies, NanoHorizons, Nanux, HeiQ Materials
Processing aids	Adding specially engineered nanoparticles to a variety of materials can improve properties like flow and dispersion	Introduction	Hybrid Plastics, Mayaterials, Applied NanoWorks, Southern Clay, Ashland
Catalysts	Nanoparticle catalysts can be made more effective for the same amount of material in chemical production	Development	Headwaters, SDCmaterials, Applied NanoWorks, Hybrid Catalysis
Antifouling and anti-corrosion coatings	Coatings based on various polymer and organic-inorganic particles can prevent crystallisation fouling and corrosion	Introduction	ItN Nanovation, Dendritech, Inframat, Nano-X, Luna Innovations, Nanofilm

Application	Description	Readiness	Key companies
Filtration	New filtration solutions using hollow nanofibers or antifouling coatings can reduce costs in an industrial setting	Introduction	Nano-porous Solutions, ItN Nanovation, Argonide, DAIS Analytic, Donaldson
Sensors to monitor water and air	Sensors based on carbon nanotubes and nanostructured devices monitor chemical or help run equipment	Introduction	NanoSelect, Nanomix, Nanoident, NVE Corporation
Anti-adhesion coatings/lubricants	Coatings based on ceramic nanoparticles and less common nanomaterials enhance mould release and anti-icing	Introduction	ItN Nanovation, CG2 NanoCoatings, ApNano, Nanomech, Nanogate, GM
Insulation	Nanoporous aerogels offer insulation in a much thinner form factor, enabling better usage of tight spaces	Scale	Aspen Aerogels, Va-Q-Tec, NanoPore, BASF

Source: Lux Research

C-7: Medical and Pharmaceutical (Key Nanotechnology Solutions)

Application	Description	Readiness	Key companies
Tissue scaffolds	Self-assembled nanofibers, peptides, and other materials provide matrices in which cells can grow and form tissues	Development	3DM, Nanotope, Donaldson, Pioneer Surgical Technology
Coatings	Medical instruments and fabrics get the antimicrobial treatment with silver NPs; also can release active drugs	Scale	Millidyne, Agion, NanoHorizons, Cinvention, Hemoteq, Bactiguard, HeiQ
Wound care	Simple wound treatments employ silver NPs, while more sophisticated approaches self-assemble into a solid form	Scale	Nucryst, AcryMed, Arch Therapeutics, Nanotope
Imaging (in vivo diagnostics)	Tracer particles can be put into a living system and then imaged to locate tumours and other diseases	Development	Luna nanoWorks, Invitrogen, GE, Aion Diagnostics, NN-Labs
In vitro diagnostics	Lab-on-a-chip and other measurements of patient samples by means of an external sensor	Introduction	Nanosphere, Nanoident, Selah, Oxford Nanopore, Oxonica, BioNanomatrix
Controlled release	Active ingredients are encapsulated in a format that will delay or extend their release once delivered to target site	Introduction	Exilica, Intrinsiq Materials, BioCure, Capsulution Pharma, pSivida
Targeted drug delivery	Pharmaceuticals are encapsulated within or attached to functionalised particles to be delivered to specific site only	Development	Luna nanoWorks, Liquidia, Novosom, Starpharma, Dendritech, Kereos
Medical device drug delivery	Alternative approach to chemotherapy sends particles to tumours where they can be heated to kill only targeted tissue	Development	MagForce Nanotechnologies, Aduro Biotech, Nanospectra Biosciences
Medical device packaging	Special labelling can guarantee authenticity of a drug; also, some require insulation for shipping under refrigeration	Scale	Va-Q-Tec, American Aerogel, Authentix
Cosmeceuticals and personal care	Nanoencapsulation and nanoporous matrices claim added efficacy for preserving and delivering cosmetic products	Scale	Dermazone, Salvona, Exilica, Evonik, Aquanova, Intrinsiq Materials, Antaria

Source: Lux Research

C-8: Oil and Gas (Key Nanotechnology Solutions)

Application	Description	Readiness	Key companies
Sensors (surface and downhole)	Surface sensors detect seismic activity, while downhole sensors monitor temperature, pressure, and corrosion	Lab	PEL Associates, Ames Research Center (NASA)
Electronics packaging	Downhole electronics need to withstand temperatures exceeding 200 °C while fitting into a compact space	Lab	GE, Aeronautics Research Mission Directorate/NASA Glenn
Downhole power	Sensors to guide drilling towards the presence of oil require local power supplies enabled by batteries and capacitors	Development	Giner, Anzode, ZPower, Filigree Nanotech, Nano-Tek, QuantumSphere
Perforators and fracturing materials	Oil-bearing rock needs to be fractured to recover the oil, and perforators make holes in the well-bore to aid recovery	Development	Intrinsiq Materials, NovaCentrix, Reactive NanoTechnologies
Proppants and binders	Proppants prop open the resulting holes for stability; binders bind the sand to prevent backflow into oil wells	Development	Engineered nanoProducts Germany, Oxane Materials, Integran Technologies
Advanced structural materials	Nanomaterials enable greater hardness, weight, and modulus in well-bores and pipelines	Introduction	American Aerogel, The NanoSteel Company, Modumetal
Advanced coatings	Coatings can protect parts of oil equipment that are more vulnerable, such as seals	Introduction	Integran, Sub-One, Advanced Diamond Technologies, Epik Energy
Catalysts	Catalysts are used both in the process of refining oil as well as downstream in automotive catalytic converters	Introduction	Nanologica, Applied NanoWorks, Headwaters, SDCmaterials, Nanostellar
Separation and recovery	Nanomaterials can improve many of the filters and chemicals involved in the process of oil refining	Development	Nano-Porous Solutions, SiGNa Chemistry, Donaldson
Water management	Filtration systems that are used in other contexts may also aid at the scale of oil and gas recovery operations	Development	DAIS Analytic, Epik Energy Solutions

Source: Lux Research

Appendix D

The Lux Research Nations Ranking Grid

Lux Research implemented a measurement framework in this report similar to the ones used in 2005 through 2007 to gauge international nanotechnology competitiveness. Forfás, in conjugation with Lux Research, analysed countries along two axes: nanotechnology activity and technology development strength.

Nanotechnology activity is an absolute measure of the raw material for nanotechnology development

This axis examines the capabilities and resources of a nation's engine for nanotechnology innovation, drawing on eight metrics, such as government funding for nanotechnology, number of patents, and number of publications. Since these metrics are based on absolute figures, larger countries hold an advantage here, while smaller countries tend to score lower.

Technology development strength is a relative measure of technology commercialisation prowess

This axis measures the capacity of a country for economic growth from general scientific and technological innovation and therefore it is not specific to nanotechnology. Technology development strength helps assess how well-positioned a nation is to profit from nanotechnology developments, by examining criteria like domestic output in high-tech manufacturing, or science and technology work force. Note that these metrics are relative measures normalised to, for instance, high-tech manufacturing as a percentage of GDP, or science and technology work force per capita so that small and large countries are compared equally.

Plotting countries on a grid, with nanotechnology activity on the vertical axis and technology development strength on the horizontal axis, provides an assessment of each nation's overall nanotechnology performance and capabilities.

This framework should help clients to:

Guide operations to best leverage assets

By illuminating the strengths and weaknesses of countries around the world, governments, companies and investors can develop the best plan of action to combine their own assets with international collaborators. For example, organisations looking for innovation can turn to start-ups in the countries with the most nanotechnology activity to identify new technology opportunities internationally.

Inform decisions on how to best exploit collaborations

Knowing the strengths and weaknesses both of one's own country and of others makes it possible to seek out partners that would best complement the organisation. Countries that are the most fertile sources of nanotechnology innovations are not necessarily the best venues for nanotechnology commercialisation and vice versa.

Table 16: Nanotechnology Activity Criteria

Criterion	Weight	Description	Why It Matters
Nanotech initiatives	15%	Qualitative assessment of the operational status, effectiveness, and coordination of nanotechnology initiatives at the national, regional and local levels	Indicator of level of planning and foresight brought to nanotechnology development
Nanotech centres	15%	Number of dedicated government and university nanotechnology facilities in country with a focus on either R&D or commercialisation	Magnets for academics, breeding grounds for start-ups and collaboration centres for corporations
Government spending	10%	Amount of funding at regional and national levels specifically allocated to nanotechnology in 2008	Clearest indication of a country's willingness and ability to develop nanotech innovations
Risk capital	10%	Qualitative assessment of availability of risk capital to fund new ventures, taking into account institutional venture capital, government grants and subsidised loans	Bridge across the "valley of death" for entrepreneurs commercialising nanotechnology
Corporate nanotech funding	10%	Estimated spending by established corporations on nanotechnology R&D in 2008, at purchasing power parity	In countries with little history of start-up ventures, large corporations drive nanotechnology development
Nanotechnology publications	15%	Number of articles in scientific journals on nanoscale science and engineering topics from 1995 through 2008	Best available indicator of nanotechnology research activity
Issued international patents	15%	Number of international patents on nanotechnology-enabled inventions issued from 1995 to 2008 to entities based in country	Indicator of intent to commercialise nanotechnology innovations globally
Active companies	10%	Qualitative score; considering both number and quality of companies active in nanotechnology, including large corporations, small and midsize companies and start-ups	Measurement of business, not academic, nanotechnology activity

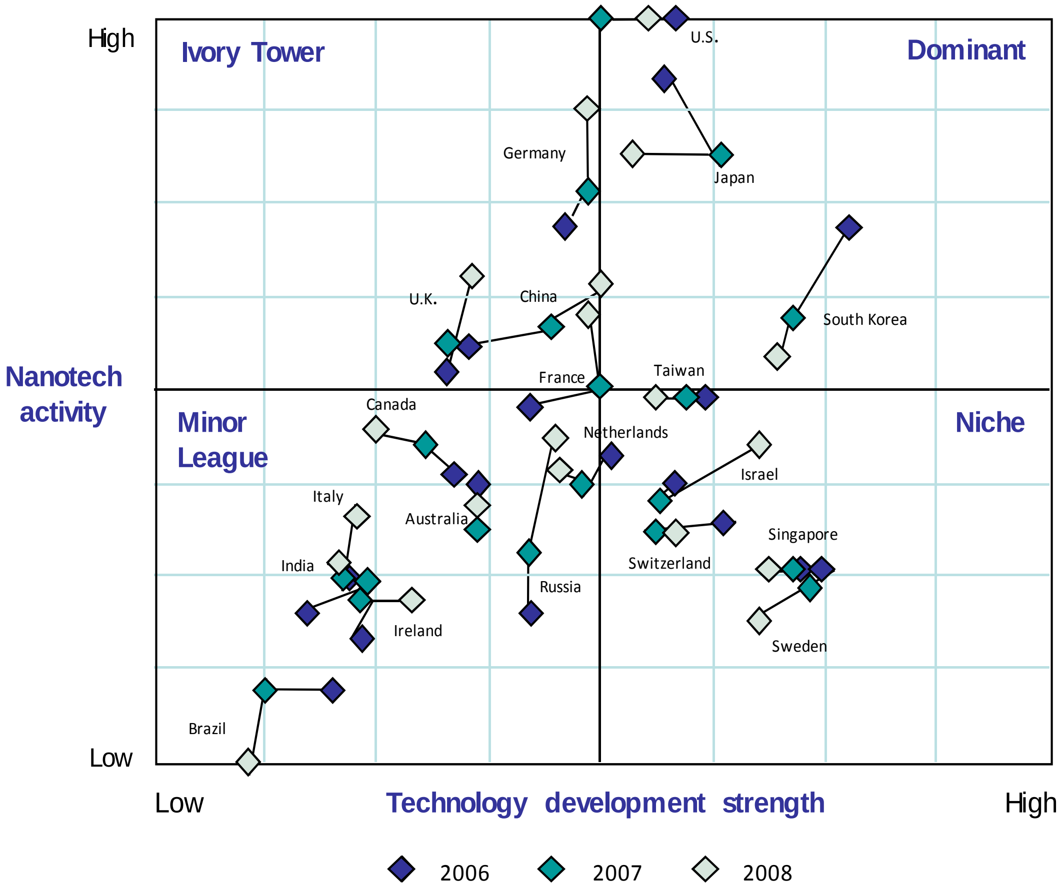
Source: Lux Research

Figure 17: Technology Development Strength Criteria

Criterion	Weight	Description	Why It Matters
High-tech manufacturing as percent of GDP	20%	Value of domestic output for high-tech chemicals, information technology products, pharmaceuticals, and life sciences products for most recent year available divided by GDP in that year	Indicator of how much a country has developed an economy that exploits high technology
R&D spending as percent of GDP	25%	Gross domestic R&D spending from both government and private-sector sources divided by GDP, for most recent year available	Demonstrates a country's private- and public-sector commitments to technology commercialisation
Technology and science workforce	20%	Number of R&D personnel per $1,000 of GDP at purchasing power parity, for most recent year available	Required to convert scientific innovations into commercially viable products and services
Science and engineering Ph.D.'s	15%	Number of science and engineering Ph.D. graduates as a percent of total population, most recent year available	Required to generate scientific innovations that feed commercialisation efforts
Expatriation of highly educated	10%	Percent of highly educated leaving country in 2008	When the highly educated expatriate, technology commercialisation suffers
Infrastructure	10%	Composite metric composed of electricity availability (2%), mobile phones per capita (2%), Internet hosts per capita (2%), Internet users per capita (2%), and abundance of roads (2%), for 2008	Basic infrastructure is required for effective technology commercialisation

Source: Lux Research

Figure 19: Technology Development Strength Criteria



Source: Lux Research

Identify new opportunities

The progress of countries through time can be used to anticipate future hot-spots in the nanotechnology space, allowing organisation to strategically build their presence to take advantage of those developments. By taking the opportunity to move in and build a dominant presence early, organisations will be able to better capitalise on and react to any developments made in up-and-coming nations.

While Figure 7 in the main text shows the Nations Ranking Grid in its standard form, Ireland tends to assess itself in GNP metric. Therefore a plotted modified version of the grid with a GNP basis above is presented (See Figure 19).

Appendix E

List of Site Visits and Interviews

Republic of Ireland

John Colreavy (CREST, Dublin Institute of Technology)

Dr Suresh Pillai (CREST, Dublin Institute of Technology)

Dr Hugh Byrne (FOCAS, Dublin Institute of Technology)

Tom Flanagan (Hothouse,Dublin Institute of Technology)

Prof. Mike Coey (CRANN, Trinity College Dublin)

Dr Diarmuid O'Brien (CRANN, Trinity College Dublin)

Prof. John Donegan (CRANN, Trinity College Dublin)

Prof. Stefano Sanvito (CRANN, Trinity College Dublin)

Prof. Igor Shvets (CRANN, Trinity College Dublin)

Prof. Brian MacCraith (Biomedical Diagnostic Institute, Dublin City University)

Prof. Roger Whatmore (Tyndall National Institute, Cork)

Brendan O'Neill (Tyndall National Institute, Cork)

Kieran Flynn (Tyndall National Institute, Cork)

Prof. Jean-Pierre Colinge (Tyndall National Institute, Cork)

Dr Damien Arrigan (Tyndall National Institute, Cork)

Dr Paul Galvin (Tyndall National Institute, Cork)

Dr Justin Holmes (Tyndall National Institute, Cork)

Prof Michael Morris (Tyndall National Institute, Cork)

Dr Aidan Quinn (Tyndall National Institute, Cork)

Dr Jim Greer (Tyndall National Institute, Cork)

Prof. Eoin O'Reilly (Tyndall National Institute, Cork)

Dr Emanuele Pelucchi (Tyndall National Institute, Cork)

Dr Guillaume Huyet (Tyndall National Institute, Cork)

Prof. Suzi Jarvis (University College Dublin)

Prof Kenneth Dawson (University College Dublin)

Prof. Abhay Pandit (NUI Galway)

Leonard Hobbs (Intel)

Gavin D'Arcy (Intel)

Sharon Higgins (Irish Medical Device Association)

Jim Lawyor (Enterprise Ireland)

Keith O'Neill (Enterprise Ireland)

Imelda Lambkin (Enterprise Ireland)

Sergio Fernandez – Ceballos (Enterprise Ireland)

Liam Brown (Enterprise Ireland)

Bill Hayes (Audit Diagnostics)

Ronan Thornton (Medtronic)

Michael Howe (Creganna)

John Dunne (Intune Networks)

Roz Carson (Invest NI)

Mike Devane, Lucent Technologies (ex-CEO)

The NanoFab Consortium

Northern Ireland

Bernard McKeown (Dept. of Enterprise Trade and Innovation, Northern Ireland)

Anne Conaty (Dept. of Enterprise Trade and Innovation, Northern Ireland)

Prof. Robert Bowman (Queen's University of Belfast)

Prof. Marty Gregg (Queen's University of Belfast)

Prof. Anatoly Zayats (Queen's University of Belfast)

Prof. Harold Gamble (Queen's University of Belfast)

Dr Mervyn Armstrong (Queen's University of Belfast)

Dr Neil Mitchell (Queen's University of Belfast)

Dr David McNeill (Queen's University of Belfast)

Dr Tony McNally (Queen's University of Belfast)

Prof. Jim McLaughlin (University of Ulster)

International Consultation

Clayton Teague (National Nanotechnology Coordination Office, US)

Travis M. Earles (National Nanotechnology Coordination Office, US)

Miriam Luizink (MESA+ Institute for Nanotechnology, Netherlands)

Lerwen Liu (SingNano, Singapore)

Karl-Heinz Haas (Fraunhofer-Institut fuer Silicatforschung, Germany)

Rafi Koriat (INNI, Israel)

Appendix F

Secondary research databases and search strings[40]

Publications and citations: ISI Web of Knowledge

- Seven databases with coverage of over 10,000 high-impact journals

Patents: Delphion

- Searches US (Granted), German (Granted), German (Applications), European (Applications), European (Granted), INPADOC, Abstracts of Japan, WIPO PCT Publications, US (Applications)
- Database size ~ 54 million patents

General "nano" search string (which is added to the respective search strings for each market - application combination below):

- **Aerospace - Avionics:** TS = (quantum dot OR nanostruc* OR nanopartic* OR nanotub* OR fulleren* OR nanomaterial* OR nanofib* OR nanotech* OR nanocryst* OR nanocomposit* OR nanohorn* OR nanowir* OR nanobel* OR nanopor* OR dendrimer* OR nanolith* OR nanoimp* OR nano-imp* OR dip-pen)

- **Aerospace - Avionics:** TS = (avionics OR aero* OR aerospace OR structural monitor OR self-healing OR smart material OR structur* materials OR antimicrobials OR flame-retardant OR conductive OR anti-icing coat* OR electrical infrastructure OR wear-resistant coat*) AND TS = (avionic* OR aviation* OR navigat* OR communicat* OR aircraft manage* OR radar OR sonar OR optic* OR memory)

- **Aerospace - Structural monitoring:** TS = (avionics OR aero* OR aerospace OR structural monitor OR self-healing OR smart material OR structur* materials OR antimicrobials OR flame-retardant OR conductive OR anti-icing coat* OR electrical infrastructure OR wear-resistant coat*) AND TS = (structur* AND monitor* OR sensor*)

- **Aerospace - Self-healing smart materials:** TS = (avionics OR aero* OR aerospace OR structural monitor OR self-healing OR smart material OR structur* materials OR antimicrobials OR flame-retardant OR conductive OR anti-icing coat* OR electrical infrastructure OR wear-resistant coat*) AND TS = (self-heal* OR self heal* OR smart OR morph*)

- **Aerospace - Structural materials**: TS = (avionics OR aero* OR aerospace OR structural monitor OR self-healing OR smart material OR structur* materials OR antimicrobials OR flame-retardant OR conductive OR anti-icing coat* OR electrical infrastructure OR wear-resistant coat*) AND TS = (self-heal* OR self heal* OR smart OR morph*)

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[40] Source Lux Research.

- **Aerospace - Antimicrobial materials**: TS = (avionics OR aero* OR aerospace OR structural monitor OR self-healing OR smart material OR structur* materials OR antimicrobials OR flame-retardant OR conductive OR anti-icing coat* OR electrical infrastructure OR wear-resistant coat*) AND TS = (antimicrob* OR antifung* OR antibact*)

- **Aerospace - Flame-retardant materials**: TS = (avionics OR aero* OR aerospace OR structural monitor OR self-healing OR smart material OR structur* materials OR antimicrobials OR flame-retardant OR conductive OR anti-icing coat* OR electrical infrastructure OR wear-resistant coat*) AND TS = (flame-retard* OR epox* OR flame retard* OR thermoplas*)

- **Aerospace - Conductive materials**: TS = (avionics OR aero* OR aerospace OR structural monitor OR self-healing OR smart material OR structur* materials OR antimicrobials OR flame-retardant OR conductive OR anti-icing coat* OR electrical infrastructure OR wear-resistant coat*) AND TS = (conductiv* OR EMI shield* OR lightning protection*)

- **Aerospace - Anti-ice coatings** : TS = (avionics OR aero* OR aerospace OR structural monitor OR self-healing OR smart material OR structur* materials OR antimicrobials OR flame-retardant OR conductive OR anti-icing coat* OR electrical infrastructure OR wear-resistant coat*) AND TS = (anti-ic* OR hydrophob*)

- **Aerospace - Electrical infrastructure** : TS = (avionics OR aero* OR aerospace OR structural monitor OR self-healing OR smart material OR structur* materials OR antimicrobials OR flame-retardant OR conductive OR anti-icing coat* OR electrical infrastructure OR wear-resistant coat*) AND TS = (electric*)

- **Aerospace - Wear-resistant coatings:** TS = (avionics OR aero* OR aerospace OR structural monitor OR self-healing OR smart material OR structur* materials OR antimicrobials OR flame-retardant OR conductive OR anti-icing coat* OR electrical infrastructure OR wear-resistant coat*) AND TS = (wear-resist* OR wear resist*)

- **Automotive - Fuel-based additives**: TS = (automo* OR car OR truck OR vehic*) AND TS = (fuel-based additive OR additive OR fuel based additiv* OR fuel additiv*)

- **Automotive - Catalysts**: TS = (automo* OR car OR truck OR vehic*) AND TS = (cataly*)

- **Automotive - Wear-resistant coatings**: TS = (automo* OR car OR truck OR vehic*) AND TS = (coat*) AND TS = (wear-resist* OR wear resist* OR anti-corro* OR anti corro*)

- **Automotive - Aesthetic coatings**: TS = (automo* OR car OR truck OR vehic*) AND TS = (coat*) AND TS = (paint* OR aesthet* OR exter* OR appear*)

- **Automotive - Tribological coatings**: TS = (automo* OR car OR truck OR vehic*) AND TS = (coat* AND tribolog*)
- **Automotive - Structural materials**: TS = (automo* OR car OR truck OR vehic*) AND TS = (structur* material*)
- **Automotive - Anti-static materials**: TS = (automo* OR car OR truck OR vehic*) AND TS = (anti-static* OR anti static*)
- **Automotive - Electronics**: TS = (automo* OR car OR truck OR vehic*) AND TS = (memory OR wire OR interconnect OR electron*)
- **Automotive - Lubricants**: TS = (automo* OR car OR truck OR vehic*) AND TS = (lubrica*)
- **Automotive - Battery/energy storage**: TS = (automo* OR car OR truck OR vehic*) AND TS = (electrode* OR battery OR energy storage OR fuel cell* OR capacitor* OR supercap*)
- **Construction - Self-cleaning coatings**: TS = (construction OR building material* OR housing* OR building*) AND TS = (coat*) AND TS = (self-clean* OR self clean*)
- **Construction - Exterior coatings**: TS = (construction OR building material* OR housing* OR building*) AND TS = (paint* OR coat*) AND TS = (UV-resist* OR UV resist* OR dirt repel* OR non-stick* OR water resist* OR discolor* or scratch* OR sealant* OR glaz*)
- **Construction - Interior coatings**: TS = (construction OR building material* OR housing* OR building*) AND TS = (paint OR anti-scratch*)
- **Construction - Antimicrobial coatings**: TS = (construction OR building material* OR housing* OR building*) AND TS = (antimicrob* OR antibact* OR antifung*)
- **Construction - Air filtration**: TS = (construction OR building material* OR housing* OR building*) AND TS = (air filtr* OR air filter* OR air treat*)
- **Construction - Structural materials**: TS = (construction OR building material* OR housing* OR building*) AND TS = (structur* material*)
- **Construction - Temperature-control materials**: TS = (construction OR building material* OR housing* OR building*) AND TS = (temperature control* OR temperature-control*)

- **Construction - Insulation**: TS = (construction OR building material* OR housing* OR building*) AND TS = (insulat* OR aerogel)

- **Construction - Photovoltaics**: TS = (construction OR building material* OR housing* OR building*) AND TS = (photovolt* OR solar OR building-integrat* photovolt* OR invert* OR BIPV*)

- **Construction - Light-control materials**: TS = (construction OR building material* OR housing* OR building*) AND TS = (photochrom* OR dye OR light-control*)

- **Electronics - Displays**: TS = (transparent conductor OR thermal management OR memory OR SRAM OR DRAM OR MRAM OR RAM OR FLASH OR electronic OR LED OR light emitting diode OR optical OR optics OR barrier coating OR lithography OR semiconductor OR communication OR telecommunication OR chip fabrication OR broadcast OR wireless OR computer) AND TS = (display*****)

- **Electronics - Memory technologies** : TS = (transparent conductor OR thermal management OR memory OR SRAM OR DRAM OR MRAM OR RAM OR FLASH OR electronic OR LED OR light emitting diode OR optical OR optics OR barrier coating OR lithography OR semiconductor OR communication OR telecommunication OR chip fabrication OR broadcast OR wireless OR computer) AND TS = (memory)

- **Electronics - Printed Electronics**: TS = (transparent conductor OR thermal management OR memory OR SRAM OR DRAM OR MRAM OR RAM OR FLASH OR electronic OR LED OR light emitting diode OR optical OR optics OR barrier coating OR lithography OR semiconductor OR communication OR telecommunication OR chip fabrication OR broadcast OR wireless OR computer) AND TS = (print* OR RFID OR flexible)

- **Electronics - LEDs and optical components**: TS = (transparent conductor OR thermal management OR memory OR SRAM OR DRAM OR MRAM OR RAM OR FLASH OR electronic OR LED OR light emitting diode OR barrier coating OR lithography OR semiconductor OR communication OR telecommunication OR chip fabrication OR broadcast OR wireless OR computer) AND TI = (LED* OR optical)

- **Electronics - Energy storage**: TS = (transparent conductor OR thermal management OR memory OR SRAM OR DRAM OR MRAM OR RAM OR FLASH OR electronic OR LED OR light emitting diode OR optical OR optics OR barrier coating OR lithography OR semiconductor OR communication OR telecommunication OR chip fabrication OR broadcast OR wireless OR computer) AND TS = (battery OR energy storage OR fuel cell OR capacitor OR supercap*)

- **Electronics - Barrier coatings**: TS = (transparent conductor OR thermal management OR memory OR SRAM OR DRAM OR MRAM OR RAM OR FLASH OR electronic OR LED OR light emitting diode OR optical OR optics OR barrier coating OR lithography OR semiconductor OR communication OR telecommunication OR chip fabrication OR broadcast OR wireless OR computer) AND TS = (barrier coat*)

- **Electronics - Packaging**: TS = (transparent conductor OR thermal management OR memory OR SRAM OR DRAM OR MRAM OR RAM OR FLASH OR electronic OR LED OR light emitting diode OR optical OR optics OR barrier coating OR lithography OR semiconductor OR communication OR telecommunication OR chip fabrication OR broadcast OR wireless OR computer) AND TS = (packag* OR solder* OR bond*)

- **Electronics - Lithography and process tools**: AND TS = (litho* OR photolitho* OR resist* OR photoresist*)

- **Electronics - Transparent conductors**: TS = (transparent conductor OR thermal management OR memory OR SRAM OR DRAM OR MRAM OR RAM OR FLASH OR electronic OR LED OR light emitting diode OR optical OR optics OR barrier coating OR lithography OR semiconductor OR communication OR telecommunication OR chip fabrication OR broadcast OR wireless OR computer) AND TS = (transparent conduct* OR ITO)

- **Electronics - Thermal management**: TS = (transparent conductor OR thermal management OR memory OR SRAM OR DRAM OR MRAM OR RAM OR FLASH OR electronic OR LED OR light emitting diode OR optical OR optics OR barrier coating OR lithography OR semiconductor OR communication OR telecommunication OR chip fabrication OR broadcast OR wireless OR computer) AND TS = (thermoelec* OR peltier OR cool* OR thermal manag*)

- **Energy & Environment - Environmental remediation**: TS = (fuel cell OR battery OR solar OR photovoltaic OR CIG OR cis OR cdte OR capacitor OR supercapacitor OR ultracapacitor OR flywheel OR lithium ion OR proton exchange membrane OR membrane electrode assembly OR energy storage OR wind OR water treatment OR air treatment OR energy conservation OR environmental remediation OR biofuel) AND TS = (environmental remed*)

- **Energy & Environment - Sustainable and bio-based materials**: TS = (fuel cell OR battery OR solar OR photovoltaic OR CIG OR cis OR cdte OR capacitor OR supercapacitor OR ultracapacitor OR flywheel OR lithium ion OR proton exchange membrane OR membrane electrode assembly OR energy storage OR wind OR water treatment OR air treatment OR energy conservation OR environmental remediation OR biofuel) AND TS = (sustainable mat* OR biopolymer* OR biomat*)

- **Energy & Environment - Battery/energy storage**: TS = (fuel cell OR battery OR solar OR photovoltaic OR CIG OR cis OR cdte OR capacitor OR supercapacitor OR ultracapacitor OR flywheel OR lithium ion OR proton exchange membrane OR membrane electrode assembly OR energy storage OR wind OR water treatment OR air treatment OR energy conservation OR environmental remediation OR biofuel) AND TS = (batter* OR energy storage OR fuel cell* OR capacitor* OR supercap*)

- **Energy & Environment - Wind**: TS = (fuel cell OR battery OR solar OR photovoltaic OR CIG OR cis OR cdte OR capacitor OR supercapacitor OR ultracapacitor OR flywheel OR lithium ion OR proton exchange membrane OR membrane electrode assembly OR energy storage OR wind

OR water treatment OR air treatment OR energy conservation OR environmental remediation OR biofuel) AND TS = (wind OR anti-ic*)

- **Energy & Environment - Photovoltaics**: TS = (fuel cell OR battery OR solar OR photovoltaic OR CIG OR cis OR cdte OR capacitor OR supercapacitor OR ultracapacitor OR flywheel OR lithium ion OR proton exchange membrane OR membrane electrode assembly OR energy storage OR wind OR water treatment OR air treatment OR energy conservation OR environmental remediation OR biofuel) AND TS = (photovolt* OR solar OR building-integrat* photovolt* OR invert* OR BIPV)

- **Energy & Environment - Water treatment**: TS = (fuel cell OR battery OR solar OR photovoltaic OR CIG OR cis OR cdte OR capacitor OR supercapacitor OR ultracapacitor OR flywheel OR lithium ion OR proton exchange membrane OR membrane electrode assembly OR energy storage OR wind OR water treatment OR air treatment OR energy conservation OR environmental remediation OR biofuel) AND TS = (water treat* OR water filt*)

- **Energy & Environment - Air treatment**: TS = (fuel cell OR battery OR solar OR photovoltaic OR CIG OR cis OR cdte OR capacitor OR supercapacitor OR ultracapacitor OR flywheel OR lithium ion OR proton exchange membrane OR membrane electrode assembly OR energy storage OR wind OR water treatment OR air treatment OR energy conservation OR environmental remediation OR biofuel) AND TS = (air filt* OR air treat* OR smog OR air pollution)

- **Energy & Environment - Fuel cells**: TS = (fuel cell OR battery OR solar OR photovoltaic OR CIG OR cis OR cdte OR capacitor OR supercapacitor OR ultracapacitor OR flywheel OR lithium ion OR proton exchange membrane OR membrane electrode assembly OR energy storage OR wind OR water treatment OR air treatment OR energy conservation OR environmental remediation OR biofuel) AND TS = (fuel cell*)

- **Energy & Environment - Waste**: TS = (fuel cell OR battery OR solar OR photovoltaic OR CIG OR cis OR cdte OR capacitor OR supercapacitor OR ultracapacitor OR flywheel OR lithium ion OR proton exchange membrane OR membrane electrode assembly OR energy storage OR wind OR water treatment OR air treatment OR energy conservation OR environmental remediation OR biofuel) AND TS = (waste)

- **Energy & Environment - Energy conservation**: TS = (fuel cell OR battery OR solar OR photovoltaic OR CIG OR cis OR cdte OR capacitor OR supercapacitor OR ultracapacitor OR flywheel OR lithium ion OR proton exchange membrane OR membrane electrode assembly OR energy storage OR wind OR water treatment OR air treatment OR energy conservation OR environmental remediation OR biofuel) AND TS = (conservation OR efficiency OR insulat*)

- **Manufacturing - Anti-wear coatings:** TS = (anti-wear coating OR electrical infrastructure OR antimicrobial coat* OR catalyst OR antifouling coat* OR anticorrosion coat* OR anti-fouling coat* OR anti-corrosion coat* OR sensor OR anti-adhesion coat* OR lubricant OR insulation) AND TS = (anti-wear OR antiwear OR wear-resist*)

- **Manufacturing - Electrical infrastructure:** TS = (anti-wear coating OR electrical infrastructure OR antimicrobial coat* OR catalyst OR antifouling coat* OR anticorrosion coat* OR anti-fouling coat* OR anti-corrosion coat* OR sensor OR anti-adhesion coat* OR lubricant OR insulation) AND TS = (electric*)

- **Manufacturing - Antimicrobial materials:** TS = (anti-wear coating OR electrical infrastructure OR antimicrobial coat* OR catalyst OR antifouling coat* OR anticorrosion coat* OR anti-fouling coat* OR anti-corrosion coat* OR sensor OR anti-adhesion coat* OR lubricant OR insulation) AND TS = (antimicrob* OR antibact* OR antifung*)

- **Manufacturing - Processing aids:** TS = (anti-wear coating OR electrical infrastructure OR antimicrobial coat* OR catalyst OR antifouling coat* OR anticorrosion coat* OR anti-fouling coat* OR anti-corrosion coat* OR sensor OR anti-adhesion coat* OR lubricant OR insulation) AND TS = (improv*) AND TS = (dispers* OR flow* OR foam*)

- **Manufacturing - Catalysts:** TS = (anti-wear coating OR electrical infrastructure OR antimicrobial coat* OR catalyst OR antifouling coat* OR anticorrosion coat* OR anti-fouling coat* OR anti-corrosion coat* OR sensor OR anti-adhesion coat* OR lubricant OR insulation) AND TS = (cataly*)

- **Manufacturing - Antifouling and anticorrosion coatings:** TS = (anti-wear coating OR electrical infrastructure OR antimicrobial coat* OR catalyst OR antifouling coat* OR anticorrosion coat* OR anti-fouling coat* OR anti-corrosion coat* OR sensor OR anti-adhesion coat* OR lubricant OR insulation) AND TS = (antifoul* OR anticorr* OR anti-foul OR anti-corr*)

- **Manufacturing - Filtration:** TS = (anti-wear coating OR electrical infrastructure OR antimicrobial coat* OR catalyst OR antifouling coat* OR anticorrosion coat* OR anti-fouling coat* OR anti-corrosion coat* OR sensor OR anti-adhesion coat* OR lubricant OR insulation) AND TS = (filter* OR filtra* OR membra*)

- **Manufacturing - Sensors to monitor water and air:** TS = (anti-wear coating OR electrical infrastructure OR antimicrobial coat* OR catalyst OR antifouling coat* OR anticorrosion coat* OR anti-fouling coat* OR anti-corrosion coat* OR sensor OR anti-adhesion coat* OR lubricant OR insulation) AND TS = (sens* OR monitor*) AND TS = (water OR air)

- **Manufacturing - Anti-adhesion coatings/lubricants:** TS = (anti-wear coating OR electrical infrastructure OR antimicrobial coat* OR catalyst OR antifouling coat* OR anticorrosion coat* OR anti-fouling coat* OR anti-corrosion coat* OR sensor OR anti-adhesion coat* OR lubricant OR insulation) AND TS = (lubric* OR anti-adhes* OR antiadhes* OR antistick* OR anti-stick* OR anti-ic* OR hydrophob*)

- **Manufacturing - Manufacturing - Insulation**: TS = (anti-wear coating OR electrical infrastructure OR antimicrobial coat* OR catalyst OR antifouling coat* OR anticorrosion coat*

OR anti-fouling coat* OR anti-corrosion coat* OR sensor OR anti-adhesion coat* OR lubricant OR insulation) AND TS = (insulat* OR aerogel*)

- **Medical and Pharma - Tissue scaffolds:** TS = (Pharma* OR food OR cosmetic OR drug OR health OR preservative OR active molecule OR drug OR biomolecule OR protein OR peptide OR nucleic acid OR cell OR fertiliser OR pesticide OR microbicide OR insecticide OR herbicide OR antimicrobial OR vitamin OR mineral OR nutrient OR flavor OR scent OR moisturiser OR humectants OR targeted delivery OR drug delivery) AND TS = (tissue scaffold* OR matrix)

- **Medical and Pharma - Coatings:** TS = (Pharma* OR food OR cosmetic OR drug OR health OR preservative OR active molecule OR drug OR biomolecule OR protein OR peptide OR nucleic acid OR cell OR fertiliser OR pesticide OR microbicide OR insecticide OR herbicide OR antimicrobial OR vitamin OR mineral OR nutrient OR flavor OR scent OR moisturiser OR humectants OR targeted delivery OR drug delivery) AND TS = (coat*)

- **Medical and Pharma - Wound care:** TS = (Pharma* OR food OR cosmetic OR drug OR health OR preservative OR active molecule OR drug OR biomolecule OR protein OR peptide OR nucleic acid OR cell OR fertiliser OR pesticide OR microbicide OR insecticide OR herbicide OR antimicrobial OR vitamin OR mineral OR nutrient OR flavor OR scent OR moisturiser OR humectants OR targeted delivery OR drug delivery) AND TS = (self-assembl* OR self assembl* OR wound)

- **Medical and Pharma - Imaging (in vivo diagnostics):** TS = (Pharma* OR food OR cosmetic OR drug OR health OR preservative OR active molecule OR drug OR biomolecule OR protein OR peptide OR nucleic acid OR cell OR fertiliser OR pesticide OR microbicide OR insecticide OR herbicide OR antimicrobial OR vitamin OR mineral OR nutrient OR flavor OR scent OR moisturiser OR humectants OR targeted delivery OR drug delivery) AND TS = (contrast OR tag OR fluoresc* OR tracer* OR MRI OR PET)

- **Medical and Pharma - In vitro diagnostics:** TS = (Pharma* OR food OR cosmetic OR drug OR health OR preservative OR active molecule OR drug OR biomolecule OR protein OR peptide OR nucleic acid OR cell OR fertiliser OR pesticide OR microbicide OR insecticide OR herbicide OR antimicrobial OR vitamin OR mineral OR nutrient OR flavor OR scent OR moisturiser OR humectants OR targeted delivery OR drug delivery) AND TS = (sensor* OR lab-on-a-chip)

- **Medical and Pharma - Controlled release:** TS = (Pharma* OR food OR cosmetic OR drug OR health OR preservative OR active molecule OR drug OR biomolecule OR protein OR peptide OR nucleic acid OR cell OR fertiliser OR pesticide OR microbicide OR insecticide OR herbicide OR antimicrobial OR vitamin OR mineral OR nutrient OR flavor OR scent OR moisturiser OR humectants OR targeted delivery OR drug delivery) AND TS = (control* release*)

- **Medical and Pharma - Targeted drug delivery:** TS = (Pharma* OR food OR cosmetic OR drug OR health OR preservative OR active molecule OR drug OR biomolecule OR protein OR peptide OR nucleic acid OR cell OR fertiliser OR pesticide OR microbicide OR insecticide OR herbicide OR antimicrobial OR vitamin OR mineral OR nutrient OR flavor OR scent OR moisturiser OR humectants OR targeted delivery OR drug delivery) AND TS = (target* AND deliver*)

- **Medical and Pharma - Medical device drug delivery:** TS = (Pharma* OR food OR cosmetic OR drug OR health OR preservative OR active molecule OR drug OR biomolecule OR protein OR peptide OR nucleic acid OR cell OR fertiliser OR pesticide OR microbicide OR insecticide OR herbicide OR antimicrobial OR vitamin OR mineral OR nutrient OR flavor OR scent OR moisturiser OR humectants OR targeted delivery OR drug delivery) AND TS = (drug device OR drug-device OR elut*)

- **Medical and Pharma - Medical device packaging:** TS = (Pharma* OR food OR cosmetic OR drug OR health OR preservative OR active molecule OR drug OR biomolecule OR protein OR peptide OR nucleic acid OR cell OR fertiliser OR pesticide OR microbicide OR insecticide OR herbicide OR antimicrobial OR vitamin OR mineral OR nutrient OR flavor OR scent OR moisturiser OR humectants OR targeted delivery OR drug delivery) AND TS = (barrier OR packag*)

- **Medical and Pharma - Cosmeceuticals and personal care:** TS = (Pharma* OR food OR cosmetic OR drug OR health OR preservative OR active molecule OR drug OR biomolecule OR protein OR peptide OR nucleic acid OR cell OR fertiliser OR pesticide OR microbicide OR insecticide OR herbicide OR antimicrobial OR vitamin OR mineral OR nutrient OR flavor OR scent OR moisturiser OR humectants OR targeted delivery OR drug delivery) AND TS = (micell* OR nanoencap* OR cosmeceut*)

- **Oil & Gas - Sensors (surface and downhole):** TS = (oil recovery OR oil drilling OR oil exploration OR gas exploration) AND TS = (sens*)

- **Oil & Gas - Electronics packaging:** TS = (oil recovery OR oil drilling OR oil exploration OR gas exploration) AND TS = (packag* OR solder* OR bond*)

- **Oil & Gas - Downhole power:** TS = (oil recovery OR oil drilling OR oil exploration OR gas exploration) AND TS = (downhole power OR remote power OR wireless power)

- **Oil & Gas - Perforators and fracturing materials:** TS = (oil recovery OR oil drilling OR oil exploration OR gas exploration) AND TS = (perforat* OR fractur*)

- **Oil & Gas - Proppants and binders:** TS = (oil recovery OR oil drilling OR oil exploration OR gas exploration) AND TS = (proppant* OR binder*)

- **Oil & Gas - Advanced structural materials :** TS = (oil recovery OR oil drilling OR oil exploration OR gas exploration) AND TS = (structur* material*)

- **Oil & Gas - Advanced coatings:** TS = (oil recovery OR oil drilling OR oil exploration OR gas exploration) AND TS = (coat*)

- **Oil & Gas - Catalysts:** TS = (oil recovery OR oil drilling OR oil exploration OR gas exploration) AND TS = (cataly*)

- **Oil & Gas - Separation and recovery:** TS = (oil recovery OR oil drilling OR oil exploration OR gas exploration) AND TS = (EOR OR separat* OR recover* OR filter* OR filtr*)

- **Oil & Gas - Water management:** TS = (oil recovery OR oil drilling OR oil exploration OR gas exploration) AND TS = (water) AND TS = (filtra* OR filter* OR membra* or manag* OR treat*)

Methodology

Publications, citations and patent data was collected for 2006, 2007, and 2008, for all 80 target applications for all 14 countries

Discarding applications with low global activity (values for > 55 percent of the cells = 0) eliminated:

- All applications under **Oil & Gas** and **Construction**
- **Aerospace**: Antimicrobial materials
- **Automotive**: Wear-resistant coatings, aesthetic coatings, tribological coatings, anti-static materials
- **Energy & Environment**: Environmental remediation, sustainable and bio-based materials, wind, waste
- **Manufacturing**: Anti-wear coatings, antifouling and anti-corrosion coatings

Values for comparison parameters (output, quality, commercial emphasis) was calculated for **49 remaining applications**

For each application, countries were sorted from highest to lowest and rated on a 1-14 scale (with highest = 14 and lowest = 1)

Analysis of quality of research produced relative to output, as well as commercial emphasis relative to output was undertaken

Appendix G

Key Findings from the primary research effort

Key Findings from the Primary Research Effort

Site visits and interviews

The key findings from the site visits and interviews (including Northern Ireland) are summarised below (organised into general, academic and business depending on the interviewee). Caution should be exercised as these are the expressed views of individuals based on their perceptions.

General findings

- Absence of translational element felt across the board but opinion divided on what that element could be
- Increased global competition in nanotechnology, with several countries making significant investments needs to be taken seriously by Ireland
- There has been substantial investment in research but not enough focus on commercialisation until relatively recently
- There is broad consensus that Ireland will need to make choices and focus limited resources
- Retention of FDI seen as critical short-term goal but long-term emphasis should be on promoting indigenous enterprise
- If Ireland decides to choose a (niche) sector investment should be comprehensive and competitive on a global scale

Academic findings

- Academia is expected to reach a certain stage of scale before industry will step in to partner; the government needs to finance the gap
- Lack of risk culture which would entice top PIs to risk their academic career in order to pursue commercial opportunities
- Although recruiting post-docs is not a problem, appropriately skilled technical staff is a different story and government has been very reluctant to fund this
- Several structural obstacles still in commercialisation: lack of speed (patent process), bureaucracy (funding process) and lack of qualified technical personnel
- EU and Framework Programme funding generated mixed opinions: desirable as alternative funding source to SFI but still cumbersome process with uncertain outcomes
- Need to develop more local companies, it is not expected that many MNCs will still be around in the not-so-distant future
- Ireland already has strong capabilities in ICT and bio so there should be more investment in the convergence area

Business findings

- Retaining MNCs is a critical aspect of any future Ireland Inc. strategy
- Academic bodies, even if industry sponsored, want to get published rather than commercialise
- MNCs can locate a new manufacturing facility anywhere in the world therefore Ireland needs to remain competitive
- A high level of highly-relevant R&D that MNCs cannot access elsewhere is required to keep them in Ireland
- Phasing of a nanofab facility might be necessary given limited resources but there should be a long-term vision and it's important to make a statement
- University spin-outs need to be made very easy so that university staff can take 3-4 years off to go try a start-up and see if it works without having to worry about having a job to come back to
- This is an opportunity to shift paradigm in the basic FDI pattern and create some meaningful strategic advantage
- Corporate horizons are two quarters long, especially in manufacturing environments, so nobody will produce proposals with ROI after 2-5 years
- Science is mobile, so if you don't make this kind of investment, science will migrate to other parts of the world
- Leadership is missing on the political front

Northern Ireland findings

- "Advanced materials" targeted at cleantech applications seen as a primary research area of the future
- There appears to be considerable industry-academia collaboration between researchers in NI and corporations and start-ups, in the UK and US
- Qualitatively, research topics in NI felt a lot more attuned to market realities than those in Ireland
- Commercialisation infrastructure, although poorly used, is well laid out; innovation studies undertaken by MATRIX are also very sound
- Industry-driven innovation communities, being proposed as part of the MATRIX exercise, promising but with significant execution challenges
- Cross-border collaboration in More Moore ICT and Advanced Materials for energy/environmental applications could be considered

Surveys

The key findings from the 2009 nanotechnology academic researcher survey (fielded by Forfás) are summarised below:

- The long-established focus of nanotechnology research (nanomaterials with specific sector concentrations in nanoelectronics, nanomedicine and medical devices) remains

- The share of fundamental research has decreased in the R&D mix; applied research and experimental development make up the bulk of Irish nanotechnology R&D activities
- A sound base of nanotechnology experience has been developed, with most PIs having at least 6 years relevant experience
- Irish researchers are open to academic collaboration and have demonstrated nanotechnology publication productivity on par with international norms
- Researchers mainly seek collaboration for sharing resources and obtaining funding; commercially-driven activity (e.g. patent filing) seems to play a minor role
- There has been a significant increase in the number of resources employed in nanotechnology research (estimated at ~40 percent since 2006)
- The broad ICT and nanobio sectors dominate commercialisation efforts; these sectors also represent the best prospects for commercialisation (a virtuous circle at work)
- Lack of funding, lack of ready channels for technology exploitation and lack of prototyping facilities seem to be the major barriers to commercialisation; a less than optimal patent filing process is a recurring favourite theme
- SFI continues to be the major source of funding for nanotechnology in Ireland
- More than 50 percent of PIs have received more than €500K in 2008; a sizable group (ca. 35 percent) received less than €300K

Appendix H

The following figures plot the quality of research and the commercial focus against the research output for each of the 49 market-application combinations that Ireland is active in. The findings below underpin the conclusions made in chapter 3.

Figure 20: Aerospace - Avionics

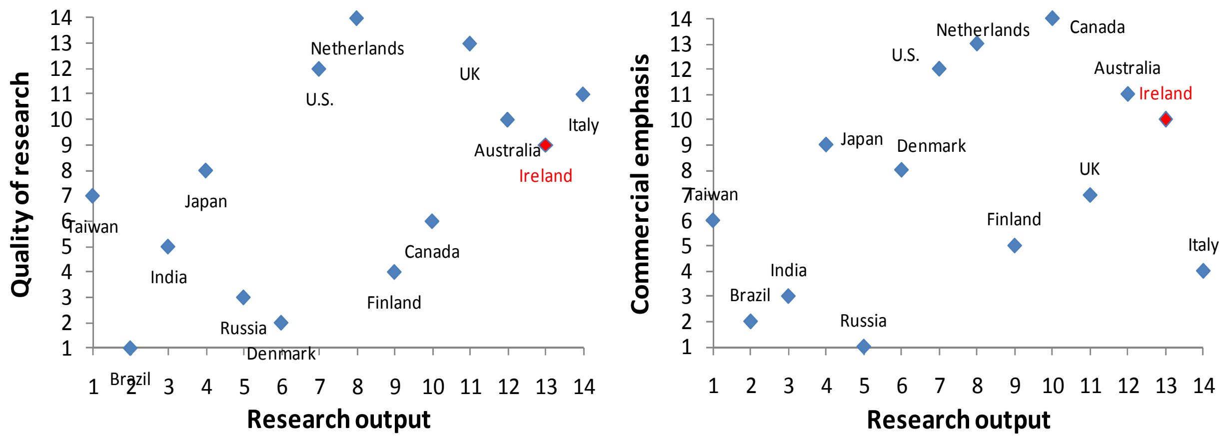


Figure 21: Aerospace - Structural Monitoring

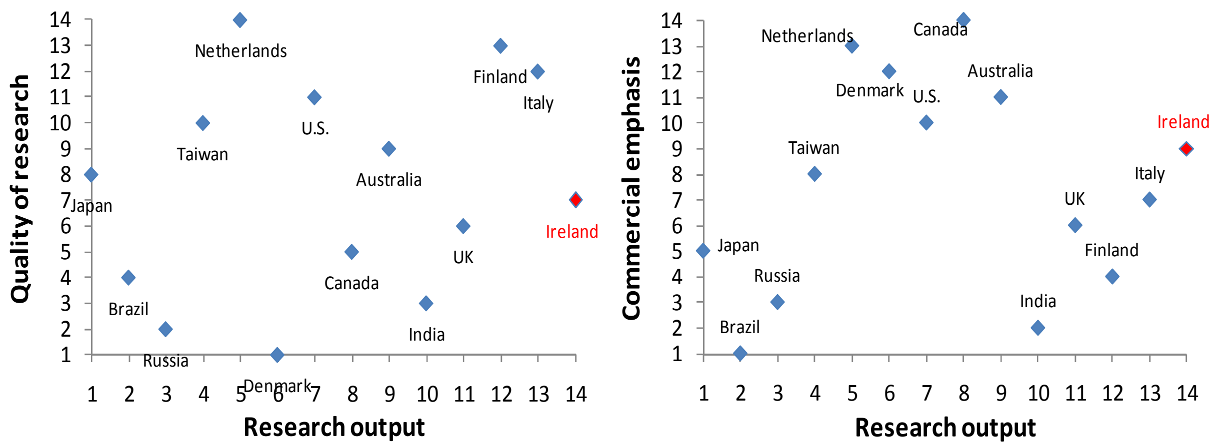


Figure 22: Aerospace - Self Healing Smart Materials

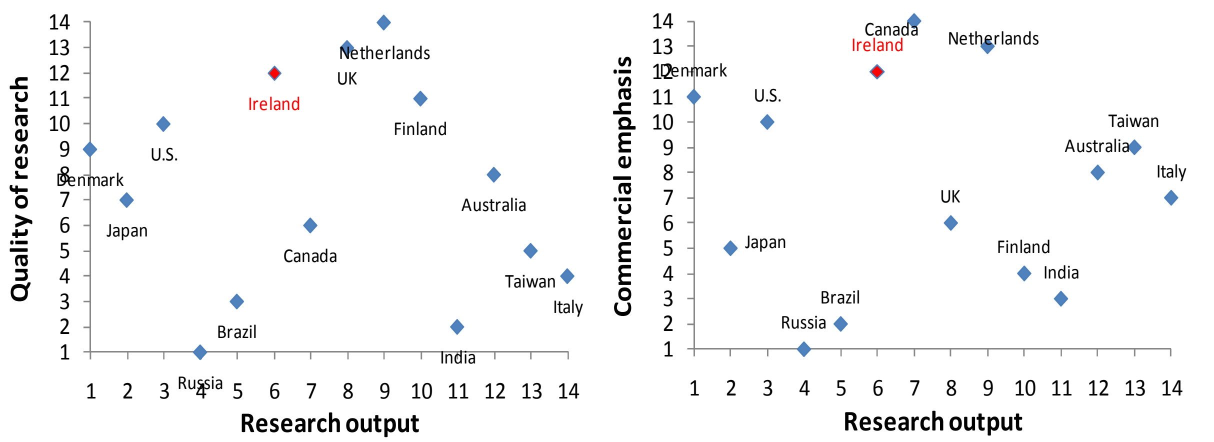


Figure 23: Aerospace - Structural Materials

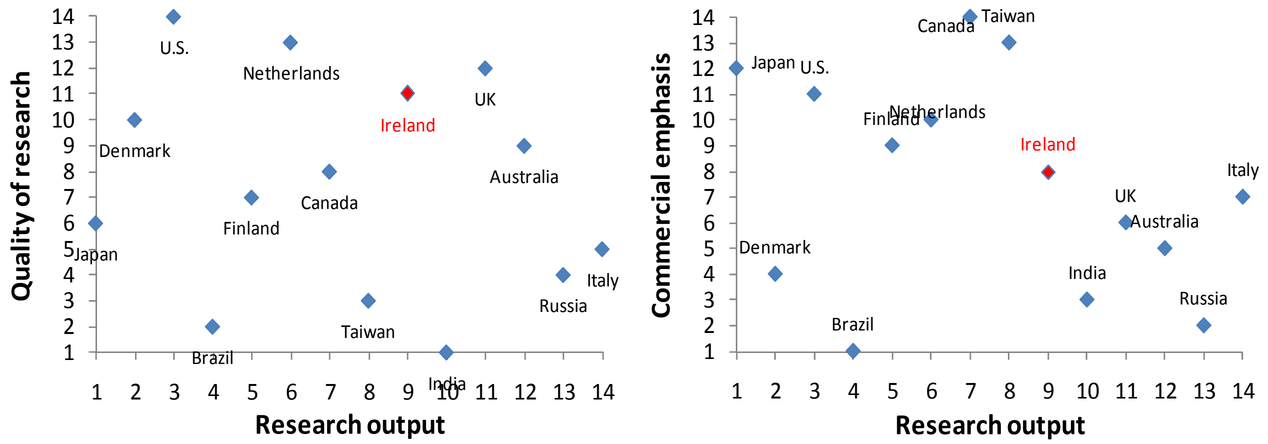


Figure 24: Aerospace - Flame Retardant Materials

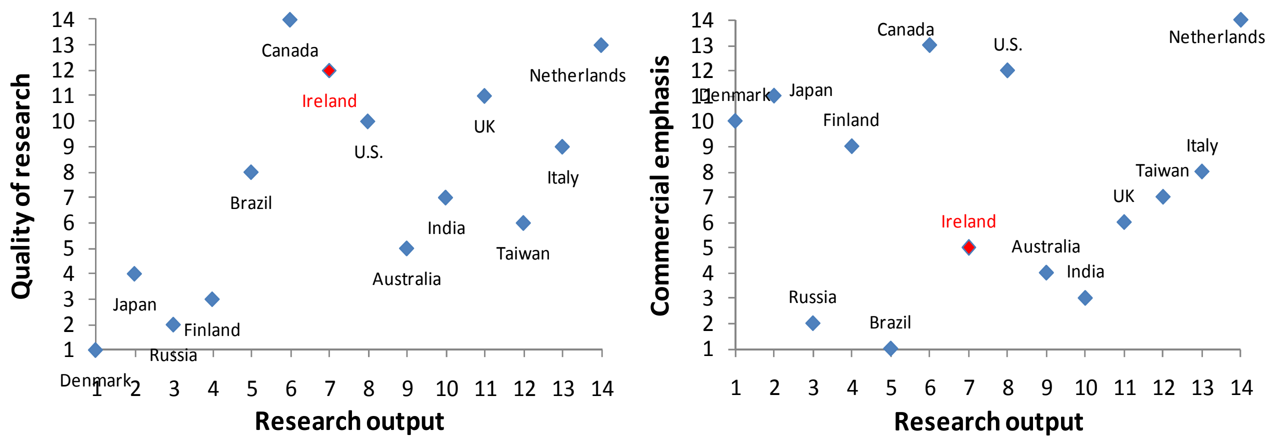


Figure 25: Aerospace - Conductive Materials

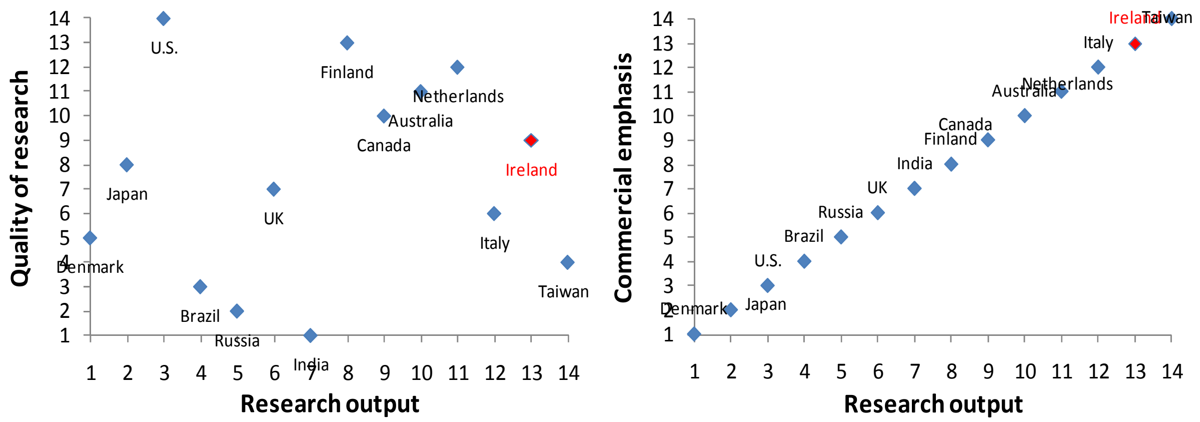


Figure 26: Aerospace - Anti-Icing Coatings

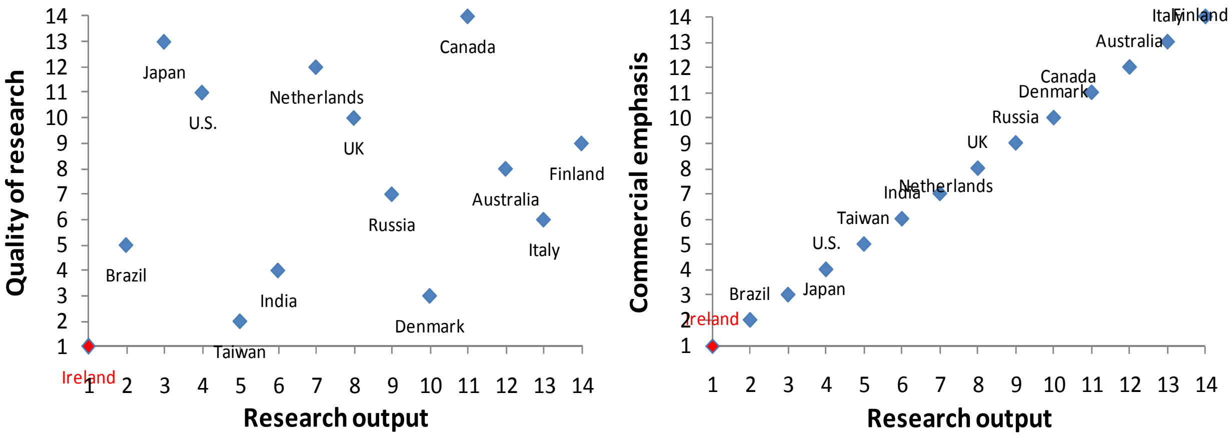


Figure 27: Aerospace - Electrical Infrastructure

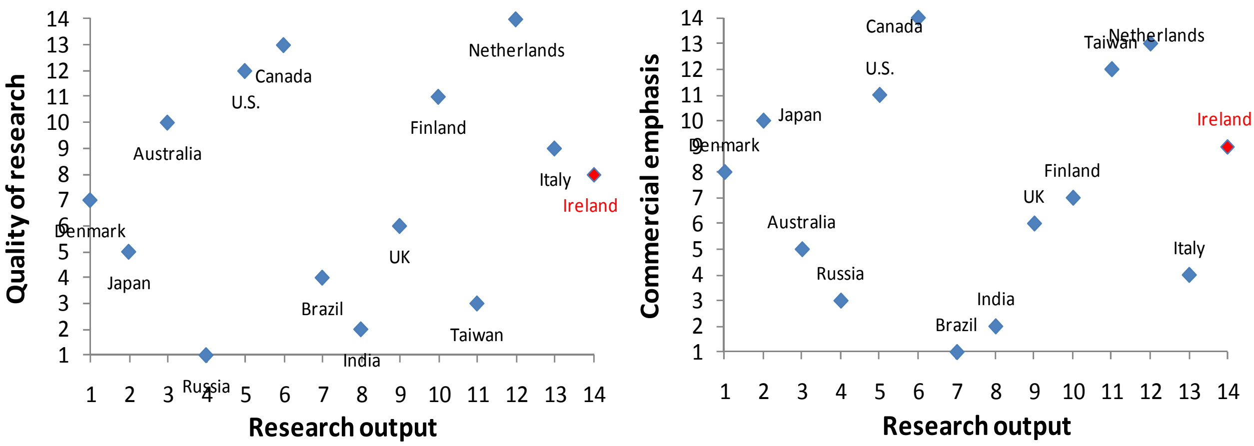


Figure 28: Aerospace - Wear-resistant Coatings

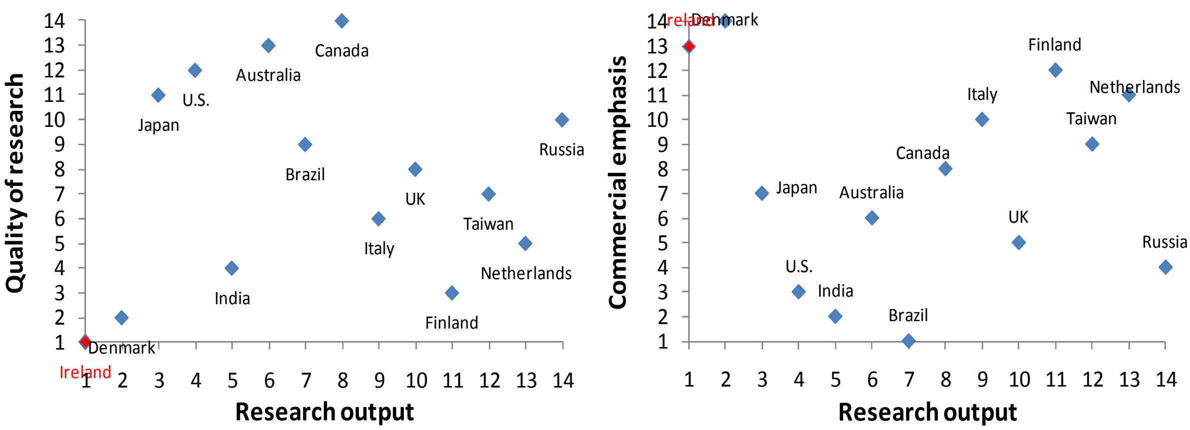


Figure 29: Automotive - Fuel-based Additives

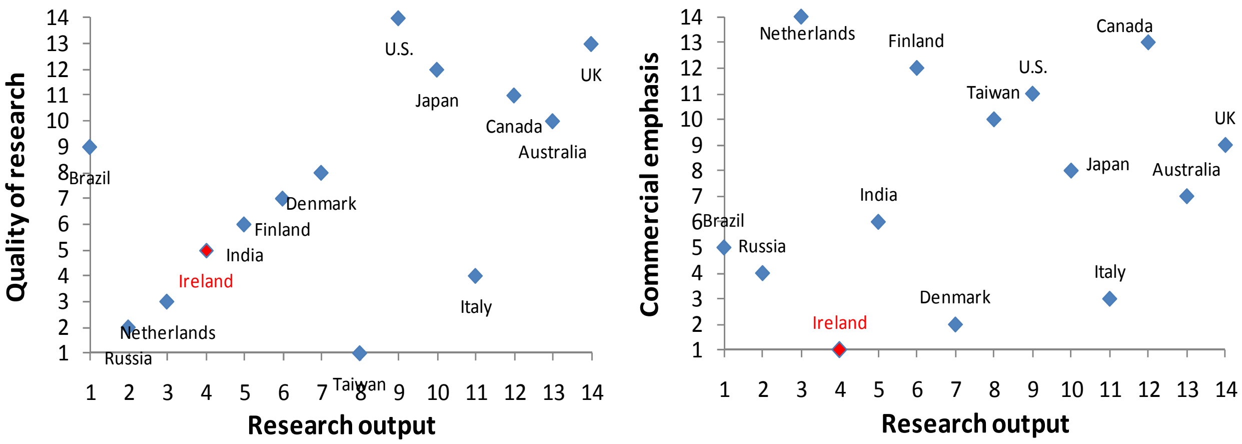


Figure 30: Automotive - Catalysts

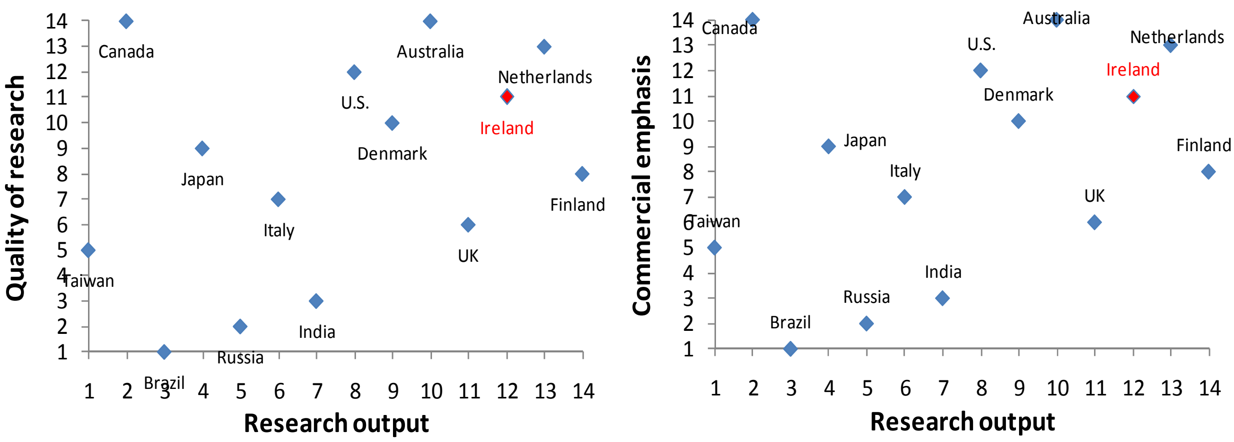


Figure 31: Automotive - Structural material

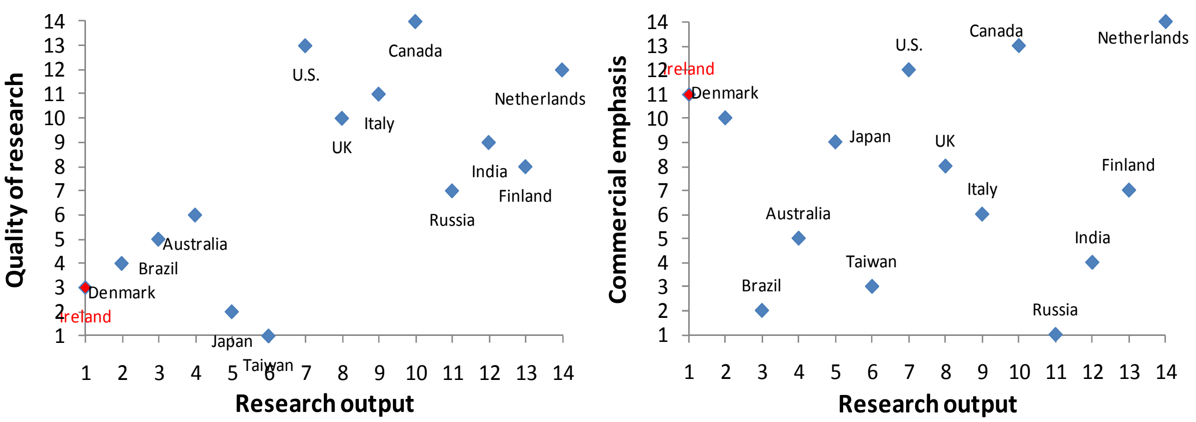


Figure 32: Automotive - Electronics

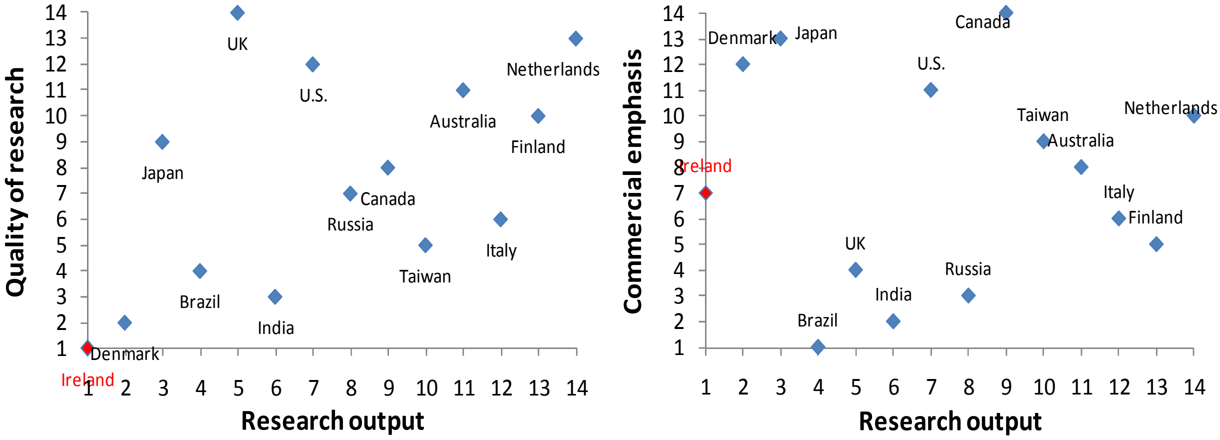


Figure 33: Aerospace - Lubricants

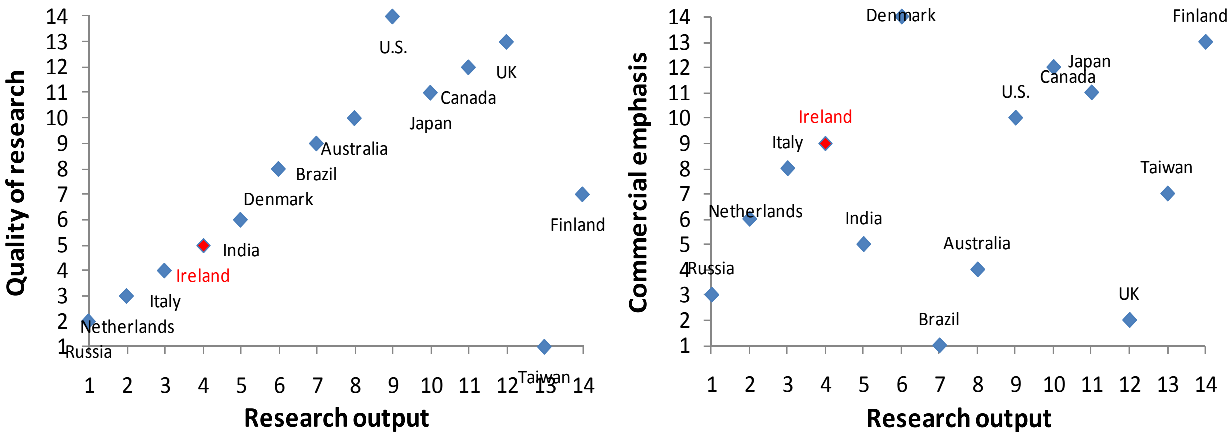


Figure 34: Aerospace - Battery/Energy Storage

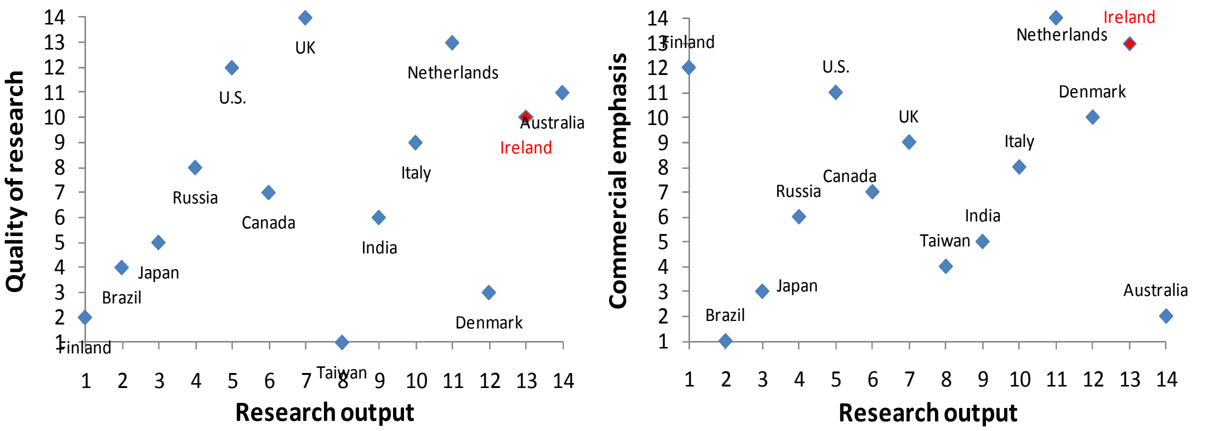


Figure 35: Electronics - Transparent Conductors

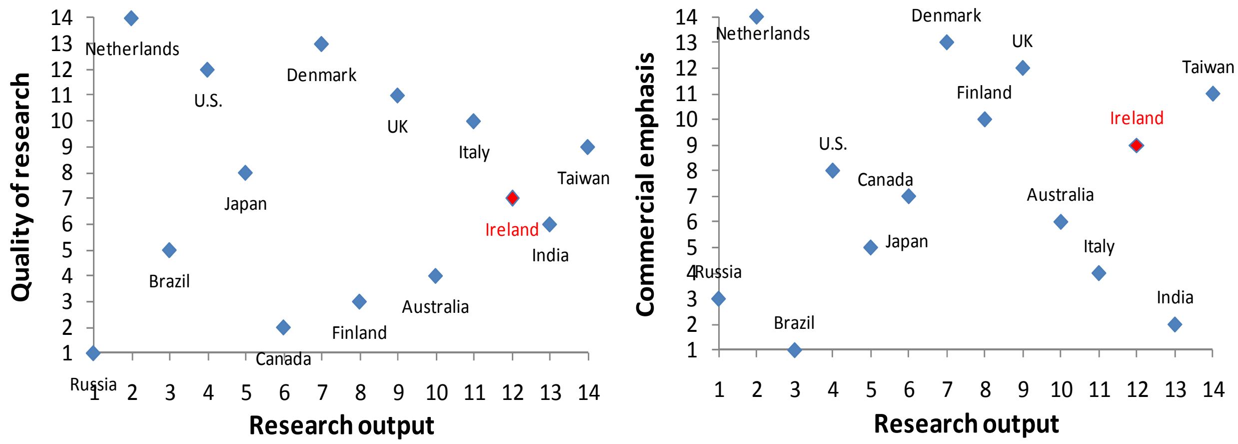


Figure 36: Electronics - Thermal Management

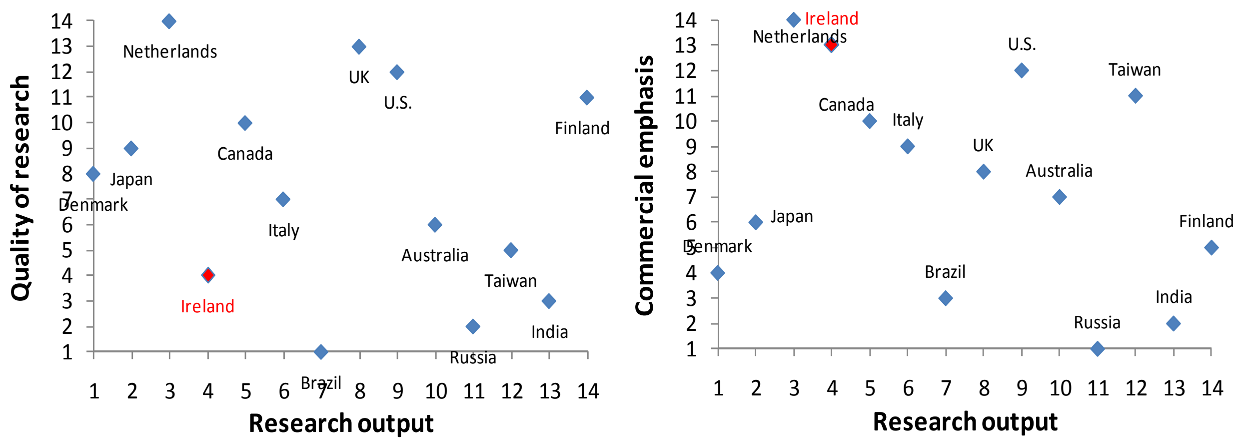


Figure 37: Electronics - Displays

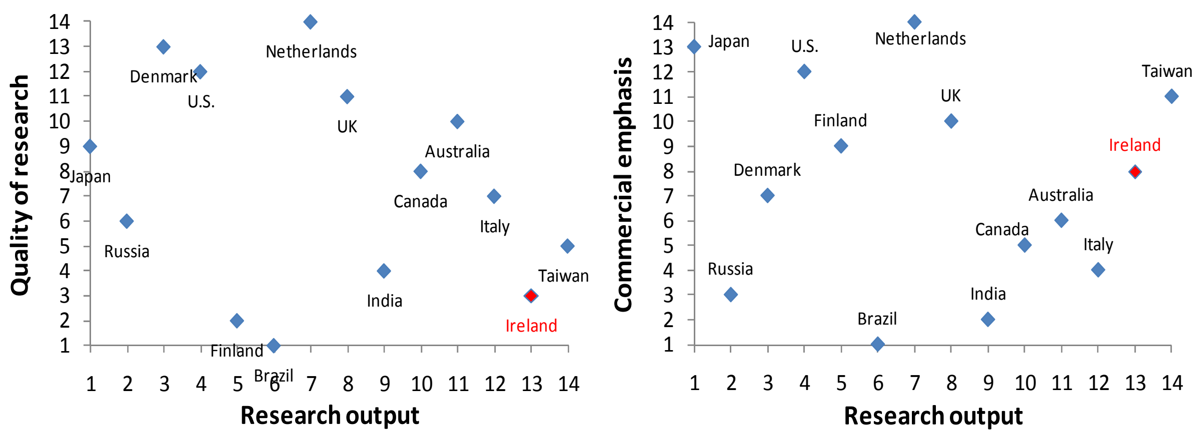


Figure 38: Electronics - Memory Technologies

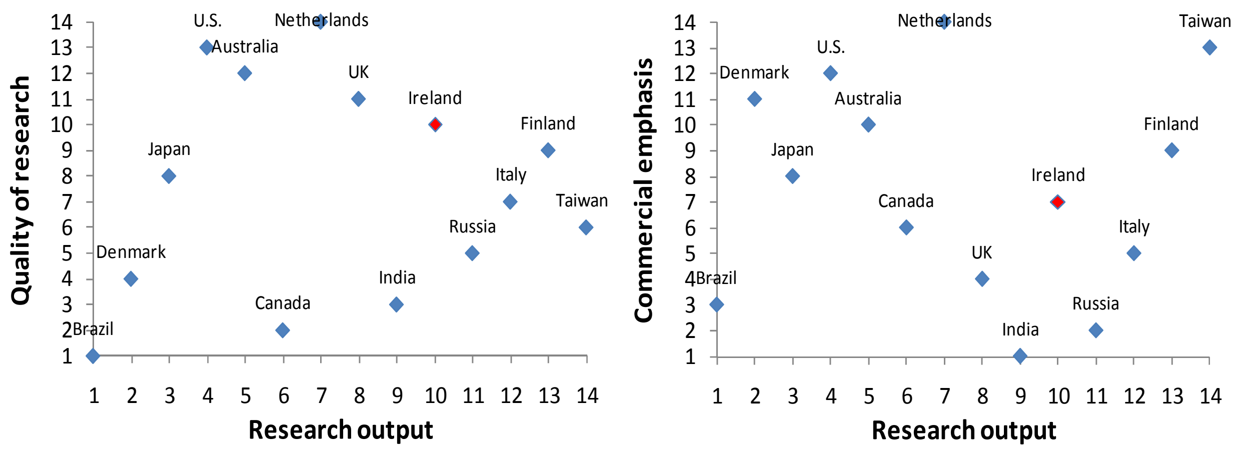


Figure 39: Electronics - Printed Electronics

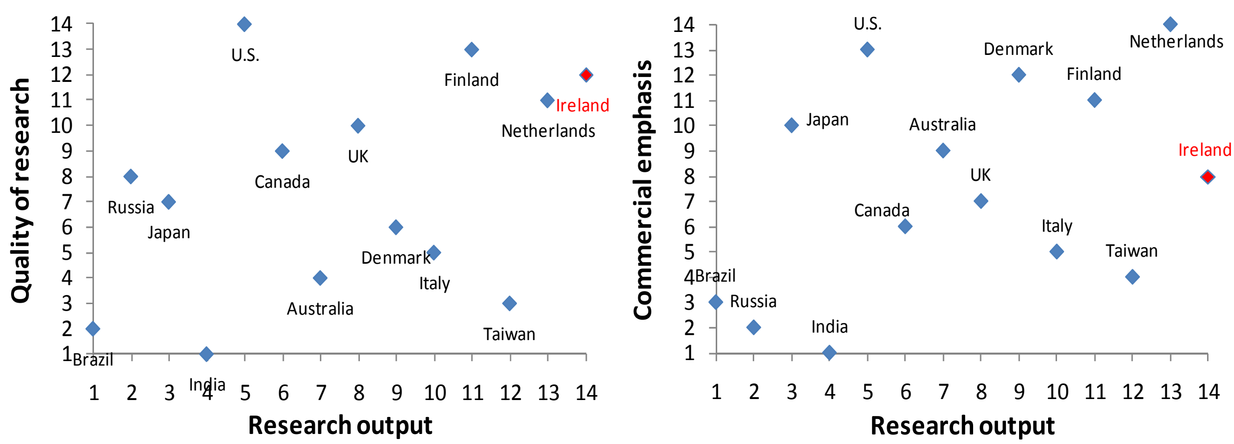


Figure 40: Electronics - LEDs and Optical Components

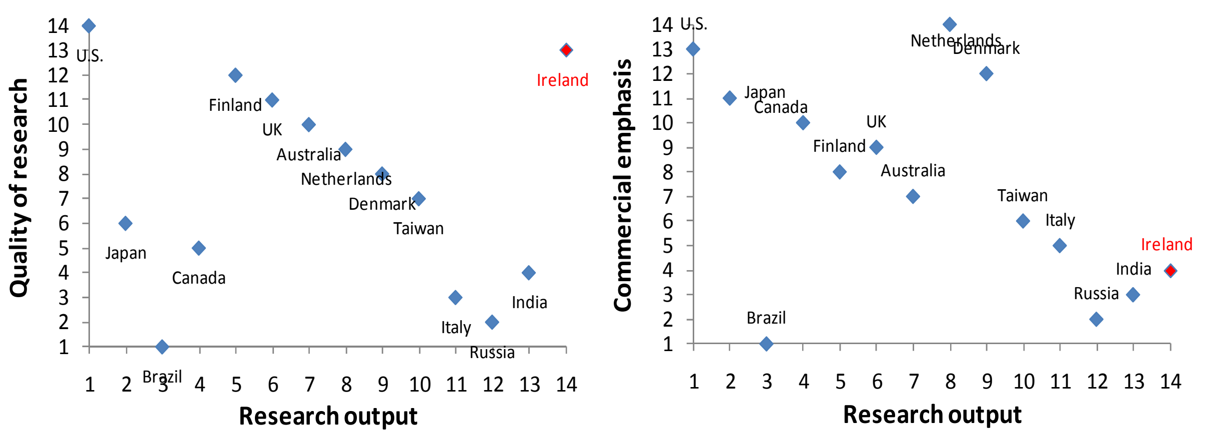


Figure 41: Electronics - Energy Storage

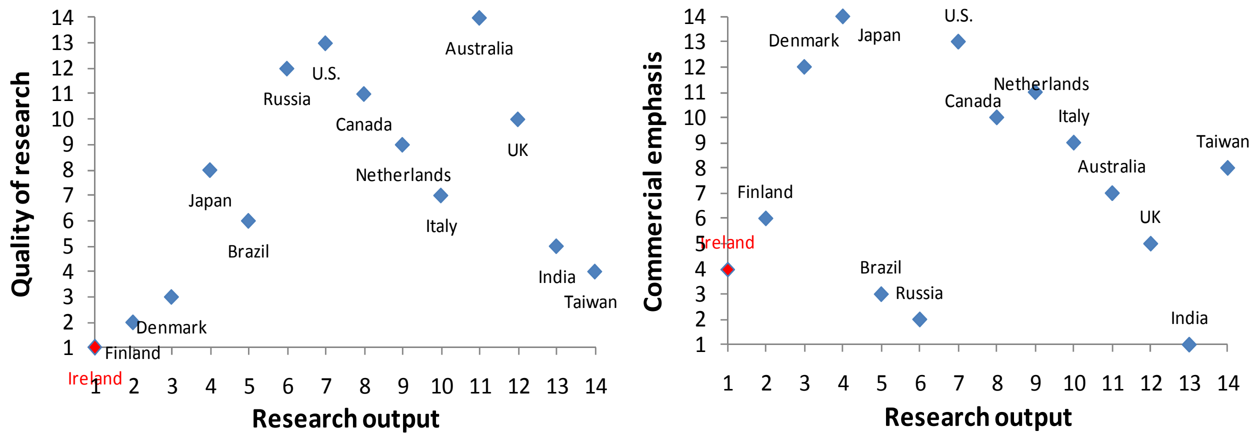


Figure 42: Electronics - Barrier Coatings

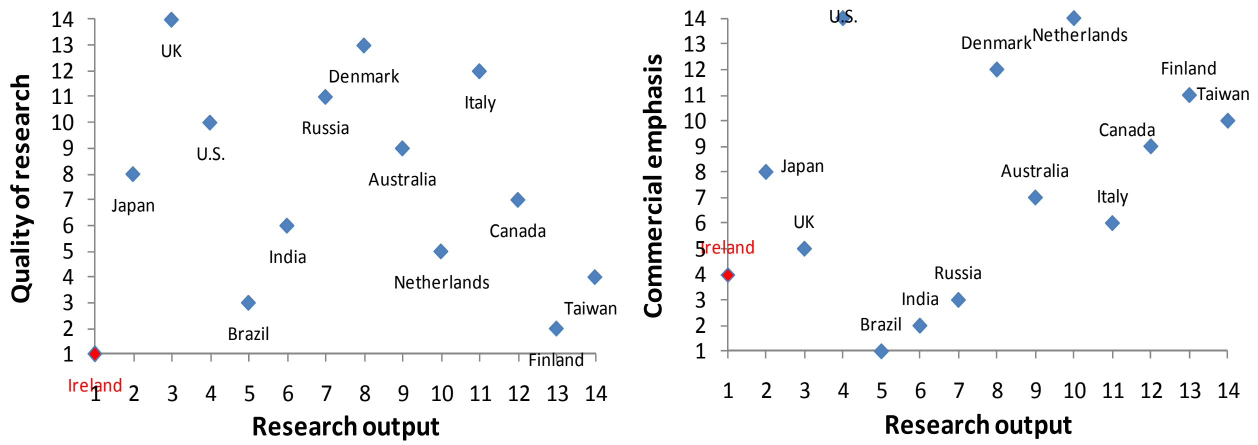


Figure 43: Electronics - Packaging

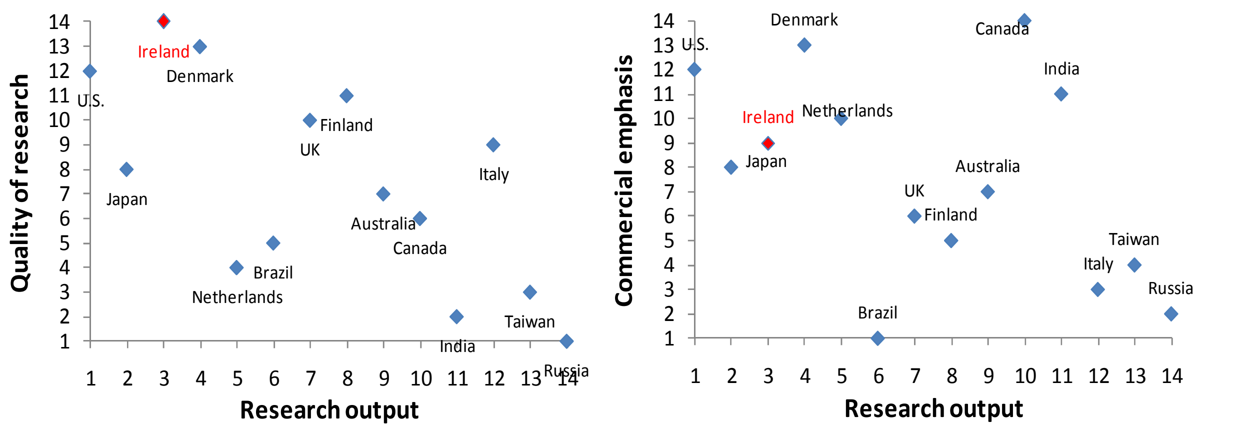


Figure 44: Electronics - Lithography and Tools

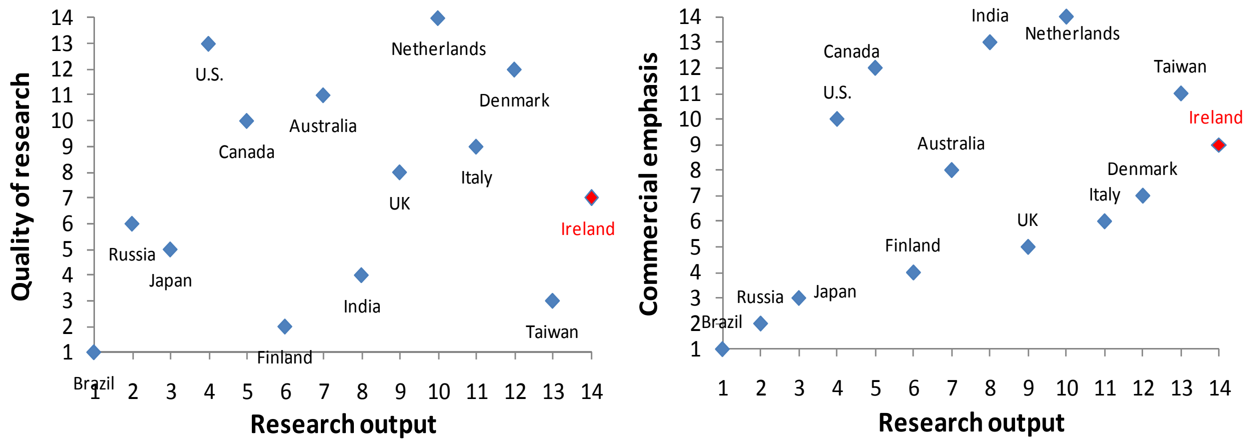


Figure 45: Energy and Environment - Energy Storage

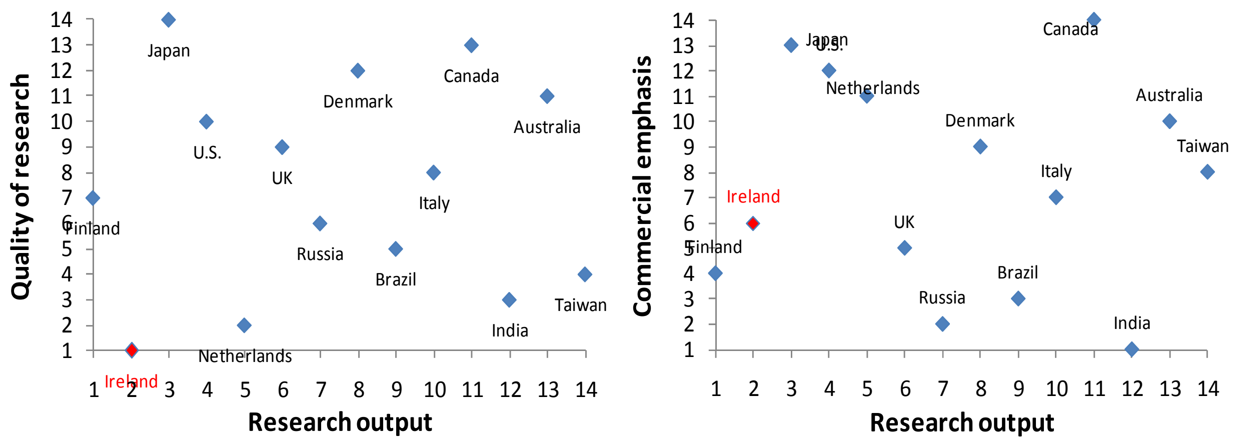


Figure 46: Energy and Environment - Photovoltaics

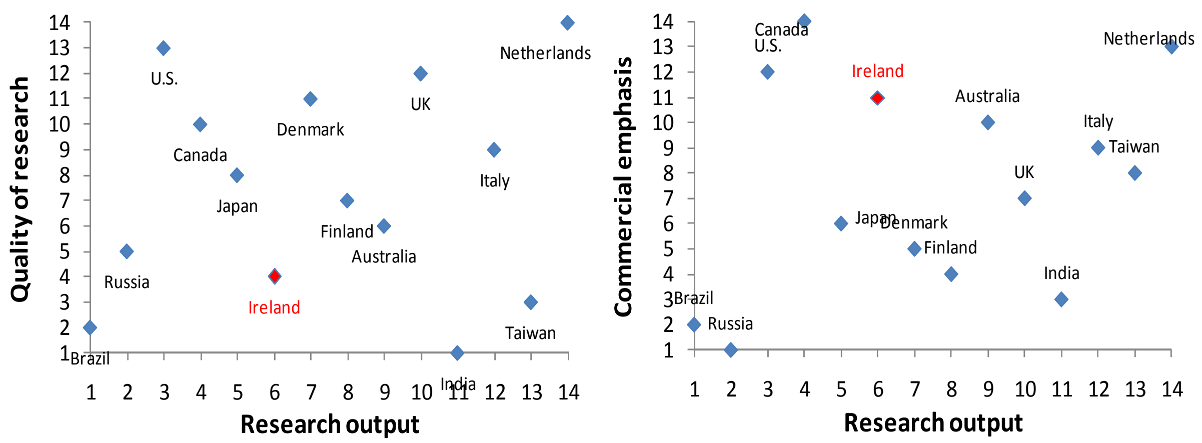


Figure 47: Energy and Environment - Water Treatment

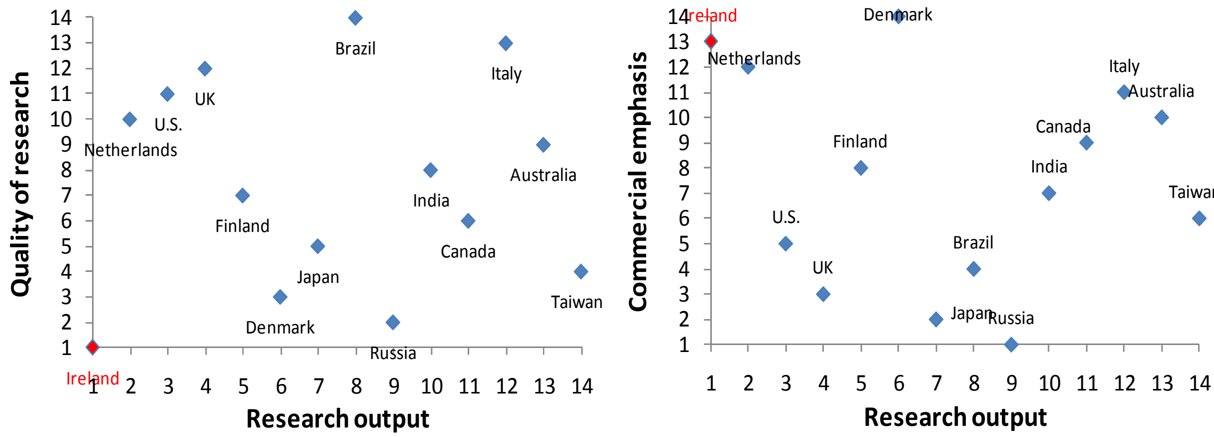


Figure 48: Energy and Environment - Air Treatment

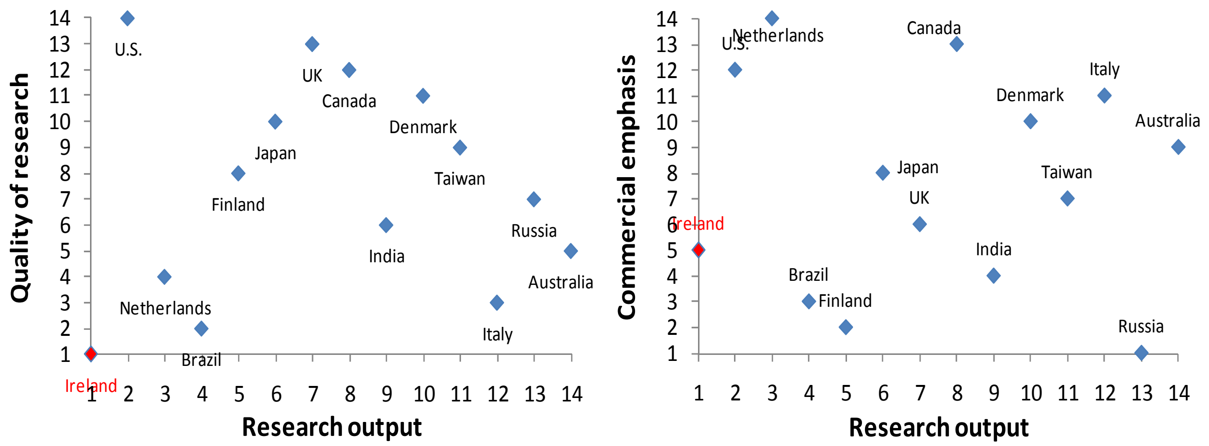


Figure 49: Energy and Environment - Fuel Cells

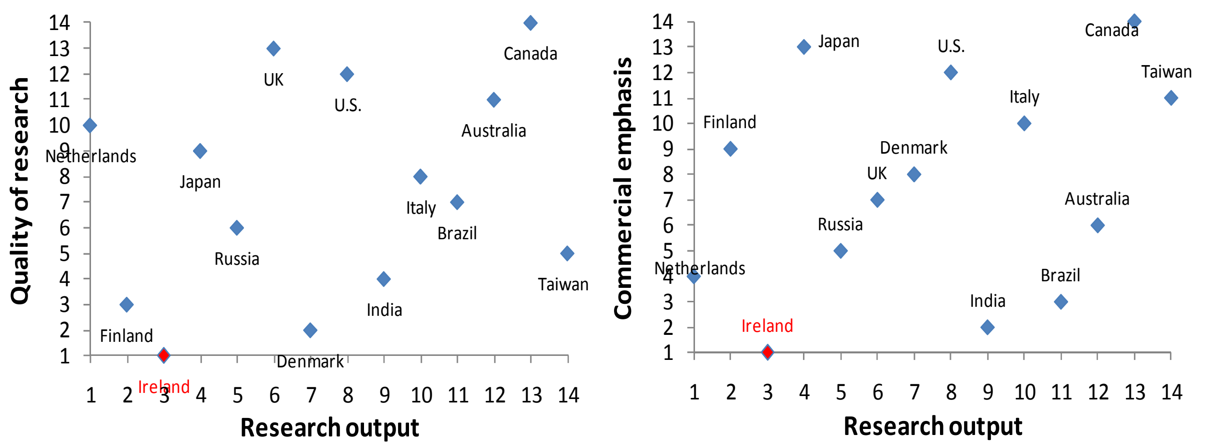


Figure 50: Energy and Environment - Energy Conservation

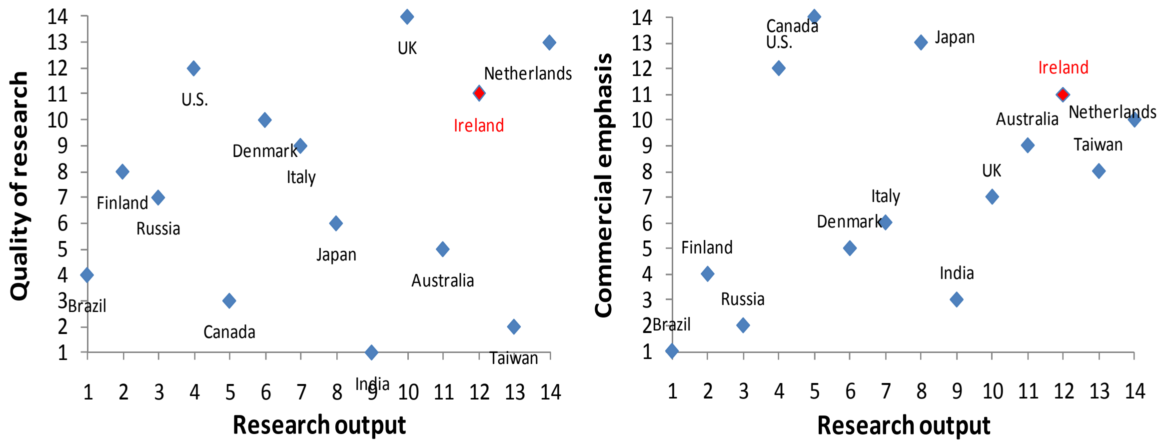


Figure 51: Manufacturing - Electrical Infrastructure

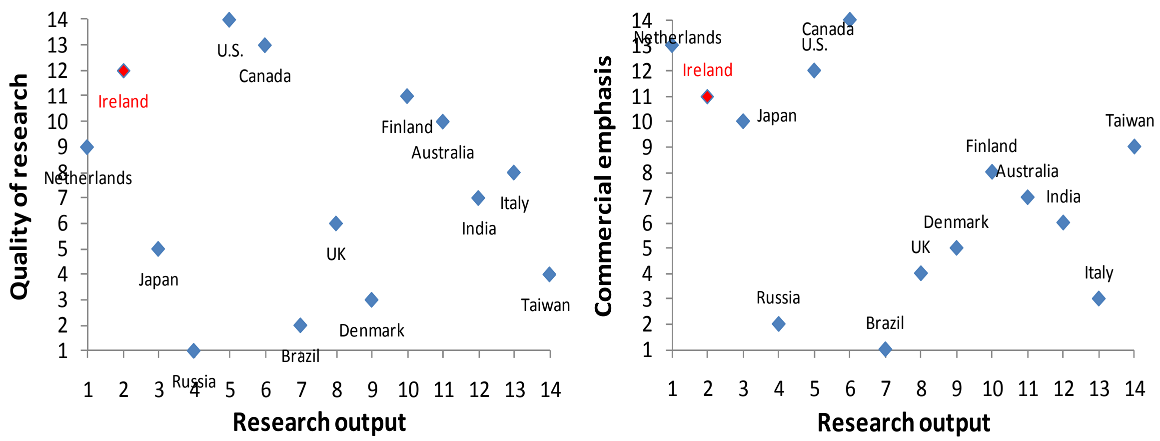


Figure 52: Manufacturing - Anti-microbial Coatings

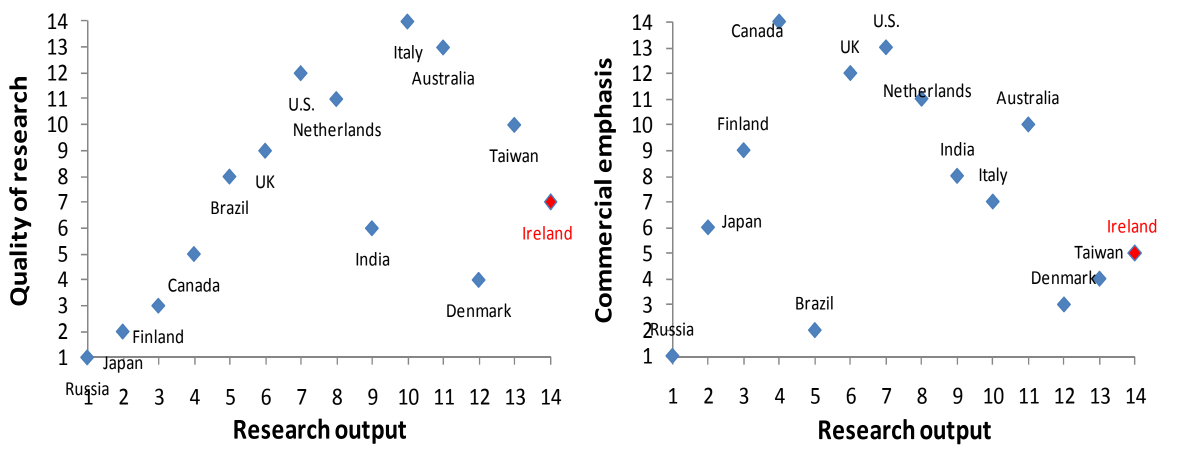


Figure 53: Manufacturing - Processing Aids

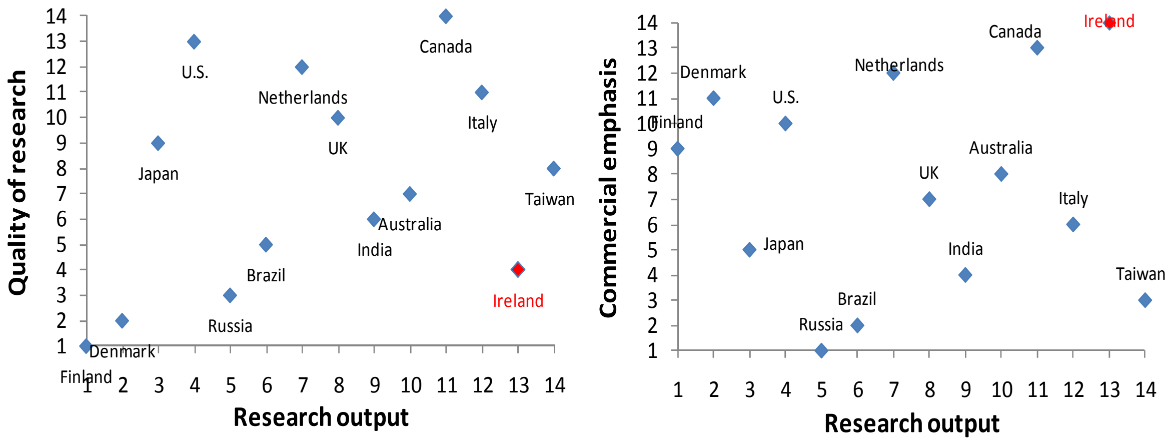


Figure 54: Manufacturing - Catalysts

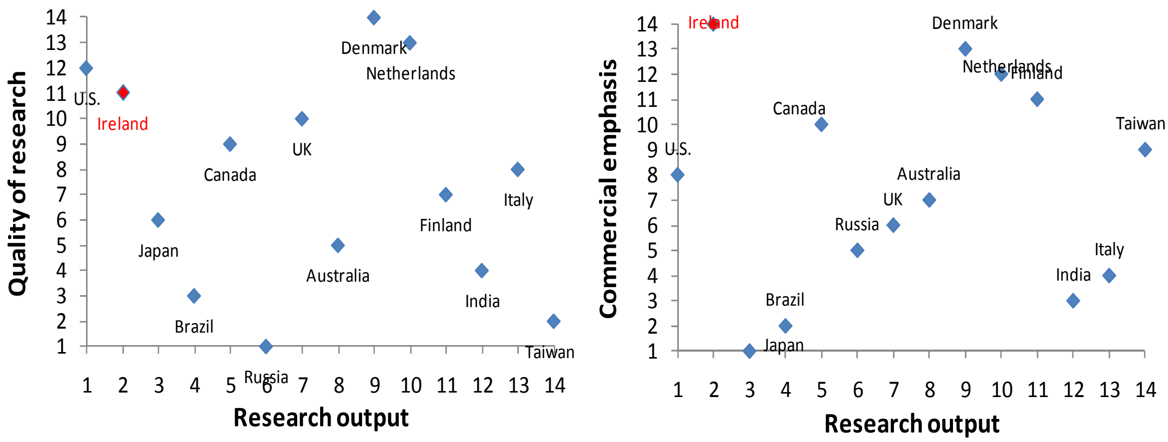


Figure 55: Manufacturing - Filtration

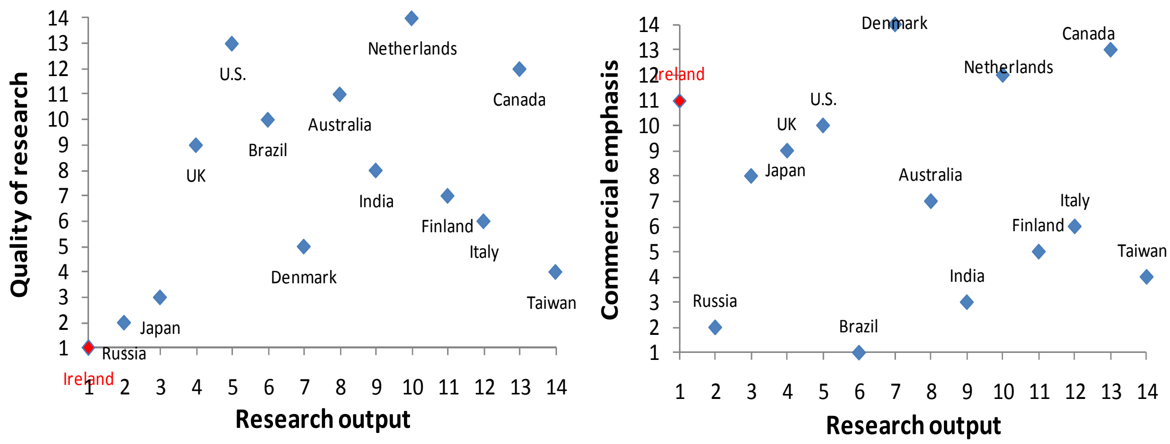


Figure 56: Manufacturing - Sensors to Monitor Water and Air

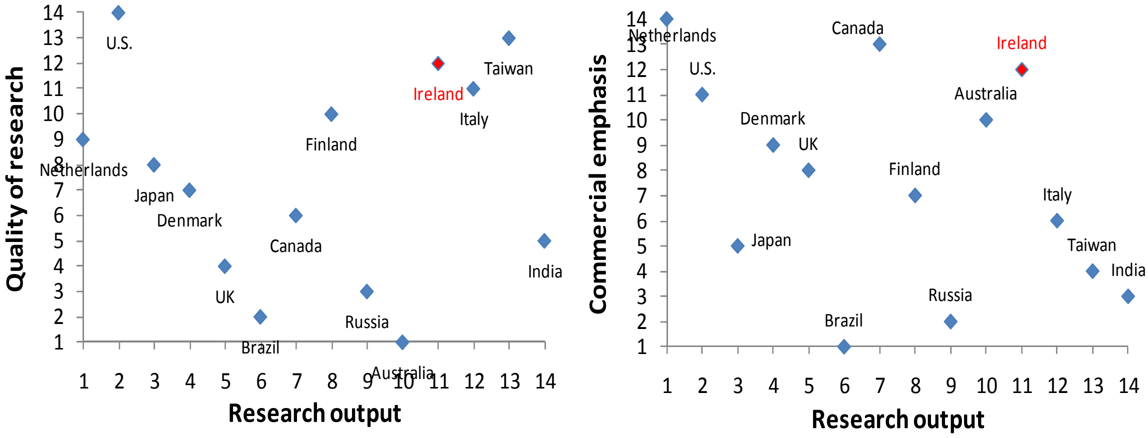


Figure 57: Manufacturing - Anti-adhesion Coatings/Lubricants

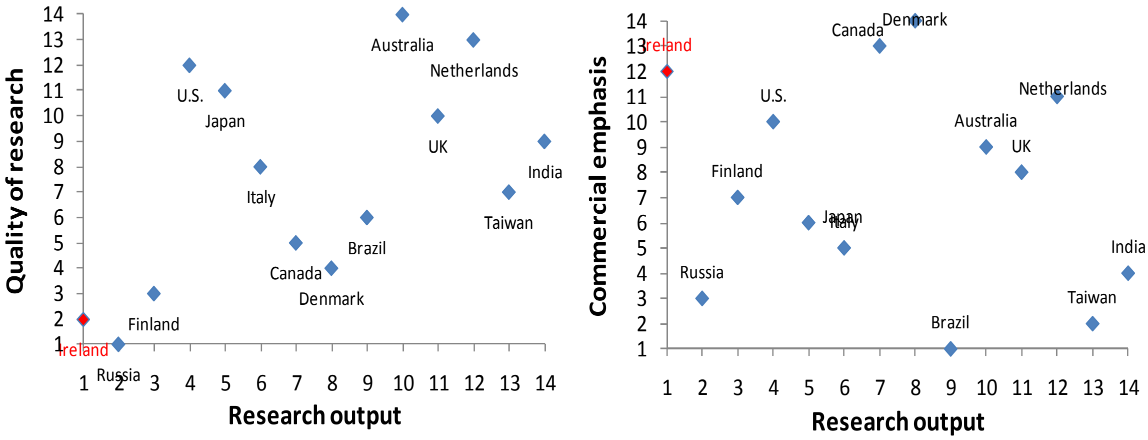


Figure 58: Manufacturing - Insulation

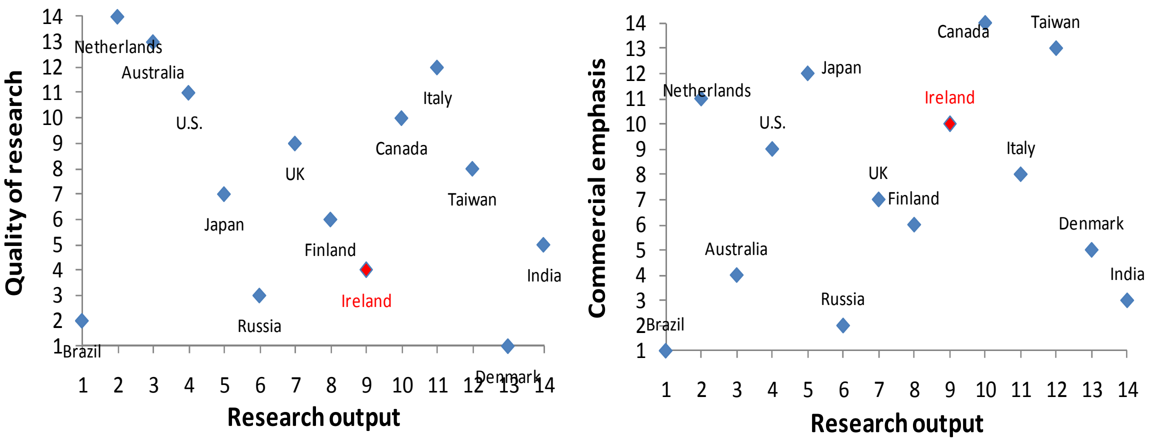


Figure 59: Medical and Pharmaceuticals - Tissue Scaffolds

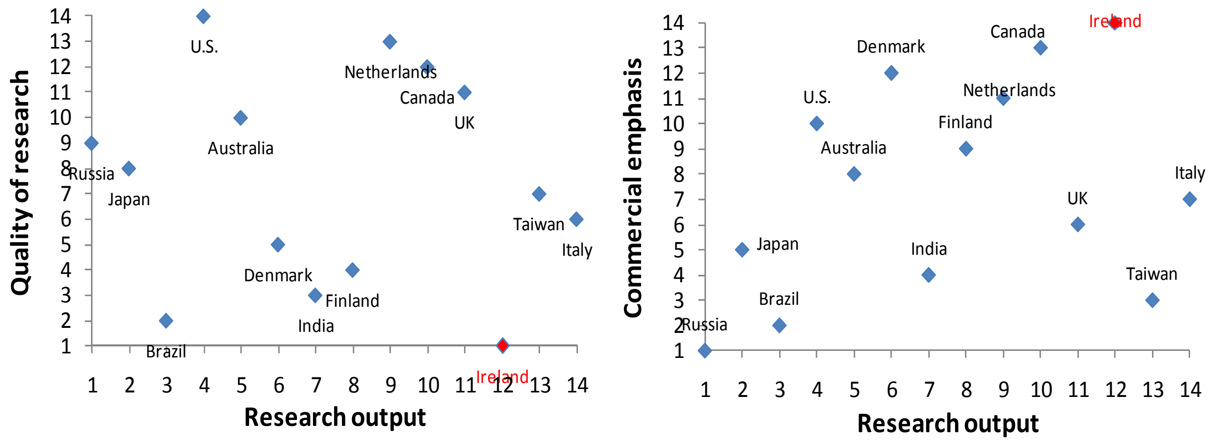


Figure 60: Medical and Pharmaceuticals - Coatings

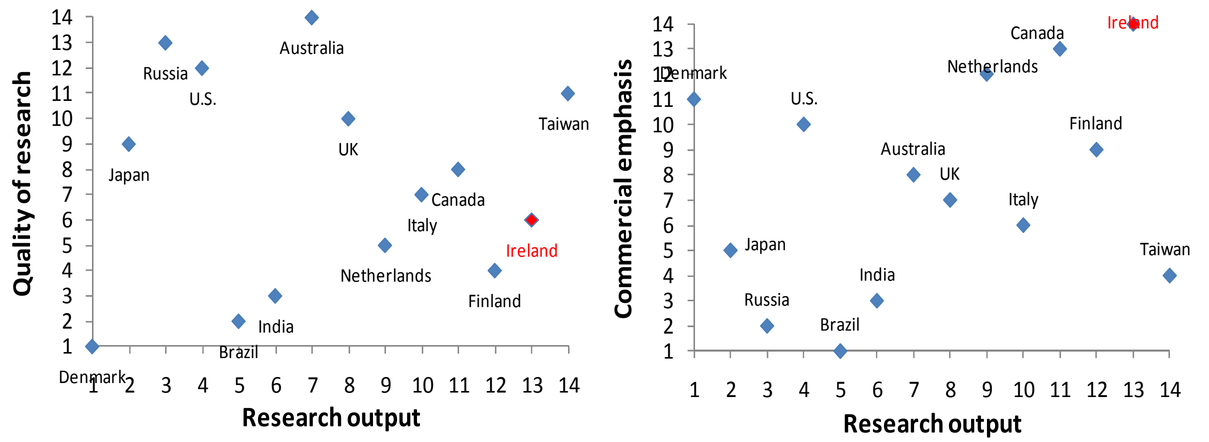


Figure 61: Medical and Pharmaceuticals - Wound Care

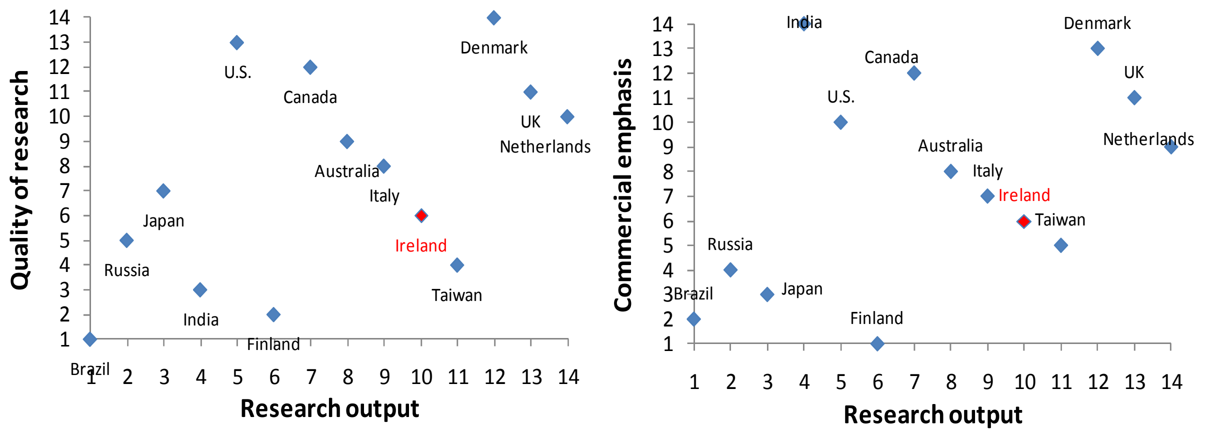


Figure 62: Medical and Pharmaceuticals - Imaging In Vivo

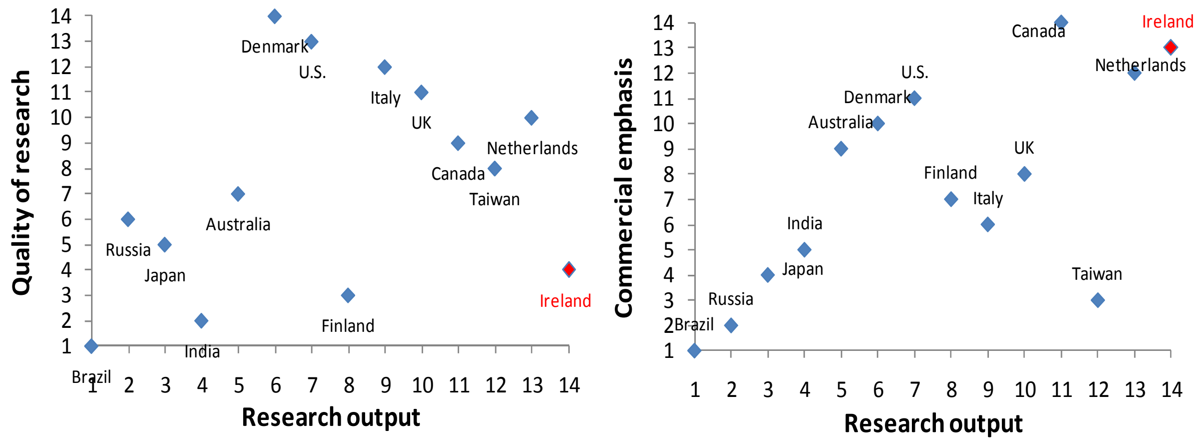


Figure 63: Medical and Pharmaceuticals - In Vitro Diagnostics

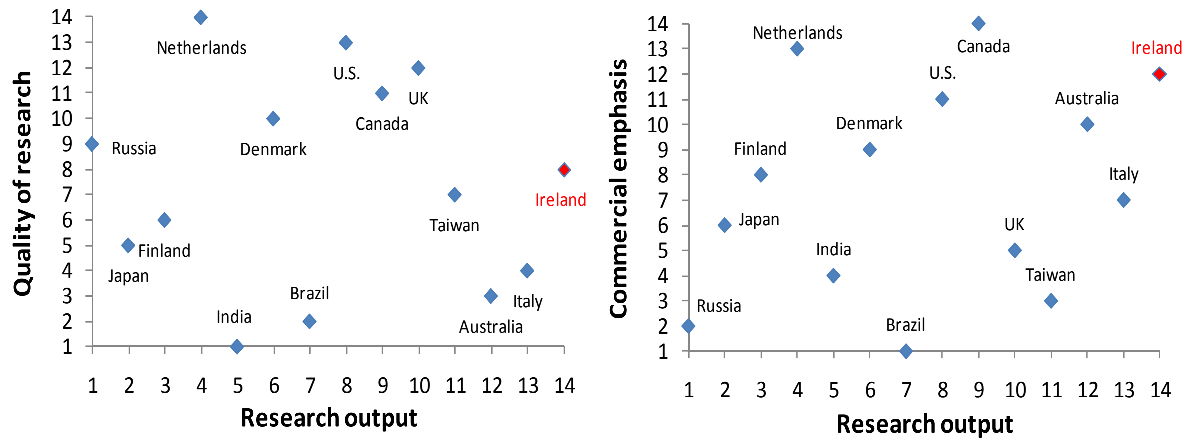


Figure 64: Medical and Pharmaceuticals - Controlled Release

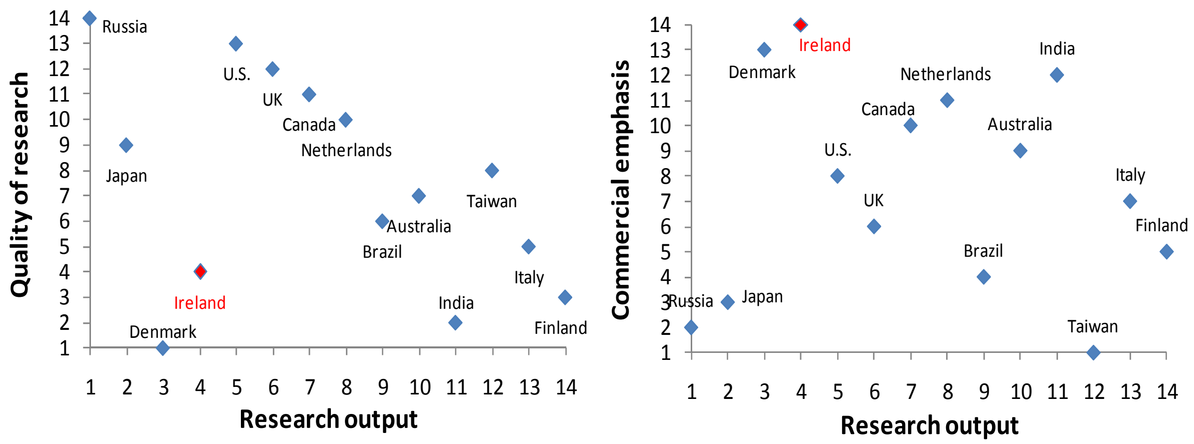


Figure 65: Medical and Pharmaceuticals - Targeted Drug Delivery

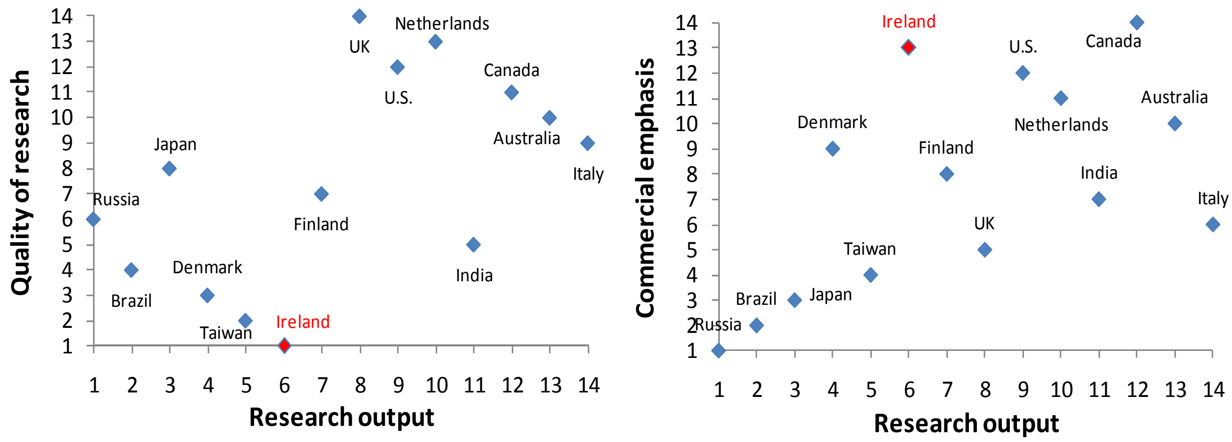


Figure 66: Medical and Pharmaceuticals - Medical Device Drug Delivery

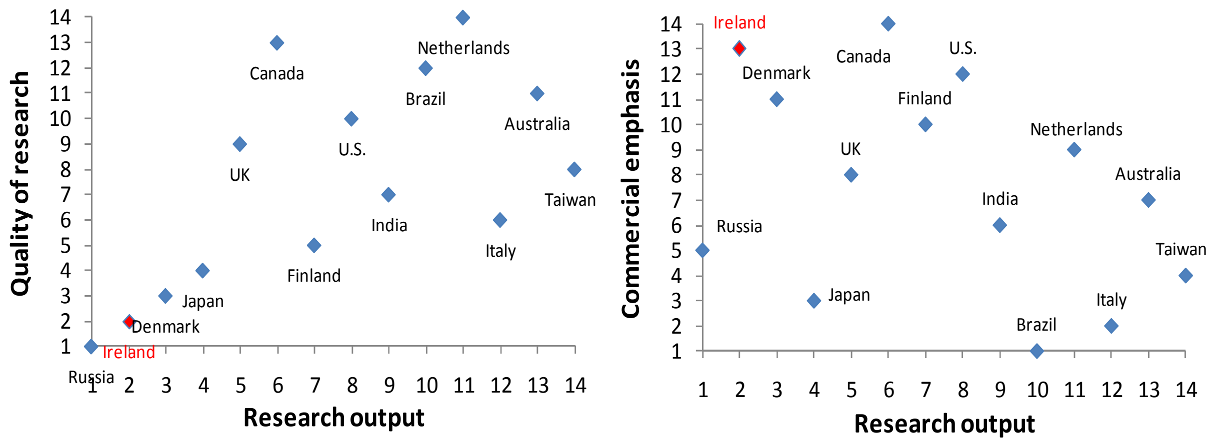


Figure 67: Medical and Pharmaceuticals - Medical Device Packaging

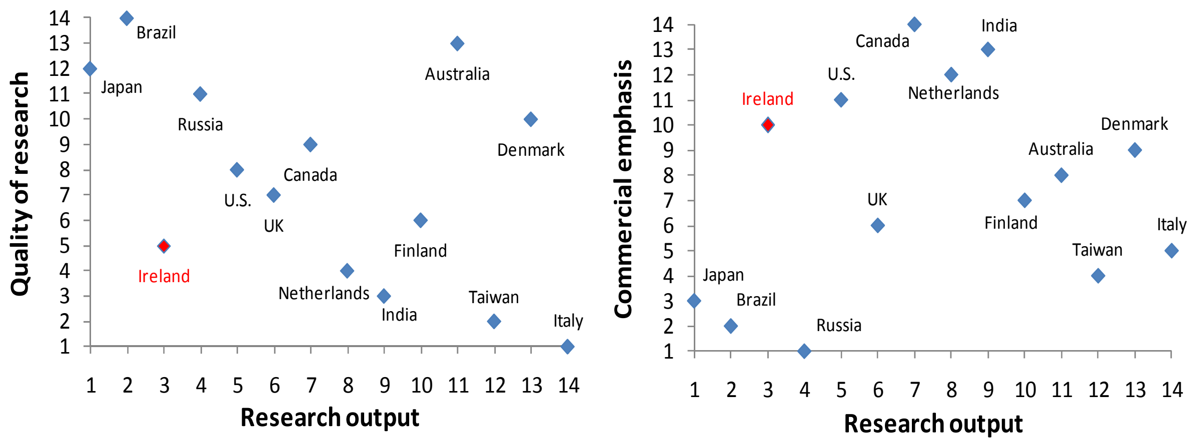
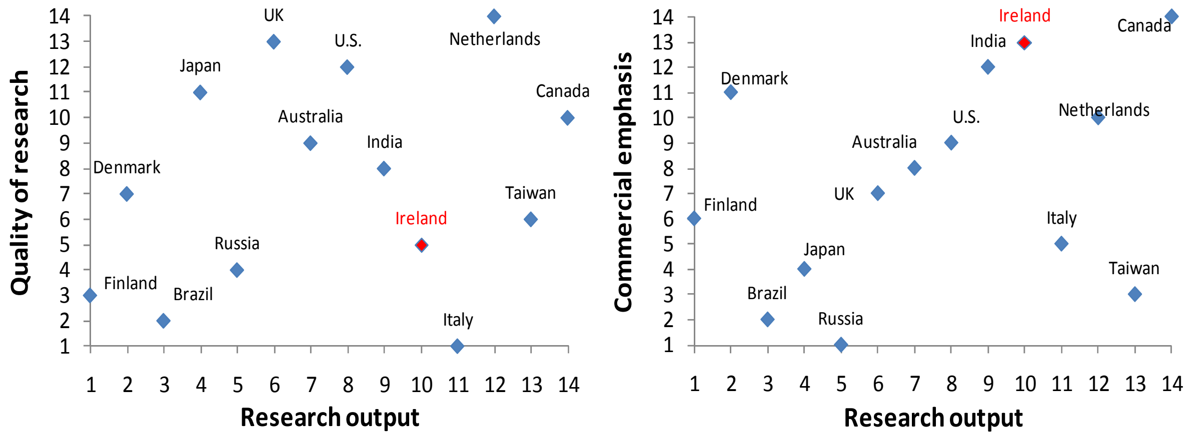


Figure 68: Medical and Pharmaceuticals - Cosmeceuticals and Personal Care



Appendix I

United States

- Although a bulk of the nanotechnology spend goes towards applied research (as opposed to basic research), the stated overall emphasis of the national programme is not on commercialisation
- The National Nanotechnology Initiative (NNI) is made up of 25 federal agencies with their own priorities and agendas. Technology-centric agendas of the National Science Foundation (NSF) and the National Institutes of Health (NIH) are **counterbalanced** by more application-driven agendas of the Department of Defence (DOD) and the Department of Energy (DOE)
- 10 percent of the total NNI funding is reserved for **infrastructure augmentation**
- Focus is multidisciplinary with a high degree of communication and collaboration between the 25 agencies
- NNI works closely with universities to ensure **creation of a trained workforce**

Germany

- Plans to spend 5 precent of gross domestic expenditure on R&D (GERD) on nanotechnology
- Like the US, the **nanoinitiative is cross ministry**, with each ministry having a different funding focus
- Each focus area (chemistry, optics, analytics, biotech) has a consortium of start-ups, SMEs, corporate and academics guiding the programme
- **Government proactively participates in commercialisation** by acting as an angel investor as well as through Small Business Innovation Research (SBIR)-type programmes
- There is a obvious heavy involvement of SMEs in driving commercialisation

Singapore

- Relative to size, Singapore has a high degree of nanotechnology activity (>1,000 researchers working in nanotechnology-related areas)
- Nanotechnology investment is geared towards existing industrial base (biosciences and manufacturing)
- Looking to significantly (>200 percent) scale up GERD
- Has discrete programmes to create start-ups as well as to help existing companies with a technology upgrade
- Quite like Ireland, the economy is MNC-dependent (~6,000) and manufacturing heavy (~25 percent of GDP)

Israel

- The 3-to-1 matching programme , where the government and the beneficiary institute both match any private investment in the institute, is extremely successful, after a spotty start
- Programme was jumpstarted by using matchmakers and unconventional cluster construction
- Israel's baseline goals were almost identical to current Irish goals

- Much higher level of binational activity relative to the other nations
- **Government provides significant matching funds** across the board, even at the EU level, augmented by vibrant VC funds
- **Very clearly defined success metrics** which include repatriation and creation of a engineering-heavy workforce
- Areas of funding focus are determined (and periodically reviewed) by a **scientific advisory board** that includes local and foreign directors

Netherlands

- Government is the primary funding source of nanotechnology (>70 percent), with the industry almost held at an arm's length
- Start-up creation is largely done by M.S. and Ph.D. students, with PIs acting only in an advisory capacity
- Mixed success of NanoNed's technology-centric programme has led to resculpting into application-driven NNI
- NanoLab NL – **a cluster of nanofabs** – is extremely successful with heavy usage by research groups as well as local industry
- **Reinvestment fund**, which requires that a recipient reinvest a certain portion of the infrastructure funding, is uniquely positioned to ensure sustainability of the nanofab infrastructure
- Government is the primary funding source for all levels of infrastructure and its approach (anti facility-push) is very pragmatic

Appendix J

United States - National Nanotechnology Initiative (NNI)

- **$1.5 billion budget of NNI**, disbursed via 25 federal agencies
- Each agency distributes allocation based on internal priorities
- Main NNI focus: **long term fundamental research** (less on translational research)
- Specific **mission-based grants** (Bioengineering, Nano-Manufacturing)
- Business support mainly through research grants for small businesses
- Business development efforts: partnerships between business schools and academic scientists
- Sponsors ‘Tech-Net’, database connecting grant recipients with business, manufacturing partners
- Infrastructure investments in User Center facilities and instrumentation make up 10 percent of total budget

Table 18: NNI 2009 proposed budget (4.5 percent growth in funding level for top 3 agencies)

Federal Agency	% of Total NNI Budget
Department of Defense	28.2
National Science Foundation	26.0
Department of Energy	20.3
Department of Health and Human Services	15.2
Department of Commerce	7.2
Others	3.1
Total Budget	$1.53 billion

Source: Lux Research

NNI has identified 10 high-impact application opportunities and critical research needs, as part of its strategic plan:

1. Rapid, multiplexed detection of disease markers
2. Exposure measurements for engineered nanoscale material
3. Nanobiotechnology
4. Nanotechnology-based water purification and testing
5. Future information processing technology from nanotechnology
6. Predicting toxicity before manufacturing
7. Societal dimensions of nanoscale science & technology

8. Lightweight magnetic and structural nanomaterials
9. Reference materials for commerce and safety monitoring
10. Meeting the energy challenge

Efforts to aid commercialisation

- Department of Commerce established Center for Nanoscale Science and Technology (CNST) to **translate nanotechnology breakthroughs into practical realities**
- Features a Nanofab facility (**fee-based, shared used basis)** to access advanced nanofabrication instrumentations
- Research arm focuses on designing measurement methods in:
  - Nanomanufacturing
  - Transport and Energy Conversion
- Maintains permanent research staff of 15 scientists together with post doctoral fellows and process engineers
- Produced 44 publications in span of two years (2007-2009)
- Other government infrastructure facilities available to researchers include:
  - Network for Computational Nanotechnology
  - DOE Nanoscale Science Research Centres (5 National Centres)
  - Naval Research Lab's Institute for Nanoscience
- Small Business Evaluation and Entrepreneurs (SBEE) at Kellogg School of Management in collaboration with NSF funded Nanoscale Science Center
- Small Business Innovation Research Programme (SBIR), enforces 11 federal agencies to **reserve portion of R&D funding for small businesses**
- Small businesses qualify based on degree of innovation, technical merit and future market potential
- Small Business Technology Programme (STTR) promotes joint venture opportunities for small business and not-for profit organisations

Germany -High Tech Strategy for Germany (NanoInitiative - Action Plan 2010)

- € 640 million Federal Government Budget for the 2006 – 2010 period
- Aiming to reach Federal R&D funding of 3 percent of GDP by 2010
- 5 percent of Federal R&D funding budget (€ 12.36 billion)
- R&D initiative coordinated on **cross-ministry** basis
- Not-for-Profit Network of Universities, research institutes, private companies
- Fraunhofer Nanotechnology Alliance including close to 60 research institutes
- Metrics for receiving Federal funding
  - Importance of research objective: social needs and product relevance
  - Quality and viability of recovery plan and commercialisation prospects

- Innovation level and novelty of approach
- Quality of Project Management

Areas of Focus

Main areas of focus in German Nanotechnology R&D are Cross-Sectional Technologies, having multiple impact areas.

- NanoChemistry
  - Research in NanoCoatings also benefiting NanoOptics
- NanoOptics and Lighting Technologies
  - Funding of **collaborative projects under industrial leadership** by Government Ministry of Education and Research (BMBF)
  - Includes companies, institutes and value chain of diode suppliers and manufacturers
- NanoAnalytics
  - Methodologies to examine vast properties of NanoMaterials on Atomic Scale
- NanoBiotechnology
  - Focus on targeted drug delivery and pharmaceuticals
  - e.g. world's first Nano Cancer Therapy

Federal Ministry funding vehicles

- Ministry of Education and Research (BMBF):
  - R&D grant programme, started in 2007 with € 200 million for 5 years
  - Funding NanoChance, programme helping SMEs start companies for proof of concept, expanding business models, or product line extension
  - Focused on Chemical, Energy and Materials
- Ministry of Economics and Technology (BMWi)
  - BMWi together with KfW banking group and companies like German Telekom, Siemens, Daimler running Venture Fund
  - Provides seed funding before private investments in start-ups
  - Fund volume of € 272 million in 2005, 177 deals completed
- ValiTT Continuous Funding Programme
  - Provides grants up to € 500,000 per year for 3 years
  - Focus on feasibility studies, technology adaptation and incremental advance

Other Initiatives

- Fraunhofer Nanotechnology Alliance:
  - Largest independent organisation for applied research in Europe
  - Unique model of contract research, performance based financing

  - Included 57 institutes, 15,000 employees and € 1.4 billion research volume
  - Only € 220 million from federal government grant
- NanoBioNet
  - Not-for-profit network of research institutes, companies, hospitals and experts from industry, finance and technology transfer
  - Runs a fund for conducting feasibility studies for members
  - Other services include **scouting for technology partners** for R&D projects
  - **Finding project partners** and establishing initial contact

Singapore - Agency for Science, Technology and Research (A*STAR):

- $20 million annual budget for A*STAR's Nanotechnology Initiative
- Roughly 1000 researchers working in nanotechnology related fields
- A*STAR Nanotechnology Funding Distribution:
  - Research Grants
  - Investigatorship
  - Translational research investigator award
  - Local symposium sponsorships
- Focus Areas for A*STAR's Nano Research:
  - Biosciences
  - Manufacturing
  - Silicon NanoDevices and Materials

A*STAR Funded Institutions and Initiatives:

Universities and Research Institutions:

- Institute of Bioengineering and Nanotechnology (IBN)
  - Research focus on biosensors, pharmaceuticals and drug delivery
  - 111 publications and 16 patents from 2007 – 2008
  - Collaboration with MIT, Cornell University, John Hopkins University
- National University of Singapore
- Nanyang Technological University
  - Focus on Precision Engineering for Nanomaterials

Exploit Technologies Pte. Ltd.

- Marketing and commercialisation arm of A*STAR
- IP Management – Licensing technology to national and international firms
- Provides comprehensive technology transfer services:
  - IP cluster mapping

- Training and certification of TTO professionals

Growing Enterprises with Technology Upgrade (GET-UP) Initiative:

- To boost global competitiveness of local technology-intensive enterprises
- Providing expert advice on Operation and Technology Roadmapping
- Tap on technical expertise of senior research staff from Research Institutes
- Leverage (pay-per-use basis) research institutes' laboratories
- **Favourable Tax Laws**: Deduct against taxable income, twice the eligible expenses incurred in market development activities

1.1 **Bilateral Partnerships**

- Singapore Government and AMR technologies (Canada)
- Collaboration with Beijing University of Chemical Technology
- Collaboration of Nanyang Technical Institute and MIT

Israel -Israel National Nanotechnology Initiative (INNI)

- Shared initiative of Israel's Forum for National Infrastructures for Research & Development (TELEM) and Israel's Ministry of Trade and Industry
- Funding
  - 2001–2005; $45 million (primarily to build state-of-the-art research facilities)
  - 2006–2011; $82 million (for basic research), $8 million (equipment purchases and advanced research projects in water treatment)
- Triangle Donation Matching Programme
  - **3-to-1 matching funds** for all private donations to nanotechnology centres
- Gives preference to highest potential areas
  - Nanomaterials
  - Nanobiotechnology
  - Nanoelectronics
  - Nanotechnology applications in water treatment and alternative energy

Commercialisation efforts

- Global Enterprise R&D Cooperation Framework by Office of Chief Scientist (OCS)
  - Promoting joint R&D between Israeli and Multinational Companies (MNCs)
  - **Government financial assistance** of 50 percent of Israeli company's project
  - MNC's making investment in Israel receive credit worth 150 percent of investment
- OCS Incubator Programme
  - Funds entrepreneurs at earliest stages of innovation
  - **2-3 year loans** in form of soft loans and grants

  - **Payback in case of success**: 3 - 3.5 percent of product sales up to grant amount
- Magneton (one of 6 sub-programmes under MAGNET)
  - Promotes technology transfer from academia to industry
  - Supports **formation of consortia** of industrial companies and academia
  - Grants up to 66 percent of approved budget
- Heznek – Government Seed Fund
  - Government and Investor matching funds in seed companies
  - Grants up to 50 percent of approved work programme
- ISERD
  - Offers Israeli companies and research organisations to jointly participate with European counterparts
  - Grants to universities are 100 percent of costs, 50 percent of costs for Industrial R&D
- Bi- National Funds
  - BIRD (Israel – USA)
  - BRITECH (Israel – Britain)
  - SIIRD (Israel – Singapore)
  - KORIL – RDF (Israel – Korea)
  - Grants are 50 percent of R&D expenses of each company

Recent trends in Israeli nanotechnology world

- Number of Israeli nanotechnology companies **doubled from 2005 to 2007**
- Israeli and overseas scientific funds account for 45 percent of capital invested in academic nanotechnology research; VC's account for 1 percent
- Israeli Nano Research Stage Breakdown:
  - Preliminary/Fundamental Research – 58 percent
  - Prototyping – 24 percent
  - Testing – 14 percent
  - Commercialisation – 4 percent
- Last decade yielded over 100 patents and 2000 publications in nanoscience
  - 80 percent publications from Research Universities
  - 20 percent publications from hospitals, private companies and start-ups

Netherlands -NanoNed

- € 235 million (for the 2005 – 2009 period)
- R&D initiative: 8 academic centres of excellence and Philips Research Laboratories (PRL) Europe
- Successor to NanoImpuls (2003 – 2007, €18 million)

- Investments in
    - scientific research: Flagships (~ 64 percent)
    - experimental facilities: NanoLab NL (~ 34 percent)
    - knowledge dissemination: Technology Assessment (TA) programme (~ 2 percent)
- To be followed by Netherlands Nano Initiative (2010-2020, €1 billion)
    - 50 percent from Dutch government
    - 15 percent of budget reserved for EHS and societal aspects research
    - 4 knowledge production domains (more than Moore, nanomaterials, bionanotechnology, nanofabrication) and 4 application domains (nanomedicine, food, energy, clean water)

Flagships:

- **11 large interdependent programmes**, based on national R&D strengths and industrial relevance
    - Advanced Nanoprobing
    - Bottom-up Nano Electronics
    - Chemistry and Physics of Individual Molecules
    - BioNanoSystems
    - NanoElectronic Materials
    - NanoFabrication
    - NanoFluidics
    - NanoInstrumentation
    - NanoPhotonics
    - NanoSpintronics
    - Quantum Computation
- Each programme led by an independent scientific leader and has a size of ~ 50 man-years of research capacity per year
- ~ 200 research projects defined (more than 1200 man years of research)
- Combination of generic, technology-oriented modules with more application-oriented programmes, to create a nation-wide and cohesive effort

NanoLab NL

- Aim is to build up, maintain and provide a **coherent and accessible infrastructure** for nanotechnology research and innovation in the Netherlands
- Combines the existing state-of-the-art facilities of Universities of Twente, Delft and Groningen (with content support from the PRL)
- Offer **a range of *basic* and *expert* functions**: The basic functions provide a general infrastructure suitable for common fabrication activities and are replicated at most

locations. The expert functions (ion beam etching, e-beam induced deposition, interferometry, etc.) are unique to a facility

- Year plans includes **both investment and matching parts** and are submitted for approval by the NanoNed board; individual partners have limited flexibility to deviate from the investment scheme
- Individual partners also reinvest up to 1 percent from the subsidy part per year for 10 years towards a **reinvestment fund** to enable the continued build-up of vital nanotechnology equipment even after the closure of the funding programmemes
- Heavy focus on ensuring future availability of well trained workers for Dutch knowledge driven industry
- Most of the nanotechnology research is supported by public funds (~ 70 percent of all funding being direct or indirect government funding)
- Government ministries like Ministry of Economic Affairs and Ministry of Education, Culture and Science (OCW) provide the bulk of the funding (~50 percent)
- Government-sponsored autonomous research funding organisations like the Netherlands Organisation for Scientific Research (NWO) and the Royal Netherlands Academy of Arts and Sciences (KNAW) provide ~20 percent
- Individual partners must raise the rest of the funds in third-party funding from public authorities, companies, charities and foreign backers
- Most spin-off companies are created by M.S. or Ph.D. students, with professors acting in an advisory capacity

Appendix K

US

The vision of the National Nanotechnology Initiative (NNI) is a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society.

The National Nanotechnology Initiative expedites the discovery, development, and deployment of nanoscale science and technology to serve the public good, through a program of coordinated research and development aligned with the missions of the participating agencies. In order to realize the NNI vision, the participating agencies are working collectively toward the following four goals:

1. Advance a world-class nanotechnology research and development program.

The NNI ensures United States leadership in nanotechnology research and development by stimulating discovery and innovation. This program expands the boundaries of knowledge and develops technologies through a comprehensive program of research and development. The NNI agencies invest at the frontiers and intersections of many disciplines, including biology, chemistry, engineering, materials science, and physics. The interest in nanotechnology arises from its potential to significantly impact numerous fields, including aerospace, agriculture, energy, the environment, healthcare, information technology, homeland security, national defense, and transportation systems.

2. Foster the transfer of new technologies into products for commercial and public benefit.

Nanotechnology contributes to United States competitiveness by improving existing products and processes and by creating new ones. The NNI implements strategies that maximize the economic benefits of its investments in nanotechnology, based on understanding the fundamental science and responsibly translating this knowledge into practical applications.

3. Develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology.

A skilled science and engineering workforce, leading-edge instrumentation, and state-of-the-art facilities are essential to advancing nanotechnology research and development. Educational programs and resources are required to produce the next generation of nanotechnologies, that is, the researchers, inventors, engineers, and technicians who drive discovery, innovation, industry, and manufacturing.

4. Support responsible development of nanotechnology.

The NNI aims to maximise the benefits of nanotechnology and at the same time to develop an understanding of potential risks and to develop the means to manage them. Specifically, the NNI pursues a program of research, education, and communication focused on environmental, health, safety, and broader societal dimensions of nanotechnology development.

Germany

The Government aims at achieving the following with its "Nano-Initiative – Action Plan 2010":

- Speed up the implementation of the results of nanotechnological research in the form of diverse innovations
- Introduce nanotechnology to more sectors and companies

- Eliminate obstacles to innovation by means of early consultation in all policy areasEnable an intensive dialogue with the public about the opportunities offered by nanotechnology but also taking possible risks into account
- The Federal Government wants, above all, to improve the interface between basic research and rapid implementation.

Branch-level industrial dialogue and lead innovations

There's a lot to be done: apart from expediting the process from idea to product, in the future ever more new sectors and companies are to be introduced to the nanotechnology field. Branch-level industrial dialogue between representatives from politics, the economy and associations helps to find areas of application for economic areas not catered for so far. As well as dialogue, the action plan also promotes so-called leading innovations which the Federal Government hopes will generate a high degree of growth and employment. In the field of lighting technology, these include the "NanoLux" project and the OLED Initiative: whereas NanoLux is essentially preparing the way for energy-efficient light-emitting devices in the automotive industry, the OLED Initiative wants to create the technological basis for organic light-emitting devices as a cheap, large-scale lighting option.

Opportunities and risks

Small and medium-sized enterprises in particular often prove to be especially innovation-friendly. They receive support from the action plan by means of funding and structural measures, such as the "NanoChance" programme for start-ups. And the Federal Government is also pooling its activities with regard to potential risks. A steering group under the direction of the Federal Ministry for the Environment is assessing the chances and risks involved in dealing with nanomaterials. In the context of nanotechnology dialogue, experts from industry and society evaluate dangers as well as perspectives and also discuss tomorrow's research needs, to engender yet more discoveries in the land of ideas.

Netherlands

The objective of NanoNed is to generate a strategic impulse for the Dutch scientific and industrial knowledge position in nanotechnology.

NanoNed will:

- Maintain and strengthen the strong nanotechnology position of the involved scientific/industrial groups in the Netherlands
- Ensure the future availability of well trained workers for Dutch knowledge driven industry
- Strengthen the Dutch knowledge infrastructure through a comprehensive knowledge distribution/transfer approach, leading to industrial nanotechnology applications

The cabinet would like to see the Netherlands at least maintain its current position in the field of nanotechnology-related scientific research and innovation and where possible, enhance it. The aim of the cabinet is to exploit as fully as possible the opportunities presented by nanotechnology with a view to developing the country's knowledge economy and to achieving its social objectives. This means concentrating primarily on top-level, clearly-defined and relevant research, particularly in those areas where the Netherlands holds a strong position, in terms of knowledge, knowledge infrastructure and industrial strengths. In this context, a healthy balance between exploratory research and application-oriented research is required. In addition, scientific research must shed light on the risks associated with nanotechnology and how they can be dealt with in a responsible manner.

The nanotechnology research agenda

Following the publication of the Cabinet View, the NNI – an initiative of FOM, STW and NanoNed – have, at the request of the cabinet, started to develop a broad-based research agenda, intended to be the successor to NanoNed, among others. Whereas the Cabinet View outlined five focus areas, the research agenda now distinguishes seven. The focus area of risks and toxicology of nanotechnology has been added to the agenda, while nanotechnology for water purification and energy provision has been subdivided into two separate areas:

- More than Moore
- NanoMedicine
- Functional nanoparticles and nanostructured surfaces (nanomaterials)
- Nanotechnology for water purification
- Nanotechnology for energy provision
- Nanotechnology for nutrition and health
- Risks and toxicology of nanotechnology

The Dutch research priorities tie in well with those set at the European level. This ensures the close alignment with developments at the international R&D level. In addition, the priorities in the field of water purification, nutrition and health are very much in line with international challenges in the context of development cooperation.

Singapore

Objectives

- To develop research human capital and long-term research capabilities in the strategic field of nanoscience and nanotechnology.
- To galvanise and coordinate multidisciplinary research effort (across departments, faculties and with the RIs) in nanoscience and nanotechnology.
- To help set research priorities and directions for high impact nanoscience and nanotechnology research.

The initiative's approach to the development and promotion of nanotechnology research is to optimise resources in creating strategic high impact research while retaining diversity in research areas. Several core areas of nanotechnology research have been identified from the University's existing research. The nanoscience and nanotechnology platform will build on the strengths of the faculties and focus on strategic programmes to excel in niche areas.

Multidisciplinary

- Nanobiotechnology
- Nanomagnetics & Spintronics
- Nano/Micro Fabrication
- Nanophotonics

- Sustainable Energy Materials & Systems
- Health & Environmental Impacts of Nanomaterials
- Areas of Applications
- Biotechnology, Medicine
- Infocommunications
- Engineering Sciences

Israel

The INNI mission is to make nanotechnology the next wave of successful industry in Israel by creating an engine for global leadership.

A primary task for the INNI is to promote fruitful collaboration between Israeli and global nanotechnology stakeholders, particularly for projects that lead to continuing success in academia and industry.

To achieve this task, INNI activities include:

- Establishing a national policy for resource allocation in nanotechnology, with the aim of optimising resources for faster commercialisation.
- Formulating long-range nanotechnology programmes for scientific research and technology development in academia and industry, and promote development of a world-class infrastructure in Israel to support them.
- Leading in the creation of projects that promote agreed national priorities; allocate their budgets and review development progress.
- Actively seeking funding resources from public and private sources in order to implement the selected projects.
- Promoting development of innovative local nanotechnology industries which will strongly impact Israeli economic growth and benefit investors.
- With the creation of its newest nanotech centres -- each focused on specific disciplines and styles of research -- Israel will help set the global pace for nanoresearch in:
    - *Nanomaterials*: Nanostructures, solid nanomaterials and nanochemistry
    - *Nanobiotechnology Biology*: Biotech engineering, applied biosciences and medicine
    - *Nanoelectronics*: Electronics and photonics
    - "*Nanowater*" : Nanomembranes, nanofiltration and other nanotechnologies used in water remediation

The INNI nanotechnology R&D survey affirms Israel's strategic focus in these fields, as measured by the number of researchers devoted to a particular discipline, the number of citations for published articles in key fields, the number of patents applied for in key fields and the amount of research funding available in these fields.

Appendix L

Survey template -Research Capabilities and Capacity in Nanotechnology in Ireland

Purpose of this survey

The purpose of this survey is to assess the current research capabilities and capacity in nanotechnology in Ireland based on 2008 information. This survey will be used by Forfás as an input into the feasibility study for assessing the options to provide public and private researchers with access to nanofabrication facilities.

Definition of Nanotechnology for this study

For this survey the definition of nanotechnology is the purposeful engineering of matter at scales of less than 100nm to achieve size dependent properties and functions.

Section 1 : About your Research Group

1. What is your group's main field (s) of nanotechnology research (please select more than one as appropriate)?

Nanotechnology Field of Research	Please tick the relevant fields
Nanomaterials	☐
Nanoelectronics including nanophotonics	☐
Nanoscale biotechnology including nanomedicine	☐
Nanotools and instrumentation	☐
Nanofabrication and processing	☐
Modelling	☐

Nanotech risk assessment and toxicology	☐
Bioscience and Medical Technologies	☐
Food technologies	☐
Other (please specify)	☐

2. Briefly describe your chosen nanotechnology research area in the table below.

3. How long have you been working on nanotechnology associated projects[41]?

☐ < 1 year

☐ 1-2 years

☐ 3-5 years

☐ 6-7 years

☐ > 8 years

4. What percentage of your group's research is nanotechnology?

☐ <10 %

☐ 11-40%

☐ 41-60%

☐ 61-80%

☐ 81-100%

[41] Projects involved with the purposeful engineering of matter at scales of less than 100nm to achieve size dependent properties and functions.

5. Please indicate the percentage breakdown of your nanotechnology R&D under the following categories.

Research Category	**Percentage**
Basic Research[42]	
Applied Research[43]	
Experimental Development[44]	
Total	100%

6. How many people in your group are working on nanotechnology associated projects?

	Researchers (excluding PhD students)		**Technical Staff**		**PhD students**
	With PhD	**Without PhD**	**With PhD**	**Without PhD**	
Number					
Full Time Equivalent45					

7. Since 2002, how many Masters/PhD students with nanotech expertise has your group produced?

Number of Masters / PhD students since 2002 produced by your group?		
	Masters	PhD's
Number		

42 Experimental or theoretical work undertaken primarily to acquire new knowledge, without a particular application or use in view.

43 Original investigation undertaken in order to acquire new knowledge primarily directed towards a specific practical aim or object.

44 Systematic work, drawing on knowledge gained from research and practical experience that, is directed to producing new materials, products and devices; to installing new process, systems and services; or to improve substantially those already produced or installed.

45 Full Time Equivalent (FTE) is the estimate of time spent solely on nanotechnology R&D activities. For example if a staff member spends 80% of their time on these activities, the 1 person headcount translates in 0.8 FTE.

8 (a). Since 2002, how many publications has your group had from nanotechnology associated projects?

☐ 0-5

☐ 6-10

☐ 11-15

☐ 16-20

☐ >20

8 (b). Since 2002, how many of these publications were multidisciplinary?

☐ 0-5

☐ 6-10

☐ >10

9. What is the intended field of application and prospects of commercialisation for your research output? Please select more than one as appropriate and indicate the priority level (low, high, very high) of that area for your group.

Sector	**Low**	**High**	**Very High**
Electronics /Semiconductor / Communications	☐	☐	☐
Medical Devices	☐	☐	☐
Pharmaceutical	☐	☐	☐
Polymer and plastics	☐	☐	☐
Agri-food	☐	☐	☐
Instruments and equipment	☐	☐	☐
Environmental	☐	☐	☐
Coatings	☐	☐	☐

Energy	☐	☐	☐
Other (please specify)	☐	☐	☐

10. Briefly describe the intended field of application for the commercialisation of your research.

Section 2: Collaborations with other Academic Groups and with Industry

1. When undertaking nanotechnology research, do you collaborate with other academic groups?

☐Yes

☐No

If no, proceed to section 2, question 2

If yes, where are these groups located and what type of collaboration exists?

	Ireland	Northern Ireland	EU	USA	Other (please specify)
Exchange of researchers	☐	☐	☐	☐	☐
Funding	☐	☐	☐	☐	☐
Co-owner of patents	☐	☐	☐	☐	☐

2. Do you have formal collaborative agreements with an industrial partner (s)?

☐Yes

☐No

If no, proceed to section 2, question 3

If yes, what size of company are they?

Company type	**Please tick the relevant fields**
Medium / Large[46]	☐
Small[47]	☐

3. In relation to your applied research, what do you perceive are the main barriers to commercialisation of your nanotechnology research output (check all that apply) and indicate the difficulty level from 1 to 5, where 5 represents the greatest level of difficulty.

Main Barriers to Commercialisation of Research Output					
Barriers to commercialisation	**1**	**2**	**3**	**4**	**5**
Needs already fulfilled by other technologist	☐	☐	☐	☐	☐
Locating an industrial partner	☐	☐	☐	☐	☐
Intellectual property	☐	☐	☐	☐	☐
Difficulties in filing patents (time, cost etc)	☐	☐	☐	☐	☐
Industrial regulation /standards	☐	☐	☐	☐	☐
Funding (public)	☐	☐	☐	☐	☐
Venture Capital	☐	☐	☐	☐	☐
Licensing	☐	☐	☐	☐	☐
Design and prototyping facilities	☐	☐	☐	☐	☐
Finding a technology exploiter	☐	☐	☐	☐	☐
Ethical Issues	☐	☐	☐	☐	☐
Other (please specify)	☐	☐	☐	☐	☐

[46] For analysis purpose firms who employ more than 50 employees are classified as medium / large

[47] For analysis purpose firms who employ less than 50 employees are classified as small

4. Has your research group produced any nanotechnology associated commercial outputs and is so, was it a result of an academic or industrial collaboration.

If so, please indicate in each of the boxes below.

Commercial Output	**Please tick, and enter number of, for each of the relevant fields**	**Collaboration**
Patent Filed	☐ If so how many?	☐ Academic ☐ Industrial
Patent Granted	☐ If so how many?	☐ Academic ☐ Industrial
Spin Out Company	☐Yes If so how many?	☐ Academic ☐ Industrial
Patents licensed out	☐ Yes If so how many?	☐ Academic ☐ Industrial
Other form of IP (please specify)	☐Yes If so how many?	☐ Academic ☐ Industrial

Section 3: Funding your Research Group

1. How much funding has your group received in 2008 for nanotechnology associated projects?

☐ <100k

☐ 101k - 300k

☐ 301k - 500k

☐ 501k - 1 million

☐ 1.1 million -3 million

☐ 3.1-5 million

☐ 5.1-10 million

2. Please indicate the source(s) and percentage funding for your nanotechnology associated projects (excluding buildings but including current and equipment expenditure).

Source(s) and Percentage of Funding for Nanotechnology Associated Projects	
Funding Organisation	**Percentage of Funding**
Science Foundation Ireland	
Enterprise Ireland	
IRCSET	
Health Research Board	
Environmental Protection Agency	
IRCHSS	
European Commission	
Business (Irish)	
Business (Foreign)	
Other (please specify)	
Total	100%

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August 2010

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