United Nations
Economic Commission for Africa

Towards an African nanotechnology future

Trends, impacts and opportunities

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PREFACE

Over the years, the science and applications of nanotechnology have developed at a faster pace across various disciplines and sectors. The technology is increasingly found in many commercial products from mobile phones and cosmetics to pharmaceutical and robotics. The technology holds great promise for the development of new treatments for a wide range of diseases. It is increasingly recognized as a platform technology that could play an important role in the efforts of African countries to achieve the targets of the Sustainable Development Goals (SDGs) and realize the Aspirations of the African Union's Agenda 2063.

The African Union recognizes nanotechnology as a compelling imperative and identifies nanotechnology as one of six priority areas in its Science, Technology and Innovation Strategy for Africa 2024 (STISA-2024). Recognizing the promise of nanotechnology for their development, many countries have set up nanotechnology centres to undertake research in various areas of possible application. However, despite its potential, very few African countries have articulated a national nanotechnology policy. This lack of policy urgency has considerably slowed the development and application of nanotechnology on the continent.

A growing number of countries have launched national nanotechnology strategies and initiatives to coordinate research and development (R&D) funding, provide national direction and advance nanotechnology development. Most developed countries and a number of developing countries have since developed their own national strategies. For example, China launched its national strategy in nanotechnology in 2001 while the European Union adopted its strategy on nanotechnology in 2004.

This report shows the efforts that a number of African countries and institutions are undertaking to drive nanotechnology development. It addresses the scientific, technological, economic, social and regulatory issues arising from nanotechnology. As a distinct field of both scientific, technological and industrial interest, the report showcases steps that African countries could take to realise the economic, social and environmental benefits of nanotechnology while managing regulatory challenges the technology may impose.

Specifically, it assesses the current state of nanotechnology in Africa as well as provide an overview of nanotechnology development globally and explore opportunities to enable innovation using nanotechnology to develop safe, effective products that could make significant impacts in achieving the 2030 Agenda and national aspirati0ons. It also highlights strategies and other arrangements that African countries can use to harness global and regional knowledge in nanotechnology to drive innovation in Africa; and the role of regional blocks in building research infrastructures and industrial capacities in nanotechnology in African countries.

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The Green Economy, Innovation and Technology Section team consists of Victor Konde, Mactar Seck, Charles Akol, Louis Lubango, Laetitia Montero Catusse, Asfaw Yitna, Gedion Workneh, Hidat Mebratu and Tsigereda Assayehegn Asfaw.

The core team that prepared the report consisted of Victor Konde who provided overall guidance and authored Chapters 1 and Conclusion), Dr. Trust Saidi and Professor Tania Douglas (Chapter 2), Professor Hailemichael Teshome Demissie (Chapter 3), Professor Mmantsae Moche Diale (Chapter 4), and Dr Archana Bhaw-Luximon (Chapter 5).

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SUMMARY

Nanotechnology, from nanofilters for water purification in Ethiopia and the United Republic of Tanzania to nanocatalysts and nanosensors in Egypt and South Africa, is broadening the scope of current approaches and creating new avenues for meeting many of the development challenges that Africa faces today. This report looks at (a) current nanotechnology research and development trends and market potential, indirectly assessing the engagement of Africa in the nanotechnology field; (b) the Sustainable Developments Goals on which nanotechnology is likely to have a significant impact; and (c) steps African countries can take to develop and realize their nanotechnology potential.

The global market in nanotechnology-enabled products stood at approximately $1.6 trillion in 2014, up from $850 million in 2012. The rapid expansion of the nanotechnology market is partly driven by increasing investment in research and development, which is creating numerous innovative industrial applications. This is evident in the doubt-digit annual growth in the number of peer-reviewed articles and in the number of nanotechnology patent applications that have been filed in the last decade. It is worth highlighting that a number of developing countries, including China, the Islamic Republic of Iran, and Saudi Arabia are among those countries investing the most in nanotechnology research and development, while several African countries, including Egypt, Tunisia and South Africa, are also making steady investments in nanotechnology.

Although nanotechnology will impact all aspects of development, its greatest impact is likely to be on Sustainable Development Goals 2 (Zero hunger); 3 (Health); 7 (Energy); 8 (Economic growth), 9 (Infrastructure and industrialization); 11 (Cities) and 12 (Sustainable consumption and production). It is in these areas that the majority of patents and high-impact technologies are concentrated. However, the impact of nanotechnology on other Goals will be marginal or less direct unless the African continent invests in key nanotechnology applications that are not directly relevant to industry, such as applications that are relevant to water resources, climate change and peace and security.

Egypt is currently the top nanotechnology research country in Africa, while South Africa is the African country which has filed the most patents and established the most nanotechnology companies and institutions. Overall, Africa is lagging behind other continents in terms of nanotechnology research, inventions, standards and the number of companies operating in that area, and few African countries have developed clear national nanotechnology strategies to guide the development of the sector. Africa is at risk of becoming further marginalized in technology development and/or its governance.

CHAPTER 1.

AFRICA IN THE GLOBAL NANOTECHNOLOGY DEVELOPMENT: CURRENT PERFORMANCE

1. INTRODUCTION

Nanotechnology offers new opportunities for promoting sustainable development in ways that, only a few decades ago, were perceived as impossible. Today, cheaper but faster, smaller, smarter and energy-efficient materials, components and devices are driving growth in information technology, biotechnology, and energy and environmental technologies. The significant progress that has been achieved at the global level in robotics, electronics and artificial intelligence would not have been possible without the development of increasingly light, small and strong nanotechnology materials and components. Indeed, a smartphone today has more storage capacity and processing power, and longer battery life, than the average laptop of two decades ago. At the heart of this revolution lies nanotechnology, which enables manufacturers to manipulate matter at a scale that is invisible to the naked eye and to build increasingly small, light, strong and smart materials and devices.

Nanotechnology is an enabler and enhancer of other technologies and products. It is the power behind most recent advances in energy, health, information and transport technologies as well as recent improvements in electronics, sports and security and defence products and processes. As a result, it has been seen as offering "jumbo-sized hope for mankind".[1]

Recognizing the promise of nanotechnology for development, several countries worldwide have set up nanotechnology initiatives to spearhead research, development and innovation. Those initiatives include training programmes at universities and research and development facilities to advance nanotechnology development, technology convergence, standards for nanotechnology products, nanotechnology material and product safety, and industrial applications of and markets for nanotechnology products.

The launch of the United States National Nanotechnology Initiative (NNI),[2] in 2000, is credited with coordinating research and development funding, providing national direction and advancing nanotechnology development.[3] NNI was based on the work of the Interagency Working Group on Nanotechnology, which set out a 10-year vision in that area.[4] Several developed countries, and a number of developing countries and regional organizations, including the European Union, have since developed their own strategies. For example, China and the Islamic Republic of Iran launched their national strategies in nanotechnology in 2001 and 2002, respectively, while the European Union adopted its strategy on nanotechnology in 2004. Since then, over 60 countries have adopted national nanotechnology policies and strategies in the light of the potential economic, health and security benefits of that technology.

At the continental level, nanotechnology is also increasingly recognized as a platform technology that can facilitate efforts by African countries to achieve the targets of the Sustainable Development Goals and realize the Aspirations of Agenda 2063 of the African Union. The African Union recognizes nanotechnology as a compelling imperative and identifies nanotechnology as one of six priority areas in its Science, Technology and Innovation Strategy for Africa 2024.

However, despite recognition at the continental level of the potential of nanotechnology, very few African countries have articulated national nanotechnology policies and/or strategies. This lack of policy urgency has significantly impeded the development and application of nanotechnology on the continent. As a result, African countries are failing to keep up with global trends and with their peers in other developing regions.

1 As expressed by Kim Woo-Sik, Deputy Prime Minister and Minister of Science and Technology, Republic of Korea.

2 Further information available at: www.nano.gov

3 The National Academies, A Matter of Size: Triennial Review of the National Nanotechnology Initiative(Washington, D.C., National Academies Press, 2006). Available at: www.nap.edu/read/11752/chapter/1.

4 Williams, R.S., and Alivisatos, P., eds., Nanotechnology Research Directions: IWGN Workshop Report; Vision for Nanotechnology in the Next Decade, (Springer, Dordrecht, The Netherlands, 2000).

2. NANOTECHNOLOGY CONCEPTS AND DEFINITIONS

The term "nanotechnology" is said to have been coined in 1971 by Norio Taniguchi[5] but its core as an area of research interest can be traced back to a lecture entitled "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics" delivered by Nobel Laurate Richard Feynman in 1959 to the American Physical Society[6]. Feynman visualized, inter alia, the possibility of "swallowable doctors", "small computers that can read and recognize faces", "micro devices for health" and "microscopes that can see DNA".

Today, nanotechnology is making remote health monitoring of patients possible through wearable sensors[7] and smart textiles,[8] facilitating diagnoses through a so-called lab-on-a-chip,[9] and extending the shelf-life of food though nanotechnology-enabled packaging.[10] The dream of nanotechnology-enabled products is being realized not just in high-tech sectors such as electronics, but also in low- and medium-tech industries (for instance, in the production of ceramic tiles that are easy to clean, textiles that repel dirt and cleaning materials that pick up dust).

The prefix "nano" comes from the Greek word "nanos" (meaning dwarf) but is used in science and technology to mean one billionth. It is for this reason that "nano" is also used to mean "small" such as in the expression "nano-sim card". In the case of nanotechnology, it refers to a billionth of a metre (or nanometre). Although there is no universally agreed definition, nanotechnology refers to the manipulation and engineering of matter and devices at less than 100 nanometres. However, the Organization for Economic Cooperation and Development (OECD) has proposed a set of definitions for statistical purposes (see Box 1).

5 Norio Taniguchi, "On the Basic Concept of "Nano-Technology"", Proc. Intl. Conf. Prod. Eng. Tokyo, Part II, Japan Society of Precision Engineering (1974).

6 Available at: calteches.library.caltech.edu/1976/1/1960Bottom.pdf.

7 Majumder, Mondal, and Deen, "Wearable Sensors for Remote Health Monitoring", Sensors 17(1), 130 (Basel, Switzerland, 2017).

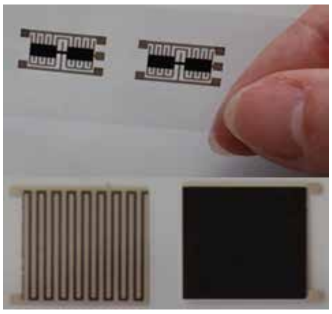
8 Chi Cuong Vu and Jooyong Kim, "Human Motion Recognition by Textile Sensors Based on Machine Learning Algorithms", Sensors, 18(9), 3109 (Basel, Switzerland, 2018).

9 Hong Su, Yafei Wang, Yuanliang Gu, Linda Bowman, Jinshun Zhao and Min Ding, "Potential applications and human biosafety of nanomaterials used in nanomedicine", Journal of Applied Toxicology, 38:1, pages 3-24 (2018).

10 Sharma, Dhiman, Rokana and Panwar, "Nanotechnology: An Untapped Resource for Food Packaging", Frontiers in Microbiology, 8, 1735 (2017).

What is a nanotechnology product or service?

(a)



(b)

(c)

(a) Gongali Model, the United Republic of Tanzania

(b) PST Sensors, South Africa

(c) NanoTech Egypt

Above are examples of both basic and sophisticated uses of nanotechnology. In (a) a youth from the United Republic of Tanzanian who studied nanotechnology in the Republic of Korea, returned to his home country to establish a water purification plant that employs nanofilters. In (b), a company established as a spinoff at Cape Town University manufactures heat sensors using innovative technology that enables manufacturers to print silicon at room temperature on any material. In (c), the first company in the Arab world manufactures custom-tailored nanomaterials. While these are all examples of nanotechnology, the levels of sophistication differ widely, and the benefits may be determined by needs. While the technology used in (a) is used in water purification, the technologies used in (b) and (c) can be used in a wide range of applications, including in the fields of health, transport and textiles.

While size broadly defines nanotechnology, it is the changes in the chemical and physical properties of matter at the nanoscale compared with its properties at bulk scale that makes it more valuable. For instance, silver at nanoscale kills bacteria and masks odour, making it a perfect addition to sports clothing and food packaging. At the macroscale, silver is relatively inert, which is partly the reason it is used in silverware production. Similarly, the melting point of gold drops from 1,064 degrees Celsius to approximately 100 degrees as its size shrinks below 100 nm. These changes in the physical and chemical properties open up opportunities for designing and developing novel applications at both the nanoscale and macroscale. They also give rise to new economic, social, safety and ethical concerns.

Box 1. The Proposed OECD single and list-based statistical definitions of nanotechnology

The single statistical definition of nanotechnology: The understanding of processes and phenomena and the application of science and technology to organisms, organic and inorganic materials, as well as parts, products and models thereof, at the nanometre-scale (but not exclusively below 100 nanometres) in one or more dimensions, where the onset of size-dependent phenomena usually enables novel applications.

The list-based statistical definition of nanotechnology:

Nanomaterial: material with any external dimension in the nanoscale or having internal structure or surface structure in the nanoscale.

Nanoelectronics: field of science and technology concerned with the development and production of functional electronic devices with nanoscale components.

Nanophotonics: branch of photonics concerned with the interaction of photons with nanomaterials aiming to design optical or optoelectronic components.

Nanomedicine: medical application of nanotechnology (e.g. medical applications of nanomaterials and biological devices, nanoelectronic biosensors, and even possible future applications of molecular nanotechnology such as biological machines).

Nanomagnetics: the study of the magnetic response of nanomaterials to an applied magnetic field, and their applications.

Nanomechanics: a branch of nanoscience concerned with fundamental mechanical (elastic, thermal and kinetic) properties of physical systems at the nanometre scale.

3. CURRENT STATE OF NANOTECHNOLOGY

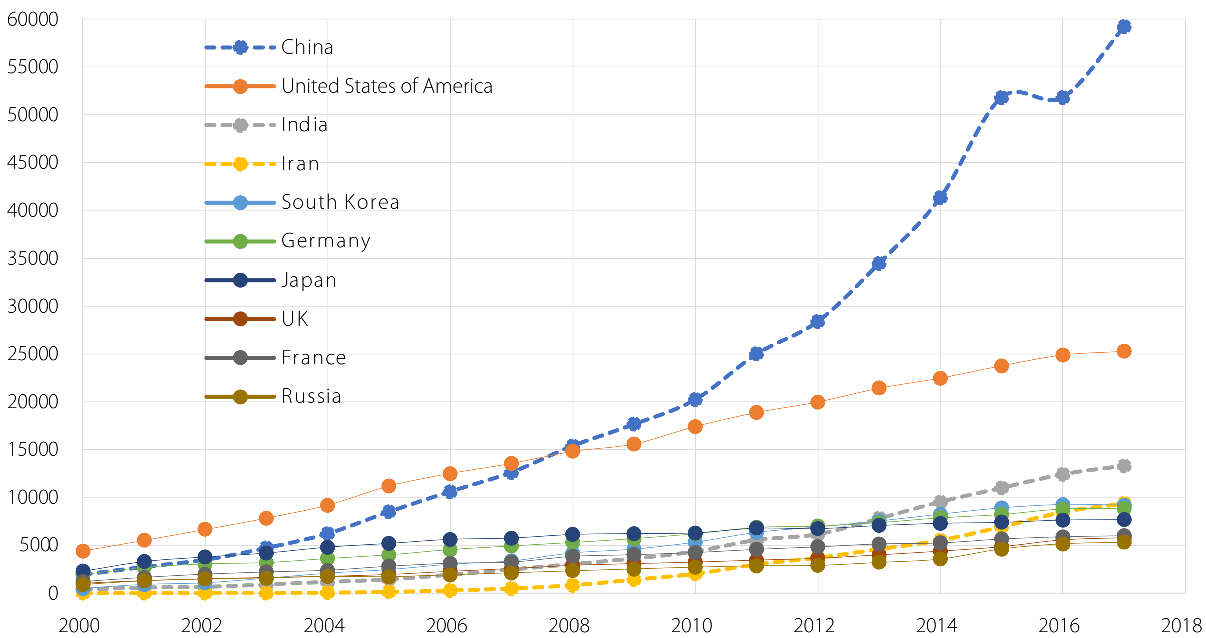
Nanotechnology has been termed "pervasive" and an "enabler" and "key driver" of the next industrial revolution. Estimates suggest that revenues for nanotechnology enabled-products increased from $850 million in 2012 to approximately $1.6 trillion in 2014 – a growth of about 90 per cent. It is nearly impossible to avoid products that include aspects of nanotechnology in the market place; nanotechnology is found in washing machines and washing detergents, cosmetics, medicines, food packaging, infrastructure, electronic appliances and many other products. It is expected that the market share of nanotechnology-enabled products will continue to rise.

Assessing the scope of African countries' participation in the global nanotechnology market is beyond the scope of this report. However, an indirect assessment of Africa in the global nanotechnology sphere can be assessed indirectly by looking at knowledge generation (approximated by research outputs), emerging industrial nanotechnology companies (approximated by patents), and emerging markets for nanotechnology (approximated by the number of standards).

3.1. A GROWING RESEARCH BASE

The number of universities and research institutions investing in nanotechnology training of skilled manpower and pursuing nanotechnology-related research and development continues to grow. The number of universities and research centres with nanotechnology teaching and research departments has grown rapidly since the 1990s. Indeed, by 2016, the number of journals that included nanoscience and nanotechnology in their titles had risen to 86 and there were approximately 192 nanotechnology institutes.[11] The number of public and private sector initiatives to finance, train, monitor and evaluate research in nanotechnology has also increased. This can be indirectly assessed by counting the number of relevant scientific publications published in peer-reviewed journals. Overall, the number of nanotechnology-related science publications increased from about 13,000 in 1997 to some 154,000 in 2016 – equivalent to a 14 per cent annual growth rate.[12] This is higher than the estimated 3.7 per cent annual growth rate in the number of research papers across all fields of research during that same period. As shown in figure I, China has seen its share of nanotechnology research publications rise from about 5 per cent of the global total to approximately one third of world output. The top nanotechnology research publishing countries are largely developed countries, with China, India and the Islamic Republic of Iran also among the top 10 countries.

Figure I Nanotechnology articles indexed by Web of Science

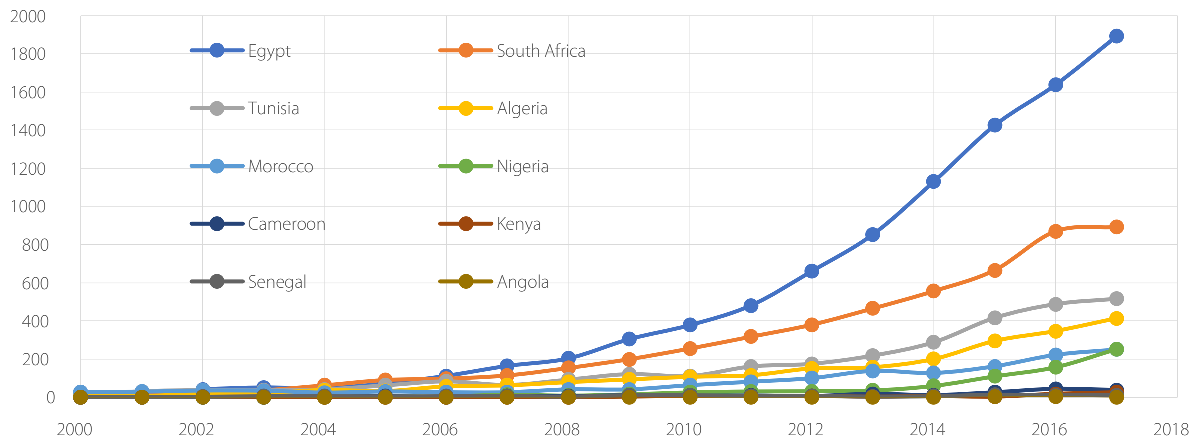


Source: *NanoStat database.*

At the continental level, Egypt is the largest contributor of nanotechnology publications, followed by South Africa, Tunisia and Algeria (see figure II). Nigeria registered the fastest growth between 2010 and 2017 (an increase of approximately 900 per cent), followed by Egypt (400 per cent) and Tunisia (364 per cent). Certain African countries are therefore contributing to the growing global knowledge in nanotechnology. This suggests that, if adequate and appropriate support is provided, several regional research collaboration initiatives could be launched and regional centres of excellence in nanotechnology established.

11 Chinese Academy of Sciences, "Small science in big China" (Springer Nature, 2017).
12 Zhang Li, "Nanoscience as a microcosm of the success of Chinese science" (Springer Nature, 2017).

Figure II Nanotechnology articles published by the top 10 African countries



Source: *NanoStat database.*

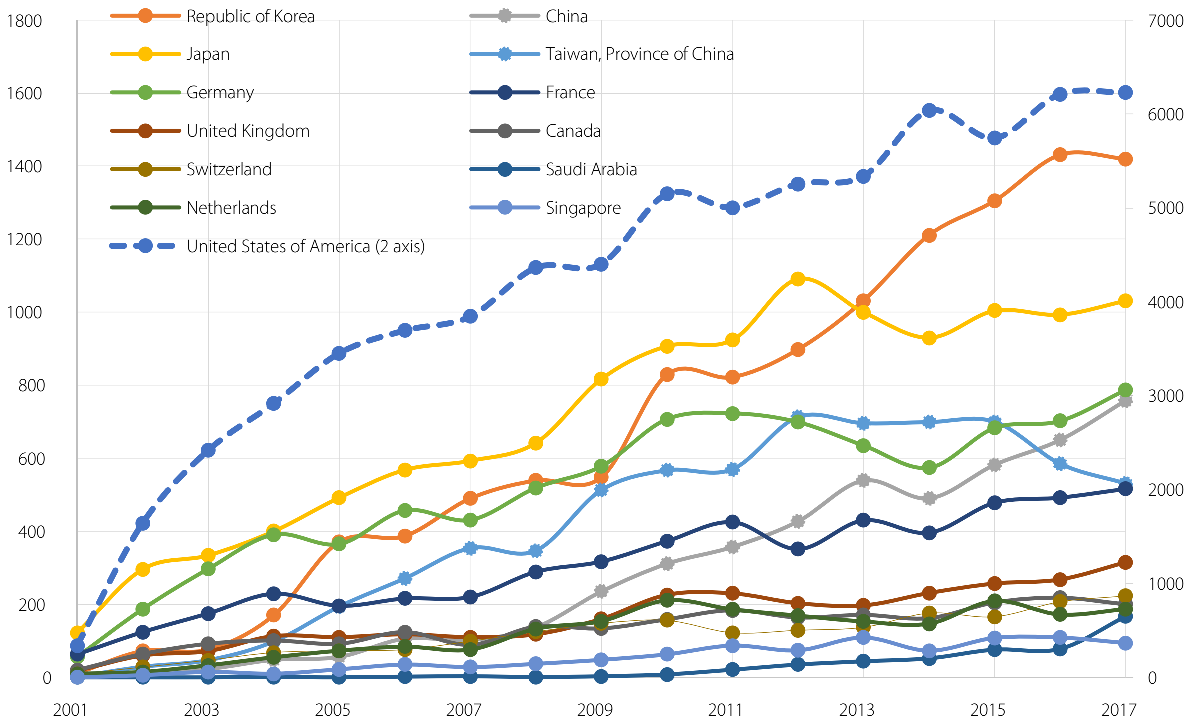
The divergence in nanotechnology publication trends among African countries is a source of concern. The divergence is not directly related to the size of countries' research and development budgets, but is associated with a number of factors, including national policies, the existence or otherwise of international partnerships and prior areas of research excellence. For example, Egypt publishes slightly fewer papers than South Africa in all areas of research. However, according to a study conducted by the Economic Commission for Africa (ECA) in 2013, some 16 per cent of publications in Egypt are in chemistry, 15 per cent in engineering and 14 per cent in physics and astronomy, while in South Africa, some 7 per cent are in chemistry, 13 per cent in engineering and 10 per cent in physics and astronomy. According to a study conducted by the New Partnership for Africa's Development (NEPAD) in 2014, these differences are also reflected in the distribution of researchers by their main fields of research.

3.2. NANOTECHNOLOGY INVENTIONS

The trends in patent applications may provide an indication of the perceived value of the knowledge generated in economic and technological terms. This is based on the assumption that patents are expensive to register, maintain and defend. As such, individual inventors, institutions and companies weigh the costs and benefits of patenting. By looking at patents filed with the two major patent offices that are regarded as global repositories of knowledge of global importance (the United States Patent and Trademark Office (USPTO) and the European Patent Organization (EPO)), it is possible to take into account national differences in patenting practices.

Between 2001 and 2017, some 141,170 patent applications were filed with the two aforementioned offices. The United States remains the largest contributor, followed by the Republic of Korea, Japan and Germany (see figure III). Between 2010 and 2017, the fastest growth rate was posted by Saudi Arabia (from 8 to 167 applications, equivalent to an increase of some 2,000 per cent), followed by China (143 per cent) and the Republic of Korea (71 per cent). However, most mature economies registered modest growth rates during that period.

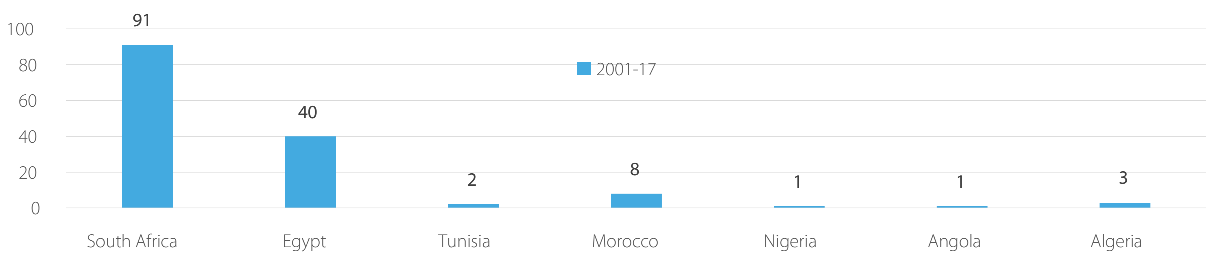
Figure III Patent applications (USPTO plus EPO): top countries



Source: *NanoStat database.*

At the continental level, Egypt and South Africa lead in terms of the number of patent applications filed with the two offices. Between 2001 and 2017, South Africa filed 87 patent applications for nanotechnology-related inventions with USPTO and only seven with EPO (see figure IV). All of the 40 patent applications of Egypt were filed with USPTO. Although an increasing number of patent applications are being filed by African countries, growth remains uneven and limited. Indeed, Saudi Arabia applied for more nanotechnology patents with USPTO in 2017 than the total number of nanotechnology patent applications that have been filed by South Africa and Egypt over the last 17 years.

Figure IV Patent applications by selected African countries (total, 2001-2017)



Source: *NanoStat database.*

3.3. STANDARDS AS INDICATORS FOR NANOTECHNOLOGY READINESS

Another indirect way of assessing nanotechnology development and/or its technological readiness is by looking at the adoption of technology specific standards. Standards are important in that they promote innovation and efficiency among companies and facilitate international trade. Standards also reduce barriers to entry into existing industries by facilitating the use of existing goods, services and infrastructure. However, standards are also important tools for policymaking and corporate planning in that they provide clear guidelines on safety, quality and performance expectations. Standards facilitate communication and understanding and thus promote interoperability and compliance with national and international laws and regulations.

In 2005, the International Organization for Standardization (ISO) established a technical committee on nanotechnologies (TC 229), which has played a key role in developing standards. Other efforts include those exerted by the European Committee for Standardization (CEN) and the American Society for Testing and Materials International (ASTM). ISO TC 229 focuses on setting standard with a view to:

> Understanding and controlling matter and processes at the nanoscale, typically, but not exclusively, below 100 nanometres in one or more dimensions where the onset of size-dependent phenomena usually enables novel applications;
>
> Utilizing the properties of nanoscale materials that differ from the properties of individual atoms, molecules and bulk matter to create improved materials, devices, and systems that exploit these new properties.[13]

TC 229 has established 65 standards and 45 more standards are currently under development (both counts include updates). These standards are for "terminology and nomenclature; metrology and instrumentation, including specifications for reference materials; test methodologies; modelling and simulations; and science-based health, safety, and environmental practices."[14] Of the 39 participating member countries, Africa is represented by only one country – South Africa – while Asia is represented by seven countries and Latin America by three. Another five African countries – Egypt, Ethiopia, Kenya, Morocco and Zambia – serve as observer members.

Table 1 Number of nanotechnology standards established by selected developing and developed countries since 2013

	2013	2014	2015	2016	2017	2018 [June]
China	18	15	9	58	21	
European Union	2	4	8	8	16	1
France	6	9	18	1	10	
Germany	2	12	8	8	4	
India	1				3	
Indonesia	3		13	15	2	
Iran (Islamic Republic of)	4	13	13	10	26	10
Japan	14	3	7	9	18	
Peru				2	3	
Republic of Korea	5	6		7	7	
Russian Federation	2	6	4	20	10	14
Sweden	9	1	11	10	1	
Taiwan Province of China	8		2			6
Thailand		7				
United Kingdom	9	11	14	16	51	5
United States of America	12	4	5	4	5	
World	18	12	37	45	87	5

Source: *Nanostat database (accessed October 2018).*

Working definition used by Nanostat: Standard is a document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context.

13 See www.iso.org/committee/381983.html

14 Ibid.

Australia, China and the Republic of Korea had established at least one nanotechnology standard by 2001 and they were soon joined by Japan and United States of America by 2004. Since then, the number of countries adopting nanotechnology standards, as well as the overall number of nanotechnology standards, have both grown rapidly (see table 1). In particular, a rise in the number of nanotechnology standards established by the Islamic Republic of Iran, the European Union, the Russian Federation and the United Kingdom has been noted in recent years. While there are at least seven Asian countries and territories and one Latin American country that have published a nanotechnology standard, there seems to be no African country that has so far done so.

3.4. AN EMERGING NANOTECHNOLOGY INDUSTRIAL BASE

One can divide nanotechnology businesses into two major categories: (a) companies that make the tools and devices needed to operate at nanoscale, and (b) companies that integrate nanotechnology into their existing products. The first category of firms includes manufacturers of equipment and devices that can observe and measure materials at nanoscale, such as electron microscopes (e.g. Thermo Fisher Scientific, Nanosurf) and drug delivery systems (e.g. 10Angstroms, a provider of a lithography device that enables fabrication at 5 nanometre line width), as well as developers of modelling and software (e.g. Abeam Technologies), which is facilitating the manufacture of new products. The majority of these specialized firms are start-ups or arms of existing firms that focus primarily on providing solutions for nanotechnology research and industry.

The second category comprises companies that use systems developed by the first category of companies to improve existing products and design new ones. This category primarily comprises producers of semiconductors (e.g. Intel Corporation), electronic devices, chemicals and pharmaceuticals (e.g. BASF), and energy products. While some of the technology giants may also offer solutions needed for nanotechnology research and development, their investors and shareholders tend to be particularly interested in how nanotechnology applications can improve the competitiveness of their existing and emerging product ranges (e.g. Chevron, Exxon Mobil, General Electric, Intel, Samsung and Toyota). This group of companies account for a high proportion of the nanotechnology-enabled products available in the marketplace.

There are no data available on the number of African companies marketing nanotechnology products and processes. However, a number of such firms are already in existence. The most prominent of those firms include the following: PST Sensors, founded in 2010 by researchers and with the University of Cape Town as a minority shareholder, which specializes in printed silicon technology used in temperature sensors; NanoTech Egypt, the first company in the Arab world manufacturing on-demand nanomaterials; and Comar Chemicals, a manufacturer of catalysts with plants in Cape Town, South Africa, and Muttenz, Switzerland. Numerous other manufacturers of chemicals, textiles, pharmaceuticals and cosmetics also make use of nanomaterials.

One of the emerging areas of interest is nanotechnology-enabled digital identification, where nanotechnology incorporated into physical documents or assets can provide reliable, long-term, efficient and tamper-free security, along the lines of the security that can be provided for digital assets by blockchain technology applications. Traditional identification methods, such as radio frequency identification (RFID) and related tags are easily damaged, and it is relatively simple to hack or generate fraudulent Quick Response (QR) codes.[15] Indeed, the large size and visibility of those tags and codes

15 China, one of the world's largest mobile payment markets, witnessed at least $13 million in QR code fraud in 2017. In 2018, the country introduced caps on QR code payments. Further details are available at: www.theverge.com/2017/12/28/16826698/china-qr-code-payment-regulation.

means that they are easily tampered with. On the other hand, a nano-optics code that is too small to be seen with the naked eye can be incorporated into almost any physical asset to provide a secure long-term physical-to-digital data link. Such codes could find wide applications in areas such as health care, transportation, retail, trade, education and documentation. Indeed, nanotechnology and blockchain technology could be incorporated into the proposed ECA and African Union African digital identification initiatives in order to bolster the security of those systems.

Another emerging trend is in development of the Internet of Nano Things (IoNT), [16] [17]at the heart of which is the increasing presence of nanodevices or nanocomponents capable of collecting, processing, receiving and sharing data. This is leading to the creation of micro-networks connecting a range of devices using the Internet. Such nanodevices and components, which include cameras, processors, antennas, transceivers, power systems and memory cards, can be integrated into health, industrial, transport, security and other systems. The global IoNT market was estimated to be worth some $4 billion in 2016 and is expected to achieve a Compound Annual Growth Rate of 22.8 per cent between 2016 and 2020.[18]

3.5. SOME OBSERVATIONS

Nanotechnology has often emerged as an area of research in chemistry, physics and engineering departments, laboratories and research centres. Thus, it appears that countries with more extensive research activities in those fields are more likely to conduct nanotechnology research. For instance, although the overall number of research articles published in China is comparable to that of the United States of America, twice as many nanotechnology articles are published in China than in the United States. Similarly, although the total number of articles in all fields of research that are published in India is about 25 per cent of the number published in the United States, India publishes about half the number of nanotechnology research articles as the United States does. In part, this is due to the fact that some 51 per cent of all the articles published in China and 43 per cent of articles published in India are in chemistry, engineering and physics-related fields, compared with only 24 per cent in the United States and 24 per cent in the European Union. The same is observed for Egypt when compared with its African peers.

Table 2 Research articles in various fields as a percentage of all research articles published

Field	World	United States	European Union	China	India
All articles (number)	2 295 608	408 985	613 774	426 165	110 320
Engineering	18.4	12.3	14.6	28.9	24.2
Chemistry	7.9	5.1	6.7	12.3	10.1
Physics	8.7	6.7	8.3	9.9	9
Computer sciences	8.3	6.4	8.6	8.7	14.1
Biological sciences	15.3	17.9	15	14	14.5
Medical sciences	22.1	29.3	24.4	13.3	15.3
Other fields	19.3	22.3	22.4	12.9	12.8

Source: *United States Science and Engineering Indicators (2017).*

Irrespective of the indicators one uses, it is clear that African countries lag behind most other countries in almost all areas of nanotechnology. While the research base is growing, albeit from a small base, the continent is developing virtually no products for the growing nanotechnology market. Industrialization and trade in Africa will be significantly impeded if the continent does not develop its nanotechnology

16 Anand Nayyar, Vikram Puri and Dac-Nhuong Le, "Internet of Nano Things (IoNT): Next Evolutionary Step in Nanotechnology", in Nanoscience and Nanotechnology, Vol. 7 No. 1 (2017).

17 Ezz El-Din and Manjaiah. "Internet of Nano Things and Industrial Internet of Things", in: Internet of Things: Novel Advances and Envisioned Applications. Studies in Big Data, vol 25, Acharjya and Geetha, eds. (Springer, Cham, Switzerland, 2017).

18 See: www.marketsandmarkets.com/Market-Reports/internet-nano-things-market-10414659.html

sector. For instance, improved nanotechnology-enabled packaging could be used to reduce the use of food preservatives, many of which are being restricted or banned in certain countries. It is clear that, moving forward, all countries will need to develop a basic nanotechnology base.

4. NANOTECHNOLOGY AND THE SUSTAINABLE DEVELOPMENT GOALS

Nanotechnology presents developing countries with significant opportunities and challenges for advancing their economic, environmental and social development aspirations, including the full attainment of the 2030 Agenda for Sustainable Development. As an enabling factor, nanotechnology is likely to have an impact on all 17 Sustainable Development Goals. The question one should ask is, perhaps: The attainment of which Goals is likely to be most directly facilitated by nanotechnology, and in which ways? It should be borne in mind, moreover, that, given that the 54 countries in Africa are at various stages of economic, social, technological and educational development, the potential impact of nanotechnology is likely to vary widely across the continent.

Nanotechnology is advancing rapidly and some applications that were only recently believed to be practically impossible or too expensive for real-world applications may become feasible. Our current predictions about the future of nanotechnology are likely to be guesswork at best. For instance, in 1992, Paul Horn, who at that time was employed by the company IBM, suggested that nanoscience was unlikely to have any impact on mainstream electronics technology over the following 25 years. Fifteen years later, he was betting that nanotechnology would become part of the mainstream electronics industry.[19] Indeed, it is hard to predict the future of technology as advances in available tools make technology more useful and accessible.

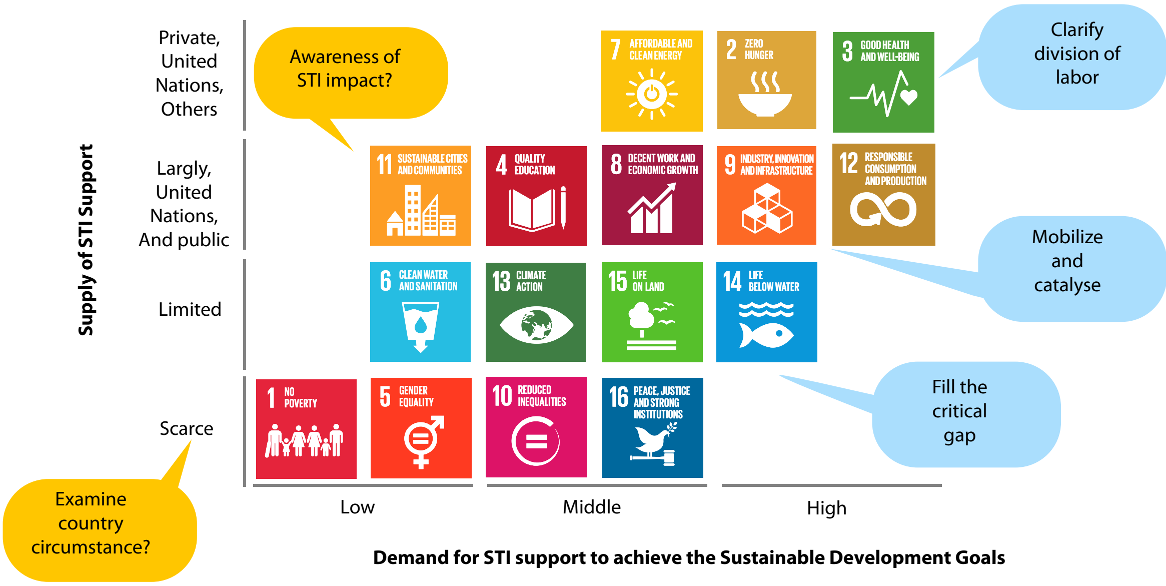
Table 3 Assessment of technology and business opportunities

Sustainable Development Goal	High impact tech	Scale of business opportunity	Interpretation
2-Zero hunger; 3-Health; 7-Energy	60	$6 trillion	Most efforts, emerging technologies and business opportunities relate to these three Goals
4-Education; 8-Economic growth; 9-Infrastructure and industrialization; 11-Cities; 12-Sustainable consumption and production	15	$5 trillion	Mostly public efforts to attract private sector engagement. Limited emerging technology and fewer private sector initiatives.
6-Water and sanitation; 13-Climate change; 14-Oceans; 15-Biodiversity, forests, desertification	7	$0.5 trillion	Global efforts to support country initiatives. Limited private sector engagement.
1-End poverty in all its forms; 5-Gender equality and women's empowerment 10-Inequality; 16-Peace, justice and strong institutions	4	$0 trillion	Role of technology largely indirect

Demand for STI support to achieve the SDGs

19 For further details, see www.forbes.com/2007/03/21/nanotech-ibm-horn-a-pf-guru-in_jw_0321soapbox_inl.html#7f442a1c7122.

Figure V Technology supply and demand



Source: *Available at sustainabledevelopment.un.org/content/documents/10789 Chapter3_GSDR2016.pdf (accessed 21 December 2019).*

As an enabling factor, nanotechnology is likely to have greater impact on those Goals for which technology supply and demand is high. Work by the United Nations inter-agency task team on science, technology and innovation for the Sustainable Development Goals shows that most emerging technologies are applicable to Goals 2, 3 and 7. This is due to the significant business opportunities that efforts to achieve those Goals could create (it is estimated that those business opportunities may generate some $6 trillion annually by 2030). Most private sector investment is thus concentrated in those areas. Although it is estimated that the business opportunities offered by Goals 4, 8, 9, 11 and 12 may generate some $5 trillion annually by 2030, investment in those areas is led, primarily, by public sector stakeholders, with only limited private sector engagement. Science, technology and innovation will have only a moderate impact on Goals 6, 13, 14 and 15 and they are likely to have only an indirect impact on Goals 1, 5, 10 and 16. Indeed, there is still no significant private sector engagement in those areas. (see table 3 and figure V). It is assumed that there will be no significant shift in current trends before 2030.

Table 4 Top 10 applications of nanotechnology in developing countries

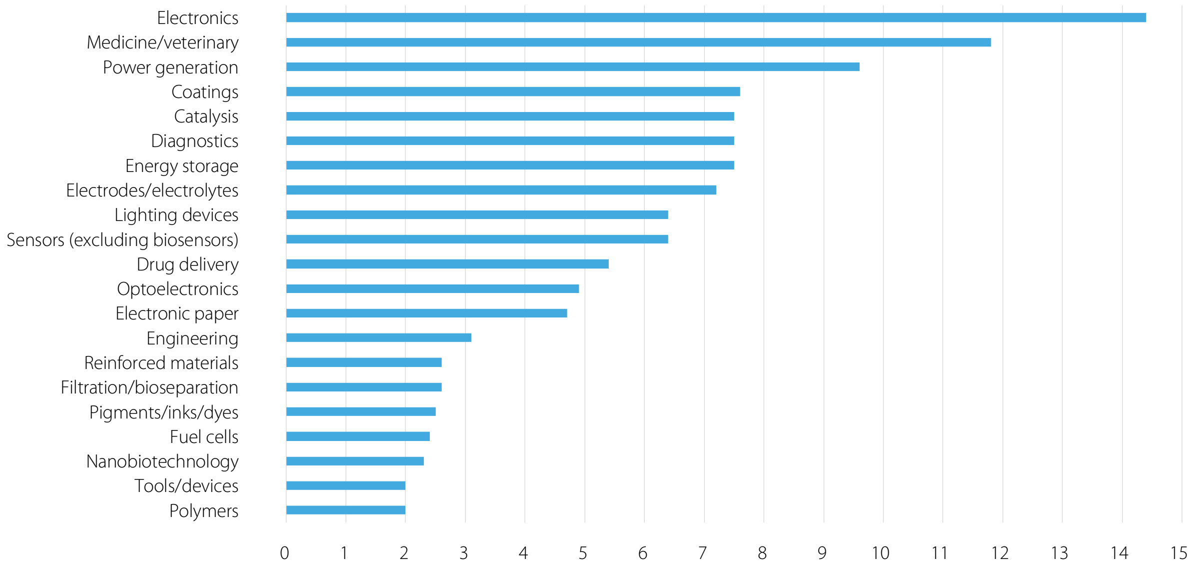
	Primary Goal	Secondary Goals
1. Energy storage, production, and conversion	7 (Energy)	9 (Infrastructure, industrialization)
2. Agricultural productivity enhancement	2 (Zero hunger)	1 (End poverty in all its forms)
3. Water treatment and remediation	6 (Water and sanitation)	3 (Health)
4. Disease diagnosis and screening	3 (Health)	9 (Infrastructure, industrialization)
5. Drug delivery systems	3 (Health)	9 (Infrastructure, industrialization)
6. Food processing and storage	2 (Zero hunger)	13 (Climate change)
7. Air pollution and remediation	11 (Cities)	3 (Health)
8. Construction	9 (Infrastructure, industrialization)	11 (Cities)
9. Health monitoring	3 (Health)	11 (Cities)
10. Vector and pest detection and control	3 (Health)	11 (Cities)

Source: *ECA, based on Fabio Salamanca-Buentello and others, "Nanotechnology and the Developing World," PLOS Medicine, vol. 2 (2003).*

There have also been a number of efforts to assess the potential impact of nanotechnology in advancing opportunities for economic growth in developing countries. For instance, one research project used a modified Delphi methodology (analysing the opinions of, among others, top industrial leaders and researchers) and identified energy, agriculture, water, health, pollution, construction and pest control as the top 10 possible applications for nanotechnology in developing countries (see table 6). There seems to be an emerging consensus that the Goals related to energy, food, health, water, cities/communities and industry/infrastructure offer the greatest potential for growth powered by nanotechnology.

Alternatively, one can ascertain which Goals are most likely to be affected by nanotechnology by looking at the number of relevant patents filed. The number of patent applications gives an indication of the fields in which inventors hope to bring products or processes to market or wish to defend market share. Most patents are filed in the areas of information technology, energy, health and life sciences and materials. That tendency was also observed in a 2004 assessment of patent applications filed with patent offices in Japan, the Republic of Korea, the European Union and the United States of America, and of patent applications registered with the World Intellectual Property Organization (WIPO).[20] It was noted in that assessment that over 80 per cent of patent applications were filed by corporations.

Figure VI Main areas in which patents are filed (as a percentage of the total number of patents filed)



Source: *Nanotech database, Springer.*

There are several ways in which these results can be interpreted. Firstly, the Goals relating to areas in which private sector stakeholders have identified significant financial opportunities are likely to benefit the most from nanotechnology applications, while Goals relating to other areas may not, unless government provides a conducive environment in which private sector interests can drive nanotechnology research and innovation. Secondly, it is possible that the legal and regulatory requirements relating to the attainment of certain Goals, particularly those relating to clean water, peace, security and the establishment of strong institutions, may discourage private sector engagement, especially by larger firms. It is possible, however, that those areas may offer attractive opportunities for public utilities and small firms. Governments could give priority consideration to those areas and provide resources and leadership to ensure nanotechnology can facilitate the attainment of those Goals. For example, a number of African countries are prioritizing the creation of a green economy and government support for the development of nanotechnology applications in that area could be encouraged (see annex 1 for examples of such applications).

20 Study available at: http://data.nistep.go.jp/dspace/bitstream/11035/2731/1/NISTEP-STT021E-77.pdf.

In sum, African countries have still not identified where they can effectively support the nanotechnology industry and have yet to give priority attention to supporting the development and application of nanotechnologies that are likely to have a significant impact on certain Sustainable Development Goals. Given African countries' limited resources and scientific, technological and industrial bases, some focus will be needed to achieve depth. However, it is possible that the areas where nanotechnology will have the greatest impact are poorly aligned with the continent's capacity and interests.

5. TOWARDS AN AFRICAN NANOTECHNOLOGY INNOVATION SYSTEM TO ACHIEVE SUSTAINABLE DEVELOPMENT GOALS

There are several definitions of a national innovation system. These include "the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies" (Freeman, 1987); "[...] the elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge ... and are either located within or rooted inside the borders of a nation state." (Lundvall, 1992) and "[...] a system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts which define new technologies" (Metcalfe, 1995). While the theoretical definitions are easier to describe, cultivating a national innovation system remains problematic because innovation does not occur independent of other components and systems within the national State.

In general, national innovation systems involve five broad spheres, namely society, policy, the knowledge base, industry and markets. Support must be provided in all those spheres in order to ensure that interactions among the various stakeholders encourage innovation. Interest or lack thereof in developing or applying a technology may be influenced by political, economic, social, cultural or governmental considerations and national policies in sectors such as agriculture, health, education, trade, industry, energy and the environment may also support or discourage innovation in certain technologies. The knowledge base, as embodied by academia, public and private research centres and research and development units, generates the skills and knowledge that is needed by and/or informs society, policymakers, industry and markets or can facilitate knowledge acquisition. Industry, as embodied by manufacturers, distribution and supply chains and sales of goods and services, drives innovation through its engagement with consumers and its promotion of knowledge transfers. Finally, market rules, conditions and standards, including those relating to finance, trade and intellectual property may also encourage or discourage technological innovation.

African countries need to create an environment in which society, policies, knowledge generation, industry and markets all support the nanotechnology industry. Below we consider a range of factors that can help create a conducive nanotechnology innovation ecosystem, bearing in mind that nanotechnology is transforming the production of almost all products, from textiles[21] to biological computers,[22] and is strengthening both established technologies, such as those used in energy generation, to emerging technologies, such as robotics and artificial intelligence. Drawing on lessons learned by other countries and regions, this report focuses on elements that can help countries with a limited scientific and

21 Kyle Wilke, Daniel Preston, Zhengmao Lu, and Evelyn Wang, "Toward Condensation-Resistant Omniphobic Surfaces", in ACS Nano, 12 (11), 11013-11021 (2018).

22 Nathaniel Roquet, Ava Soleimany, Alyssa Ferris, Scott Aaronson, and Timothy Lu, "Synthetic recombinase-based state machines in living cells", in Science, vol. 353, Issue 6297 (2016).

technological base undertake research and development, market their products and promote the adoption of nanotechnology solutions in their markets.

5.1. INSTITUTIONAL ARRANGEMENTS FOR NANOTECHNOLOGY DEVELOPMENT

Most countries that are making significant progress have established clear nanotechnology institutional arrangements. While initiatives by China, the European Union, Japan and the United States of America are often used as examples, developing countries that have made similar efforts seem to have attained good results too. For instance, Iranian nanotechnology is overseen by the Iran Nanotechnology Innovation Council (INIC), which was established in 2003 following a study conducted in 2001 of the potential of nanotechnology to promote the Islamic Republic of Iran's economic and social development. INIC is responsible for setting, coordinating and overseeing national nanotechnology initiatives and the sector's development. INIC has working groups on policy, standards, awareness raising, human resource development as well as on scientific, industrial and marketing aspects of nanotechnology. INIC held its 11th international nanotechnology festival in October 2018.

INIC supports some 80 laboratories in 40 cities by helping them maintain and/or acquire new equipment, train laboratory technicians, and attain ISO 17025 (the standard for calibration and testing laboratories). It also supports the creation of specialized nanometrology and nano-instrumentation centres and engagement with strategic partners abroad, including those in Brazil, India, the Russian Federation and Ukraine.[23] The country has taken part in a number of regional and global forums established to assess trends, including the ISO working group on nanotechnology (where most developed countries are members) and the Non-Aligned Movement Science and Technology Centre. The Islamic Republic of Iran, which is currently ranked in the top 15 nanotechnology research countries worldwide, manufactures nanotechnology products[24] that are both used domestically and exported abroad.

The Republic of Korea has also formulated a strategy to promote technology development, which facilitates collaboration between the public and private sectors in the areas of planning, implementation and monitoring technology development, and establishes clear targets to be reached, such as the number of researchers to train, the number of centres and start-ups to be established, the funds to be invested by the public and private sectors, and goals for export revenues, market share and income per capita. This facilitates the evaluation of development plans. The Republic of Korea National Nanotechnology Initiative was launched in 2000[25] and was approved by the Science and Technology Council in 2001. Furthermore, the Nanotechnology Development Act was adopted in 2002, and this has established a firm legal framework for research and development in nanotechnology. A number of specialized nanotechnology research facilities have also been developed. The country's 10-year rolling plan is reviewed every five years, and several road maps and strategies have been drawn up on industrial development, standards, training and safety. A committee to sustain government support has been created. The overall objective of the overall plan was to make the Republic of Korea one of the top three nanotechnology generating countries by 2015 (it has nearly accomplished that objective and is currently ranked fourth in the world), [26]and it focuses, in particular, on research infrastructure and manpower development, especially in areas in which the country already has a competitive advantage, such as biotechnology, information technology and environmental technology.

23 For further information, see: www.sciencedev.net/Docs/Iran_Nano.pdf.

24 See: nanoproduct.ir/index.php?lang=2.

25 Dae Sup So and others "Nanotechnology policy in Korea for sustainable growth" in Journal of Nanoparticle Research 14: 854 (2012).

26 For further information, see "South Korea Plans to Stand among World's Top 3 States in Nanotechnology", in Statnano, (2013). Available at: statnano.com/news/45450

5.2. HUMAN CAPITAL DEVELOPMENT

It is nearly impossible to ascertain the number of nanotechnologists in Africa or the number of departments with nanotechnology training and research programmes. The number of scientific articles and patents filed suggests that the nanotechnology research base of most African countries is either too small to assess indirectly or non-existent. African countries should therefore invest in training a large pool of nanotechnologists and stimulate research in nanotechnology. This could help Africa avoid the current challenges faced in finding experienced information and communications technology (ICT) and biotechnology experts and researchers. Other countries are already making progress in that area. For example, in 2001 the Republic of Korea set out to train 13,000 nanotechnology specialists by 2010. African countries may have to set similar targets in line with their available resources and needs. Nanotechnology experts who invariably have a good understanding of their background fields, such as physics, engineering and biomedical sciences, should receive nanotechnology training in their primary areas of expertise, particularly at post-graduate level. Rather than just a few dozen specialists, African countries should aim to train hundreds or thousands of nanotechnology specialists in all relevant fields and industries, including textiles, chemicals, pharmaceuticals, electronics, food and water management.

5.3. RESEARCH INFRASTRUCTURE

Nanotechnology requires large investments in research infrastructure. Countries may either build new specialized research centres (the approach taken by the Republic of Korea) or create nanotechnology institutes at existing research facilities (the approach adopted by the Islamic Republic of Iran and the United States of America). By creating a network of carefully selected laboratories and providing adequate financial and other resources, it is possible for countries to establish an effective base of expert knowledge in nanotechnology.

For example, in 1998, the São Paulo State Research Support Foundation (FAPESP) in Brazil established a virtual network of 35 independent laboratories that then formed a single genome sequencing institute. FAPESP equipped the laboratories with state-of-the-art genome sequencers, which were used to train over 200 young geneticists and successfully sequenced Xylella fastidiosa, an organism that infects oranges, in record time and within budget at a time when genome sequencing was the preserve of an exclusive club of well-funded research facilities in developed countries. The laboratories were selected on the basis of competitive bids and laboratories were paid for the number of high-quality genetic sequences deposited and not for being part of the network.

5.4. FUNDING REGIONAL RESEARCH

Funding remains a major challenge and Governments may have to take the lead in funding nanotechnology research. There are three major sources of research and development funding, namely public sector funding, private sector funding and funding provided by private-non-profit organizations. In Africa, Governments are the main source of funding, followed by donors and the private sector.[27] Data from both developed and developing countries shows that the public sector, including Governments and higher education institutions is the most significant source of funding for nanotechnology research and development.

27 NEPAD, African Innovation Outlook II (2014). Available at: https://nepad.org/publication/african-innovation-outlook-ii.

Public sector funding is sensitive to public perceptions, especially in a democracy. It is therefore important to promote the nanotechnology research agenda as a way to foster national development or address the basic needs of the population, including clean water, health care, energy and security. Another effective approach is to appeal to national pride, for example by stressing that a certain microscope is ranked as the foremost or most powerful microscope in the region. By partnering with influential individuals and respected institutions in order to promote the development message, it is possible to attract more partners and mobilize further resources for nanotechnology research and development.

5.5. GOVERNANCE OF NANOTECHNOLOGY INNOVATION SYSTEMS

The governance of nanotechnology, like other technologies, may be described as the set of institutional arrangements that guide the behaviour of public and private actors. Those arrangements may include regulations, laws and incentives. The OECD framework recognizes four levels of innovation governance: (a) Policymaking: this is guided by politicians, parliament and ministries and other stakeholders that set the nanotechnology agenda, priorities and plans; (b) Operations: this is guided by commissions, funds and other relevant agencies that implement adopted plans; (c) Science technology and innovation (STI) constituencies/actors: this is guided by industries, institutes and research groups that perform STI activities and (d) Policy analysis: this is guided by policy researchers, consultants and development agencies whose work inform decisions of policymakers and other relevant stakeholders. Countries must adopt nanotechnology governance arrangements that are likely to work in their unique political, economic and social environments and must ensure that they understand what is likely to work or fail in their countries when designing national nanotechnology initiatives or programmes.

Some governance aspects will be common to all countries. These may include setting safety and intellectual property rules to encourage safe use as well as collaboration among researchers and between researchers and industry. Standards are another important aspect of governance to the extent that they encourage collaboration, partnerships and trade. These may include standards on the safe handling of nanomaterials, good practices and assessing environmental contamination.

5.6. LEVERAGING REGIONAL AND GLOBAL RESOURCES

Although they are latecomers in the nanotechnology sphere, African countries are in a strong position to develop their nanotechnology initiatives by leveraging global and regional partnerships. The number of developed and developing countries launching and expanding nanotechnology programmes is growing rapidly. Furthermore, the number of companies that are showing interest in Africa's expanding markets is also expanding very fast. Importantly, Africa remains the final frontier for a growing number of investors and has good business and political relations with both developed and developing countries. Many of these investors are becoming increasingly aware of unmet needs across the continent, including the needs for energy, water, health-care services, education, housing, food and transport. Nanotechnology applications in these areas are expanding. Priority attention should be given to the establishment of strategic international partnerships in research, trade and marketing that ensure that African countries become major nanotechnology players on the world stage.

6. CONCLUSION

The 2030 Agenda for Sustainable Development recognizes that science, technology and innovation are key to achieving desired development outcomes and impacts. Several targets include a special focus on technology. For example, Target 2.A calls for "Increase[d] investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and plant and livestock gene banks in order to enhance agricultural productive capacity in developing countries, in particular least developed countries." Similarly, Goal 17 seeks to enhance North-South and South-South cooperation on and access to science, technology and innovation and enhance knowledge sharing, as well as to fully operationalize a science, technology and innovation capacity-building mechanism for least developed countries.

While not every African country may become a nanotechnology powerhouse, they can nonetheless leverage nanotechnology created elsewhere to achieve their development goals, in the same way that mobile devices that are not manufactured in Africa have helped to drive growth and inclusion on the continent. Africa should not wait for nanotechnology to be fully tested and approved for the following two reasons: (a) delaying the adoption of nanotechnology is likely to exacerbate knowledge gaps and further relegate African States to the status of mere consumer countries; (b) delaying the adoption of nanotechnology will erode the continent's already limited capacity to manage and regulate nanotechnology products and further increase its dependence on external experts, as has already been the case in the areas of agricultural biotechnology and biomedical engineering and with the Internet.

Table 5 Nanotechnology for the green economy

Application	Description of nanotechnology
Energy conversion and storage	Smart energy nanotechnology can improve power delivery systems so that they are safer and more efficient and reliable.
	Nanodevices can exploit renewable energy produced from naturally replenished resources, including sunlight and wind. This reduces dependence on fossil fuels and reduces greenhouse gas emissions.
	Energy efficient nanotechnology requires less energy to perform the same function – getting more use out of energy that has been generated.
Water cleanup technologies	The design of nano-enabled infrastructure necessary to manage water and keep it clean is inextricably linked to prospects for economic development and an improved quality of life.
	Access to clean water and adequate sanitation is a basic human right and is critical to the alleviation of poverty.
	Investment in infrastructure and green water policies can reduce the costs incurred by water shortages.
Construction industry	Nanotechnology can increase the efficiency of the construction industry and its use of energy, water and materials. The impact of buildings on the environment and human health can be improved through better siting, design, construction and materials removal.
	Nanomaterials applied to the surfaces of structural elements of buildings can promote environmentally-friendly cleaning by harnessing photocatalytic reactions.
Other applications	Nano-enabled applications can provide for the slow release of fertilizers and efficiently conserve water for plants. This may increase agricultural productivity, especially in countries with prolonged dry spells.
	Nanopackaging characterized by enhanced barrier and mechanical properties can improve the shelf life of foods. This is of particularly important in regions where refrigeration is not easily available.
	Nanosensors may improve the quality and reduce the cost of continuous environmental monitoring. Nanoremediation of environmental pollution may exceed conventional methods in terms of efficiency and speed.

Source: *Ivo Iavicoli and others (2014).*[28]

28 Ivo Iavicoli and others, "Opportunities and challenges of nanotechnology in the green economy", in Environmental Health, vol. 13, No. 1, p. 78 (2014).

CHAPTER 2.

NANOTECHNOLOGY FOR AFRICAN DEVELOPMENT: CHALLENGES AND OPPORTUNITIES

1. INTRODUCTION

Nanotechnology is an emerging technological field that promises to be one of the prime movers of the fourth industrial revolution.[29, 30] The key defining feature of nanotechnology is the size of the materials involved.[31] The primary appeal of nanotechnology lies in its potential to create and manipulate matter at the nanoscale, which provides control over atoms and molecules.[32, 33] This leads to the possibility of manufacturing novel materials that have specific and manipulable properties and functions. The superior properties of such materials include enhanced electrical and electronic conductivities, lower thermal transmission, and higher temperature deformation characteristics compared with their conventional bulk material counterparts.[34]

At the nanoscale, certain materials have the potential to boost performance and increase functionality in areas such as energy storage, water purification, drug delivery, robotics, artificial intelligence, autonomous vehicles and quantum computing. Over the past 30 years, there has been a sharp increase in scientific interest and research funding devoted to nanotechnology, particularly in developed countries.[35] Developing countries stand to benefit from nanotechnology as its applications are pervasive and permeate various facets of the Sustainable Development Goals such as poverty eradication, good health and well-being, clean water and sanitation and affordable and clean energy. African countries are now launching initiatives aimed at harnessing nanotechnology; these range from the enactment of policies to the establishment of programmes which bring academic and industrial players together.

2. APPLICATIONS OF NANOTECHNOLOGY IN DEVELOPING COUNTRIES

Nanotechnology is emerging as an indispensable component of the global development discourse in the light of expectations that it will be instrumental in alleviating poverty and promoting sustainable development.[36 37] Advances in nanotechnology are profoundly influencing the ways in which future possibilities and human abilities are conceptualized. For example, the convergence of nanotechnology with biotechnology, information technology, cognitive science, and engineering provides opportunities for the improvement of human performance at a number of levels.[38] The applications of nanotechnology are summarized in table 6.

29 Liming Dai, "From conventional technology to carbon nanotechnology: the fourth industrial revolution and the discoveries of C 60, carbon nanotube and nanodiamond", in Carbon nanotechnology: Recent Developments in Chemistry, Physics, Materials Science and Device Applications, (Elsevier B.V., 2006) pp. 3-11.

30 Andrew Maynard, "Navigating the fourth industrial revolution" in Nature nanotechnology, vol. 10, No. 12, pp. 1005-1006 (2015).

31 Cynthia Selin, "Expectations and the Emergence of Nanotechnology" in Science, Technology and Human Values, vol. 32, No. 2 (2007), pp. 196-220.

32 Jürgen Biener and others, "Surface chemistry in nanoscale materials", in Materials, vol. 2, No. 4, pp. 2404-2428 (2009).

33 Ibrahim Khan, Khalid Saeed and Idrees Khan, "Nanoparticles: Properties, applications and toxicities", in Arabian Journal of Chemistry, Vol. 12, Issue 7 (November 2019), pp. 908-931.

34 Zhi-Gang Chen and others, "Nanostructured thermoelectric materials: current research and future challenge", in Progress in Natural Science: Materials International, vol. 22, No. 6 (2012), pp. 535-549.

35 Mihail Roco, Chad Mirkin and Mark Hersam. (2010). "Nanotechnology research directions for societal needs in 2020: summary of international research", in Journal of Nanoparticle Research, vol. 13, issue 3 (2011), pp 897–919.

36 Ram Prasad, Vivek Kumar and Kumar Suranjit Prasad, "Nanotechnology in sustainable agriculture: present concerns and future aspects" in African Journal of Biotechnology, 13(6) (2014), pp. 705-713.

37 Fabio Salamanca-Buentello and others, "Nanotechnology and the developing world", in PLoS Medicine, 2(5): e97, (June 2005).

38 Mihail Roco and William Bainbridge, "Converging technologies for improving human performance: integrating from the nanoscale", in Journal of Nanoparticle Research, vol. 4, No. 4 (August 2002), pp. 281-295.

Table 6 Applications of nanotechnology in developing countries

Applications of nanotechnology	Examples
Energy storage, production and conversion	Novel hydrogen storage systems based on carbon nanotubes and other lightweight nanomaterials Photovoltaic cells and organic light-emitting devices based on quantum dots Carbon nanotubes in composite film coatings for solar cells Nanocatalysts for hydrogen generation Hybrid protein-polymer biomimetic membranes
Agricultural productivity enhancement	Nanoporous zeolites for slow-release and efficient dosage of water and fertilizers for plants, and of nutrients and drugs for livestock Nanocapsules for herbicide delivery Nanosensors for soil quality and for plant health monitoring Nanomagnets for removal of soil contaminants
Water treatment and remediation	Nanomembranes for water purification, desalination and detoxification Nanosensors for the detection of contaminants and pathogens Nanoporous zeolites, nanoporous polymers, and attapulgite clays for water purification Magnetic nanoparticles for water treatment and remediation TiO2 nanoparticles for the catalytic degradation of water pollutants
Disease diagnosis and screening	Nanoliter systems Nanosensor arrays based on carbon nanotubes Quantum dots for disease diagnosis Magnetic nanoparticles as nanosensors Antibody-dendrimer conjugates for diagnosis of HIV-1 and cancer Nanowire and nanobelt nanosensors for disease diagnosis Nanoparticles as medical image enhancers
Drug delivery systems	Nanocapsules, liposomes, dendrimers, buckyballs, nanobiomagnets, and attapulgite clays for slow and sustained drug release systems
Food processing and storage	Nanocomposites for plastic film coatings used in food packaging Antimicrobial nano-emulsions for applications in decontamination of food equipment, packaging Nanotechnology-based antigen detecting biosensors for identification of pathogen contamination
Air pollution and remediation	TiO2 nanoparticle-based photocatalytic degradation of air pollutants in self-cleaning systems Nanocatalysts for more efficient, cheaper, and better-controlled catalytic converters Nanosensors for detection of toxic materials and leaks Gas separation nanodevices
Construction	Nanomolecular structures to make asphalt and concrete more robust to water seepage Heat-resistant nanomaterials to block ultraviolet and infrared radiation Nanomaterials for cheaper and durable housing, surfaces, coatings, glues, concrete, and heat and light exclusion Self-cleaning surfaces (e.g. windows, mirrors, toilets) with bioactive coatings
Health monitoring	Nanotubes and nanoparticles for glucose, CO2, and cholesterol sensors and for in-situ monitoring of homeostasis
Vector and pest detection and control	Nanosensors for pest detection Nanoparticles for new pesticides, insecticides and insect repellents

Source: *Fabio Salamanca-Buentello and others (2005)*

The applications of nanotechnology are particularly relevant in the fields of water, energy and health, where it is leading to the emergence of cheaper and more efficient technologies such as improved water filters, energy storage systems, solar powered electricity and portable diagnostic kits.[39, 40] Some of the applications shown in table 6 are already on the market and the development of many more are expected. Furthermore, a number of African countries – including, in particular, Ethiopia, Kenya, Nigeria, South Africa and Zimbabwe – have launched nanotechnology initiatives to address challenges in critical sectors of their economies.

3. THE STATE OF NANOTECHNOLOGY IN SELECTED AFRICAN COUNTRIES

South Africa launched the National Nanotechnology Strategy[41] with a view to facilitating the establishment of characterization centres, creating research and innovation networks, strengthening human capacity and launching flagship projects.[42] Those interventions have provided a platform for the realization of the country's vision of economic growth, poverty reduction and an enhanced quality of life. Driven by the need to foster economic growth and social development, the Strategy identified two development clusters, namely the industrial and social clusters. The industrial cluster focuses on mining, minerals, chemical- and bio-processing and materials and manufacturing, while the social cluster aims to improve the livelihoods of communities through the provision of clean water, affordable and renewable energy and improved primary health care. The development of nanotechnology in South Africa is spearheaded by two national nanotechnology innovation centres, namely those overseen by the Council for Scientific and Industrial Research (CSIR) and by South Africa's national mineral research organization (MINTEK), which collaborate with other national institutions in the design and modelling of innovative nanostructured materials.[43] Through the collaborations established, various projects have been implemented to exploit nanotechnology. CSIR, for example, has implemented a pilot project on the removal of excessive minerals from groundwater using nanomembranes[44] and work is in progress on the development of nano-enabled drugs for the treatment of tuberculosis.[45] Furthermore, the University of Johannesburg is working on nanofilters with the aim of improving water treatment in marginalized communities.[46]

Egypt's Nanotechnology Centre, established in 2008, supports industrial research with the aim of strengthening the national economy.[47] The Centre focuses, primarily, on developing human capital, facilitating the application of nanotechnology in all sectors that are relevant to the economic development

39 Bryan Bruns, "Applying nanotechnology to the challenges of global poverty: strategies for accessible abundance", paper presented at the First Conference on Advanced Nanotechnology: Research, Applications and Policy (Washington D.C., October 2004).

40 Anisa Mnyusiwalla, Abdallah Daar and Peter Singer, "'Mind the gap': science and ethics in nanotechnology" in Nanotechnology, vol. 14, No. 3, R9 (2003).

41 Available at: chrtem.mandela.ac.za/file/35e56e36b6ab3a98fac6fc0c31ee7008/dstnanotech18012006.pdf.

42 Leskey Cele, Suprakas Ray and Neil Coville, "Guest editorial: nanoscience and nanotechnology in South Africa", in South African Journal of Science, vol. 105, Nos. 7-8, p. 242 (July 2009).

43 Anthipi Pouris, Anastassios Pouris and André Buys, "Nanotechnology and biotechnology research in South Africa: technology management lessons from a developing country", paper presented at Proceedings of PICMET '12: Technology Management for Emerging Technologies (2012).

44 Thembela Hillie and Mbhuti Hlophe, "Nanotechnology and the challenge of clean water", in Nature Nanotechnology, vol. 2, No. 11 (November 2007), pp. 663-4.

45 Trust Saidi, "Perceived risks and benefits of nanomedicine: a case study of an anti-tuberculosis drug", in Global Health Innovation, vol. 1, No. 1 (2018).

46 Dlamini, "Polymer composites and nanofiltration membranes and their application in water treatment", (University of Johannesburg, South Africa, 2012).

47 Ashraf Khaled, "Egypt: first nanotechnology centre to boost research", University World News, 26 July 2009.

of Egypt and protecting the intellectual property of innovations with potential for commercialization. The country is strengthening applied and industrial research on solar energy, health care and drug design, water purification technologies, advanced software tools, simulation methods, multi-scale modelling techniques and algorithms.[48, 49, 50] Egypt is also applying nanotechnology in the oil and gas industry to meet the increasing demand for hydrocarbon products and ensure that hydrocarbon operations are environmentally friendly.[51, 52] That particular focus is due to the fact that the oil and gas industry is facing technical challenges linked to operational conditions and geological hazards at greater depths. In addition, Egypt is using nanotechnology to enhance the agricultural sector and the food industry by changing the way in which crops and food are produced, processed, packaged, transported and consumed.[53]

Zimbabwe enacted a national Science, Technology and Innovation policy in June 2012 with the aim of promoting the use of emerging technologies, including nanotechnology, for national development.[54, 55] The country launched its first nanotechnology centre through a partnership between the Government and The State University of New York, working with local universities.[56] This was followed by the release of a nanotechnology statement, which set forth priority areas for the application of nanotechnology.[57] Zimbabwe is seeking to apply nanotechnology in areas such as water purification, energy generation, drug production and mineral beneficiation, in order to accelerate economic growth.[58] The strategic plan of the country is driven by research at tertiary institutions, and four Ethiopian universities have been integrated into clusters, with each cluster tasked with a specific aspect of nanotechnology. However, much of the research on nanotechnology is in its early stages and little progress has been made in bringing specific products to market.

Ethiopia is investing in nanotechnology to ensure the rapid advancement of its agricultural and energy sectors, and its biotechnology and manufacturing industries.[59] However, the country's nanotechnology programme has so far failed to take off because of a lack of effective legislation and policies, and inadequate infrastructure development. Postgraduate courses on nanotechnology have only recently been offered to those wishing to study the subject in Ethiopia.[60]

In Nigeria, the Government has established a national steering committee on the development of nanotechnology. That committee comprises experts and relevant stakeholders who have formulateda road map for the country's active development and use of nanotechnology.[61] The committee is

48 Waleed Abobatta, "Nanotechnology Application in Agriculture" in Acta Scientific Agriculture, vol. 2, No. 6 (2018).

49 Eman Hashem, "Nanotechnology in water treatment, case study: Egypt" in Journal of Economics and Development Studies, vol. 2, No. 3 (September 2014), pp. 243-259.

50 Khaled (2009).

51 Abdelrahman El-Diasty and Adel Salem, "Applications of nanotechnology in the oil and gas industry: latest trends worldwide and future challenges in Egypt", paper presented at the North Africa Technical Conference and Exhibition (April 2013).

52 He Liu, Xu Jin and Bin Ding, "Application of nanotechnology in petroleum exploration and development" in Petroleum Exploration and Development, vol. 43, No. 6 (2016), pp. 1107-1115.

53 Taher Salaheldin, "Green Nanotechnology for Egyptian Sustainable Agriculture Development", paper presented at the Third International Conference on Biotechnology Applications in Agriculture (Benha, Egypt, 2016).

54 Munyaradzi Makoni, "Zimbabwe backs nanotechnology as route to new drugs", SciDev.Net, 11 December 2012.

55 Zimbabwe, Ministry of Science, Technology and Development, Second Science, Technology and Innovation Policy of Zimbabwe (Harare, 2013). Available at: www.healthresearchweb.org/files/Zimbawesciencetechpolicydocumentnew.pdf.

56 Makoni (2012).

57 Comtex, "Zimbabwe launches its first nanotechnology center", Nanowork, 22 March 2013.

58 Zimbabwe, Ministry of Science, Technology and Development, 2013.

59 Henok Tibebu, "What It Takes to Penetrate the Nanotechnology World", The Ethiopian Herald, 26 May 2018. Available at: allafrica.com/stories/201806010374.html.

60 Hailemichael Demissie and others, "Africa's prominent role in the development of the global risk governance of nanotechnology", in Harnessing nanotechnology for sustainable development in Africa, Hailemichael Demissie and others, eds. (Nairobi and Gondor, Ethiopia: ACTS Press, University of Gondar Press and STIC, 2017).

61 Nkechi Isaac, "Nigeria Set To Explore Nanotechnology Development Opportunities", Leadership, 27 February 2018.

responsible for developing a policy framework and implementation strategies for addressing national needs and aspirations through the deployment of nanotechnology. According to at least one researcher, the development and application of nanotechnology in Nigeria remains limited, even though the country launched its first nanotechnology initiative in 2006.[62]

Although nanotechnology is presented as a viable instrument that developing countries can use to close technological gaps,[63], [64] few nanotechnology applications are currently available on the market in Africa, suggesting that a number of challenges continue to hinder the exploitation of nanotechnology by African countries.

4. CHALLENGES IN THE EXPLOITATION OF NANOTECHNOLOGY

Nanotechnology is capital intensive as it requires advanced microscopes and clean room facilities.[65] Many African countries, including those that have developed relevant policies and strategies, are failing to mobilize sufficient financial, human and physical resources to conduct research on nanotechnology. Instead, most of the research is done on an ad hoc basis and this makes it difficult to undertake long-term projects that could have a major impact on African societies. Indeed, most research on nanotechnology that is conducted in Africa is of only academic interest and of limited relevance to the challenges faced by local communities. To address that issue, African countries should pool the resources at their disposal and collaborate at the regional level to address the problems affecting the continent. South Africa, with its well-established nanotechnology infrastructure, is already taking a leading role in that regard, and has made its nanotechnology innovation centres and facilities available to researchers from across the continent and beyond.

Given the status of nanotechnology as an emerging technological field, many African countries are reluctant to invest in that area. Several countries have expressed interest in nanotechnology, but have yet to take an active role in that regard. Only South Africa seems to be providing substantial funding to nanotechnology research and development and this has positioned the country as an early adopter. Nanotechnology is evolving fast, however, and ongoing research is needed to keep abreast with recent developments. In 2005, the researchers Invernizzi and Foladori concluded that "Nanotechnology is still in its early stages, but the later we choose to address its social and economic implications, the less chance there will be for the technology to help the poor before it begins to put down roots within the mainstream hegemonic socioeconomic structure, characterized by worldwide inequality".[66] Nanotechnology is complex, and time and considerable effort are needed to understand the fundamentals of how materials behave at nanoscale. Although there are few products on the market to entice countries to adopt nanotechnology, African Governments still need to invest in research and development. This requires strong political will and commitments by those Governments to support policy development and resource mobilization.

62 Baraka Rateng', "Nanotech holds promise for Africa, but not prioritised", SciDev.Net, 17 October 2018.

63 "Managing nano-bio-info-cogno innovations. Converging technologies in society", William Bainbridge and Mihail Roco, eds., (Springer, Dordrecht, The Netherlands, 2006).

64 Salamanca-Buentello and others (2005).

65 Dirk Libaers, Martin Meyer and Aldo Geuna, "The role of university spinout companies in an emerging technology: the case of nanotechnology" The Journal of Technology Transfer, vol. 31, No. 4 (2006), pp. 443-450.

66 Noela Invernizzi and Guillermo Foladori, "Nanotechnology and the developing world: will nanotechnology overcome poverty or widen disparities?" in Nanotechnology Law and Business Journal, vol. 2, No. 3 (2005).

Since nanotechnology is relatively new, many institutions of higher education have yet to develop specific courses addressing that subject. Instead, nanotechnology is taught as a separate topic as part of chemistry, physics and biology courses. A shortage of skilled personnel to teach students about nanotechnology is a further challenge. Africa should seek to take advantage of the knowledge of nanotechnology experts in the diaspora. Indeed, the continent would benefit if those experts were encouraged to visit their home countries as part of capacity building initiatives. Insights can be drawn from the model used in soccer in which professional players plying their trades outside the continent are requested to render their services to their countries. In addition, there is a need to build a critical mass of skilled personnel through collaboration, advanced training, conferences, short courses and workshops.

5. CHALLENGES IN ASSESSING THE IMPACT OF NANOTECHNOLOGY

It is challenging to assess the impact of nanotechnology on development. This is due to the fact that nanotechnology is a general-purpose technological field. It is pervasive and has a propensity to spur complementary innovations that cut across many technological sectors.[67, 68] Unlike other technologies whose applications are specific, nanotechnology cuts across all manufacturing sectors. It is therefore extremely difficult to quantify the contribution made by nanotechnology to economic development. While there is no single way to address that challenge, the solution lies in developing a rigorous and comprehensive set of metrics and an aggregation of data on technology transfer and commercialization. This may take time, but should not stall progress on the use of nanotechnology on the continent.

There are numerous uncertainties associated with the use of nanotechnology, and the characteristics of nanoparticles, which result in superior properties, may also give rise to unforeseen risks and challenges. Indeed, risk assessment studies on nanotechnology have demonstrated that specific nanoparticles can threaten human health and the environment.[69, 70, 71] There is little data, however, on the extent to which nanoparticles cause harm and the mechanism by which they do so, and nanotechnology's potential social, economic, health, and environmental impact and risks are far from clear.[72] African countries should therefore strengthen their nanotechnology risk governance policies. This may entail identifying appropriate methods for testing and labelling nanotechnology products, taking appropriate precautionary measures, and engaging with the public to communicate broader nanotechnology considerations. Such an approach is vital if countries are to protect workers and consumers exposed to nanotechnology-based products.

67 Stuart Graham and Maurizio Iacopetta, "Nanotechnology and the emergence of a general purpose technology", Annals of Economics and Statistics, GENES, issue 115/116 (2014), pp. 25-55.

68 Christine Shea, Roger Grinde and Bruce Elmslie. "Nanotechnology as general-purpose technology: empirical evidence and implications", Technology Analysis and Strategic Management, vol. 23, No. 2 (2011), pp. 175-192.

69 Tamara Forbe, Mario García and Eric Gonzalez, "Potential risks of nanoparticles", Food Science and Technology, vol. 31, No. 4 (2011), pp. 835-842.

70 Günter Oberdörster, Vicky Stone and Ken Donaldson, "Toxicology of nanoparticles: a historical perspective", Nanotoxicology, vol. 1, No. 1 (2007), pp. 2-25.

71 Thomas Schneider, Evaluation and control of occupational health risks from nanoparticles (Copenhagen, Nordic Council of Ministers, 2007).

72 Jane Macoubrie and Michael Cobb, "Public perceptions about nanotechnology: risks, benefits and trust", Journal of Nanoparticle Research, vol. 6, No. 4 (2004), pp. 395-405.

6. THE WAY FORWARD

Africa as a continent should seek to learn from the experience of South Africa in the application of nanotechnology. That country has put in place initiatives to address a number of the challenges related to nanotechnology use that are highlighted in this report. It has, for example, launched the National Nanotechnology Strategy, and provides funding for research and development through the Department of Science and Technology. It also supports a cooperative nanotechnology programme that operates under the auspices of the India-Brazil-South Africa Dialogue Forum. Furthermore, a consortium of four universities in South Africa now offers a master's degree in nanoscience and nanotechnology. To provide a platform for the participation of different stakeholders in the development of nanotechnology, South Africa runs a Nanotechnology Public Engagement Programme. With these initiatives already in place to serve as a template, African countries need not start from scratch in their quest to exploit nanotechnology. Instead, they should capitalize and build on the best practices. To take advantage of the opportunities for development offered by nanotechnology, it is crucial that African countries engage in rigorous research and promote the appropriation and adaption of nanotechnologies to meet the developmental needs of the continent.

CHAPTER 3.

REGULATORY, SOCIETAL, DEVELOPMENTAL AND SUSTAINABILITY ISSUES OF NANOTECHNOLOGY: AN OVERVIEW

1. INTRODUCTION

The past few decades have witnessed intense innovation at the nexus of ICT, biotechnology, cognitive sciences and nanotechnology. Indeed, such rapid acceleration in innovation has brought many science fiction scenarios closer to reality. Nanotechnology is catalysing "a revolution of a kind never experienced before" in other technologies[73] and has even been dubbed the "revolution of revolutions" or a "meta-revolution".[74] However, the regulatory, legal, ethical, societal, environmental, economic and geopolitical ramifications of this revolution have not been thought through with the urgency and seriousness they deserve. While there have been numerous debates on nanotechnology, it is evident that those debates have focused, primarily, on the concerns of rich countries. Debates have also focused on how nanotechnology can be incorporated into existing paradigms and it is not yet clear how far our existing systems of regulation, ethical engagement, socioeconomic and environmental governance can be adapted to address issues that the meteoric rise of nanotechnology is pushing to the fore.

2. THE RISE AND RISE OF NANOTECHNOLOGY

Nanotechnology is heralded as the technology ushering in "the next industrial revolution", "the post-industrial world" and "the age of mastery" marking the transition to and beyond the upper end of "the age of discovery". While some sceptics have dismissed the promises made about nanotechnology as overhyped ambition, the developments in nanotechnology thus far have proved that this is not the case. Understood as a platform, general purpose and enabling technology, the impact of nanotechnology is such that it is set to change everything and to turn science fiction or even biblical scenarios into reality. Former United States Undersecretary of Commerce for Technology, Philip Bond, for example, is known for his zealous conviction on the promise of nanotechnology:

> On a human level, nano's potential rises to near biblical proportions. It is not inconceivable that these technologies could eventually achieve the truly miraculous: enabling the blind to see, the lame to walk and the deaf to hear; curing AIDS, cancer, diabetes and other afflictions; ending hunger; and even supplementing the power of our minds, enabling us to think great thoughts, create new knowledge, and gain new insights.[75]

Nanotechnology has transformed itself from a virtual non-existent phenomenon two decades ago into a discipline in its own right, and it is now touted as a mega discipline, an "***über***-science", "a super-discipline" and a "proto discipline". The discreet march of nanotechnology is rightly dubbed "a tsunami' – a metaphor that captures the stealth and transformative potential of the technology.[76]

The "tsunami" metaphor is particularly useful in explaining the exponential yet barely noticeable development of the technology. The thousands of nanotechnology consumer products that are on the

73 Denis Loveridge, "Converging technologies-a commentary- Part I", University of Manchester, 2004.

74 Geoffrey Hunt, "The global ethics of nanotechnology", in Nanotechnology: Risk, Ethics and Law, Geoffrey Hunt, and Michael Mehta, eds. (London, Earthscan, 2006).

75 See George Kimbrell, "Governance of nanotechnology and nanomaterials: principles, regulation, and renegotiating the social contract", Journal of Law, Medicine and Ethics (Winter 2009).

76 Hailemichael Demissie, "Taming matter for the welfare of humanity: regulating nanotechnology", in Regulating Technologies: Legal Futures, Regulatory Frames and Technological Fixes, Roger Brownsword and Karen Yeung, eds. (Hart Publishing, 2008).

market but are not labelled as such are proof of the quiet swift entry of nanotechnology into the lives of millions of people around the world. Consumers using the latest iPhone or Samsung mobile phones do not often realize that nanotechnology has played a crucial role in the production of those devices, which are nanotechnology-enabled products containing nanocircuits and nanostructures. Commenting on "on-the-ground nano-developments", Vivian Weil, an advisor at the Centre on Nanotechnology and Society at Arizona State University, observed how quickly but discreetly nanotechnology is entering society:

> The products of this activity have barely been noticed by the public. Nano-developments receive little coverage in mainstream news media and the popular press. Yet, on the World Wide Web, commercial nano-enterprises, including companies, commercial research and promotional associations, conferences, and newsletters of various kinds, have rapidly become ubiquitous.[77]

Ten years on from this comment, nanotechnology is marching forward on many fronts. The vast investment allocated by Governments in developed and developing countries alike to the technology is stimulated by the realistic promise that nanotechnology can help tackle real-world economic, societal and environmental challenges. The global challenges of economic development, poverty, growing inequality, the depletion of natural resources, environmental degradation and climate change can all be tackled by the incredible applications of nanotechnology. Ranging from extremely efficient solar panels to efficient cars and airplanes, from cheap water filtration and treatment products to ubiquitous sensors monitoring ecological systems, the economic and environmental benefits of nanotechnology are overwhelming.

There is some disagreement as to how much of nanotechnology's potential has been realized thus far and when it will be realized fully. In a report comparing nanotechnology with biotechnology and ICT that was published in 1999, OECD concluded that nanotechnology "– the technology of producing goods out of individual atoms and molecules – is but a faint glow on the distant horizon."[78] A more sceptical view has been expressed by Friends of the Earth,[79] which has asked whether the advocates of nanotechnology are making "over-heated-promises and hot air" and warn that "[v]ery few people have looked beyond the shiny promise of nanotechnology to try and understand how this far-reaching new technique is actually developing". Neither of those organizations has denied that the technology has great potential, however, and the OECD publication in particular underscored that nanotechnology "promises the greatest revolution in production since the first stone tool was produced by flaking chips off flints."

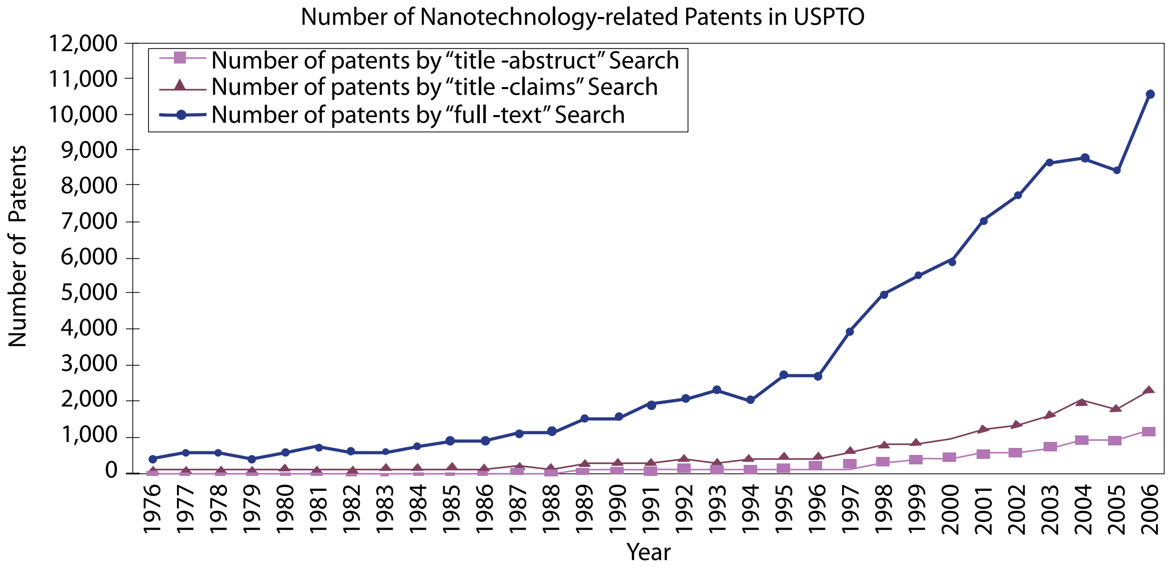
Conclusions about the realization of the promises of nanotechnology can be drawn from such indicators as the number of patents registered, the types of products commercialized, and the benefits that are being exploited. The nanotechnology market was expected to hit and surpass the $3 trillion mark in 2018. The steep rise in patent applications in nanotechnology and the explosion in the number of publications in that area demonstrate that nanotechnology is on track to deliver on the promises that have been made about it. Figure VII illustrates the trend in nanotechnology patenting in the early decades of its development.

77 Vivian Weil, "From the lab to the marketplace: managing nanotechnology responsibly", in Nanoscale: Issues and Perspectives for the Nano Century, Nigel Cameron and Ellen Mitchel, eds. (Hoboken, Wiley and Sons, 2007).

78 Organization for Economic Cooperation and Development (OECD), The future of the global economy: towards a long boom? (OECD Publications, 1999).

79 Friends of the Earth, Nanotechnology, climate and energy: overheated promises and hot-air (2010).

Figure VII Nanotechnology-related patents issued by United States Patent and Trademark Office



Source: *Fisher and others (2008).*

A more concrete illustration of this trend is the commercialization of thousands of consumer and industrial products that are either classified themselves as nanotechnology products, or incorporate nanotechnology. According to the futurist, inventor and entrepreneur, Ray Kurzweil, by 2030 most technology will have become either nanotechnology or will incorporate nanotech components.[80] His other exciting prediction sees the year 2040 as the year when "nanotech foglets" will start to "make food out of thin air and create any object in the physical world at a whim".[81]

There are vast numbers of nanotechnology projects already on the market or in the pipeline, and nanotechnology has become a general purpose, infrastructure platform technology. Nanotechnology is an essential element of ICT, with nano-electronics powering the miniaturized chips and transistors packed into processors and hard drives with almost unlimited processing and storage capacity. Furthermore, the development of innovative computing capabilities and architecture is likely to depend on nanotechnology innovations.[82] Nanotechnology is also accelerating biotechnology and converging with it to create forms of nanobiotechnology. Biology and biotechnology have, in fact, been among the earliest areas in which commercial applications of nanotechnology, such as scanning probe microscopy, have been brought to market. Nanotechnology has thus been identified as a "technology that enables science".[83]

Nanotechnology is also characterized as "an enabler expected to impact all manufactured goods",[84] and is now an integral component of advanced manufacturing. The more visible technologies of the ongoing fourth industrial revolution, referred to as "the technologies of Industry 4.0", are IT, electronics and robotics. However, it is evident that nanotechnology plays a crucial and indispensable role as the

80 Ray Kurzweil, testimony to the Committee on Science, United States House of Representatives (9 April 2003). available at www.kurzweilai.net/testimony-of-ray-kurzweil-on-the-societal-implications-of-nanotechnology.

81 Peter Diamandis, "Ray Kurzweil's mind-boggling predictions for the next 25 years", Singularity Hub, 26 January 2015. Available at singularityhub.com/2015/01/26/ray-kurzweils-mind-boggling-predictions-for-the-next-25-years/.

82 National Academies of Sciences, Engineering, and Medicine, Triennial review of the National Nanotechnology Initiative (The National Academies Press, Washington, D.C., 2016).

83 Stephen Wood, Richard Jones and Alison Geldart, eds., The social and economic challenges of nanotechnology, (Economic and Social Research Council, Great Britain, 2003).

84 Sonia Miller, "Regulating nanotechnology: a vicious circle" in Nanoscale: Issues and Perspectives for the Nano Century, Nigel Cameron and Ellen Mitchel, eds. (Hoboken, Wiley and Sons, 2007).

infrastructure that supports those technologies.[85] The United States Government, moreover, recognizes nanomanufacturing, the specialized aspect of advanced manufacturing involving nanoscale materials and processes, as a focus area of nanotechnology "warranting special attention".[86] Overall, nanotechnology combines the impacts of other, relatively mature technologies, and is thus said to have a greater impact than those technologies often have.

2.1. THE FOUR STAGES OF NANO-DEVELOPMENT

Mike Roco, the chief architect of NNI, speaks of the four "overlapping stages" of nanotechnology's development.[87] The first two stages began in 2000 and 2005, respectively. These were the stages of the development of passive nanotechnology structures (nanomaterial remains static after being encapsulated) and active nanotechnology structures (nanomaterial changes its properties when triggered or exposed to a certain environment). Such nanostructures range from titanium dioxide in sunscreens to therapeutic molecules encapsulated in new drug delivery particles. These are the stages in which nanomaterials reinforce some other material in order to create a new functionality or value.

In these stages, nanotechnology is able to penetrate the market by piggybacking on established technologies. In 2005, there were already between 500 and 700 products containing nanoscale particles, including cosmetics, foods, therapeutic goods, clothing and sports goods. The reinforcement of existing products with nanotechnology is ongoing with more and more products containing nanofeatures are entering the market. High performance nanocoated cookware and nanocoated super-gliding iron plates for pressing clothes are examples of nanotechnology being used in conjunction with traditional technologies. Nanotechnology firms are now exploiting low-tech products as carriers of nanotechnology with a view to carving out a share of the emerging nanotechnology value chain. Helmut Schmidt, a nanomaterials expert and entrepreneur, describes the benefits of that strategy and the reason why it is here to stay, despite the fact that nanotechnology is well into its third and fourth stages of development, as follows:

> In order to receive sufficient revenue from a nanomaterial, it is essential that a value-added step is incorporated. In this case, the value-added step is the production of coated parts by a highly sophisticated technology leading to glasslike coatings that could not be produced otherwise - the so called "low tech by high tech" strategy. This means that nanomaterials are applied to the surfaces of already existing products. This leads to fast market penetration with low market risk and requires very limited marketing effort.[88]

Although advanced nanotechnology products are already with us today, the commercialization of those products is a complex process. As of 2010, it has been possible to exploit nanostructures and complex nanodevices or "systems of nanosystems" with such functions as tissue regeneration or even artificial organ generation, by taking advantage of the self-assembly property of many nanostructures.

In the last of the four stages, which were expected to begin between the years 2015 and 2020, Roco predicted the expansion of molecular nanosystems whose performance exceeds that found in biological systems.[89] This is the stage Kurzweil was referring to in his prediction that it will be possible to "make

85 Anne Dujin, Cornelia Geissler and Dirk Horstkötter, eds., The new industrial revolution: how Europe will succeed, (Ronald Berger Strategy Consultants, 2014).

86 National Academies of Sciences, Engineering, and Medicine (2016).

87 Mihail Roco, "National nanotechnology initiative: past, present, future" in Handbook of Nanoscience, Engineering and Technology, William Goddard and others, eds. (CRC Press, 2007).

88 Helmut Schmidt, "Commercial success with nanomaterials", in Nano (June 2009).

89 Mihail Roco (2007).

food out of thin air and create any object in the physical world at a whim". In those stages, matter can be manipulated at the atomic and molecular level to make objects from the bottom up, molecule by molecule.

Roco is certainly optimistic, but others are even of the view that research is proceeding at such a rate that even the most optimistic forecasts might need to be revised substantially.[90] The strategy to be followed with regard to products created in the latter stages can be summarized as "high tech by high tech", whereby markets need to be created and specific industrial structures established.[91] Although this lengthens the time frames needed to bring products to market, some products of this type have already been developed. Developments so far have shown that the future of nanotechnology is most certainly a future of unheralded breakthroughs "coming sooner than you think".[92] On that understanding, policymakers around the world are promoting and supporting the development of nanotechnology as a matter of priority and with such enthusiasm that they are in effect de-prioritizing the regulation of that technology.

3. THE REGULATION OF NANOTECHNOLOGY[93]

Nanotechnology is currently being prioritized at the expense of other key concerns, including regulatory issues. In a survey of nanotechnology in Latin America, researchers found that all proposals by Latin American countries for nanotechnology initiatives are characterized by an eagerness to promote nanotechnology and a conspicuous lack of concern for environmental, health and safety implications, socioeconomic impacts or ethical issues.[94]

A failure to give adequate attention to those issues is not unique to Latin American countries but is typical of nanotechnology initiatives almost everywhere. Governments currently place great emphasis on incentivizing and facilitating the adoption and development of nanotechnology,[95] and the foremost objective of nano-specific legislation in Latin American and other countries has been to promote the nanotechnology sector. In fact, that objective is clearly expressed in the title of the United States law on that subject, namely the 21st Century Nanotechnology Research and Development Act.

While supporting the development of nanotechnology remains the dominant policy position, other issues are becoming too urgent to be ignored by policymakers and regulators. Policymakers are now grappling with the wider regulatory, ethical, legal, societal and economic implications of nanotechnology, along with issues related to global equity, strategic research priority setting, workforce training, nanotechnology education and other themes.

The formulation of appropriate policy and governance mechanisms has been slow and incoherent. The authorities in certain jurisdictions have done practically nothing on the grounds that existing policy is "probably adequate".[96] However, as more and more countries have formulated nanotechnology initiatives and programmes (in just a decade, more than 70 countries have put in place national nanotechnology

90 Glen Reynolds, "Nanotechnology and regulatory policy: three futures" in 17:1 Harvard Journal of Law and Technology vol. 17 (2003), p. 179.
91 Helmut Schmidt (2009).
92 Jim Saxton, "Nanotechnology: the future is coming sooner than you think", paper presented to the United States House of Representatives Joint Economic Committee (Washington D.C., 2007).
93 Portions of this section are based on Demissie (2008).
94 Noela Invernizzi and Guillermo Foladori, eds., "Nanotechnologies in Latin America" (Rosa-Luxemburg-Stiftung, 2008).
95 Roger Brownsword, "What the world needs now: techno-regulation, humanity, human rights and human dignity" in Global governance and the quest for justice, vol. 4, Roger Brownsword, ed., (Oxford, Hart Publishing, 2004).
96 George Kimbrell (2009).

initiatives, often drawing on the approach adopted by the United States of America)[97] it has become increasingly clear that such an approach is far from ideal.

The overwhelming beneficial aspects of nanotechnology have encouraged policymakers to ignore or defer consideration of the risks associated with that technology. Many Governments, which shoulder primary responsibility for regulating the development and deployment of technology, have been accused of acting as "cheerleaders rather than regulators." [98] Nonetheless, while global competition has driven issues other than the accelerated development of the technology down the agenda of Governments, the accelerated development of the technology, as demonstrated by the entry into the market of hundreds of nanoproducts, is now pushing regulatory concerns to the fore.

Policymakers and regulators find nanotechnology a particularly difficult subject matter and "a slippery customer".[99] The uncertainty regarding the "regulability" of nanotechnology clouds debate in both the regulatory and scientific communities.[100] The uncertainty emanates from the very unusual nature of the technology. Indeed, Richard Feynman, the American physicist widely regarded as the father of nanotechnology, underscored its unusual nature when he stated in 1959 that "[a]toms on a small scale behave like nothing on a large scale" (author's emphasis).[101] Uncertainty within the scientific community regarding the benefits and risks of nano-engineered materials has exacerbated the indecision of regulators, who frequently invoke the lack of sufficient scientific evidence that is needed to formulate effective regulatory policies.[102]

The challenges of nanotechnology policymaking also stem from the newness of the technology, the rapid pace of its advance, uncertainty surrounding its fundamental features, and uncertainty surrounding the type and level of governance required, namely whether regulation should be at the national, subnational, regional or global level and whether it should be mandatory or voluntary. In essence, nanotechnology is at a stage of development in which "[w]e are in this awkward middle territory where we have just enough information to think there is an issue, but not enough information to really inform policymakers about what to do about it." [103]

In the light of the above, regulators around the world have adopted divergent positions on the importance of nanotechnology regulation, ranging from a "hands-off, no new regulation" approach to an insistence on very strict regulation, under which all nanotechnology research and development is prohibited.

97 Sudan is one of the countries that has recently started preparations to launch a nanotechnology initiative along the lines of the United States NNI. One of the recommendations of a workshop convened in March 2018 by the United Nations Educational, Scientific and Cultural Organization (UNESCO) was, in fact, the establishment of a Sudanese NNI. For further information, see: en.unesco.org/news/workshop-nanotechnology-applications-environment-energy-medicine-and-electronics-promotion

98 Kathy Wetter, "100 years after the Pure Food and Drug Act: FDA's current regulatory framework inadequate to address new nano-scale technologies", Presentation on behalf of ETC Group, United States Food and Drug Administration Nanotechnology Public Meeting (10 October 2006).

99 Paul Borm, "A classical dilemma for nanotechnologies", in Nano (December 2007).

100 Roger Brownsword (2004).

101 Richard Feynman, "There is plenty of room at the bottom: an invitation to enter a new field of physics", paper presented to the annual American Physical Society meeting, California Institute of Technology (Pasadena, 29 December 1959).

102 United Kingdom Health and Safety Executive, Review of the adequacy of current regulatory regimes to secure effective regulation of nanoparticles created by nanotechnology (Sudbury, June 2006). Available at: https://www.hse.gov.uk/nanotechnology/regulatoryreview.pdf.

103 Kulinowski, quoted in: Gary Marchant and others, "Risk management principles for nanotechnology" in NanoEthics, vol. 2 (2008) pp.43-60

3.1. HANDS-OFF APPROACH

To date, uncertainties surrounding nanotechnology and its great diversity have engendered a hands-off approach by regulators and few regulatory interventions specific to nanotechnology have been adopted worldwide. The hands-off approach to regulation is also driven by the need for a hassle-free environment that facilitates efforts to harness the enormously beneficial uses of the technology. Untimely regulatory intervention could impede research and limit the potential of the technology. In the absence of a global consensus in that area, no country will adopt regulatory hurdles that impede its national nanotechnology research and development initiatives.

There is no conclusive scientific evidence that certain nanomaterials are toxic or hazardous[104] and there is as yet insufficient scientific data to justify the adoption of robust regulatory frameworks. An often-quoted United Kingdom Royal Society and Royal Academy of Engineers report stopped short of categorizing any nanomaterials as toxic or harmful but instead suggested that research should be undertaken to determine the toxicity, persistence, epidemiology and bioaccumulation of manufactured nanoparticles and nanotubes.[105] Nonetheless, despite the fact that the toxicity of nanomaterials has not been reliably assessed to warrant a regulatory intervention, some organizations have already taken the position that nanomaterials may be the "next asbestos."[106]

It is important to avoid making hasty generalizations regarding the safety of nanomaterials. What is certain, however, is that no particular nanomaterial has been shown conclusively to be hazardous to human health or the environment.[107] The most that can be said of those materials is that they are neither "inherently unsafe" nor "inherently benign."[108, 109] A presumption that nanomaterials are generally safe is therefore not warranted. In a 2007 interview, David Reinhoudt, Chairman of the Board of NanoNed, the Dutch Network for Nanotechnology, remarked that "with nanoparticles, they can be good or bad, and in every application, you have to test them according to the rules." The asbestos debacle and numerous more recent incidents involving the withdrawal of drugs following the discovery of their nefarious effects suggest that stakeholders should not be complacent regarding the potential risks of nanotechnology applications, particularly as their harmful effects may not become apparent for several decades, even if stringent regulations on the use of nanotechnology have been adopted.

No reasonable person would rush to the conclusion that the technology is safe at this stage and, given the limited information available, the prevailing stance is to presume otherwise. This is understandable not only because the technology is not fully understood, but also because it is known that nanomaterials are capable of penetrating into parts of the human body where no alien material has ever reached. For example, certain nano-engineered materials can pass through unbroken skin, cell membranes and even the blood-brain barrier. Further research into the potential health and environmental risks posed by nanomaterials is clearly required. David Reinhoudt, Chairman of the Board of NanoNed, the Dutch Network for Nanotechnology, cautions that although nanoparticles are nothing new, as they occur in the environment, they should be tested, particularly "if you are going to make them intelligent and introduce them into our biological systems."

104 Paula Gould, "Nanomaterials face control measures" in Nanotoday, vol. 1:2 (May 2006).

105 United Kingdom Royal Society and Royal Academy of Engineers, Nanoscience and nanotechnologies: opportunities and uncertainties (London, July 2004).

106 Friends of the Earth, Workplace exposure to nanomaterials: will nano be the next asbestos? (2006).

107 Paula Gould (2006).

108 Kathy Wetter (2006).

109 Robin Wilson, "Nanotechnology: the challenge of regulating known unknowns", Journal of Law, Medicine and Ethics (Winter 2006).

The immaturity of the technology has been invoked to justify a hands-off approach to its regulation. However, as the technology advances, which it is doing at an exponential rate, anxieties that it is developing within a "regulatory vacuum" have given rise to calls for urgent regulatory intervention.[110] In a 2007 report, the United Nations Environment Programme (UNEP), appealed for "swift action" by Governments in that regard. Little progress has been made, however, and activist organizations continue to call on Governments to regulate the nanotechnology sector. The regulatory and nanotechnology communities have barely started addressing the rudimentary questions of which aspects of nanotechnology should be regulated, how regulation should be carried out, and which authorities should oversee regulation activities.

Governments sometimes believe that, by refraining to regulate the nanotechnology sector, they can accelerate progress in that area. Such "deregulation as a form of regulation" approaches are similar to the approaches adopted by certain Governments to the biotechnology sector.[111] Although the adoption of a hands-off approach in order to avoid any premature regulatory meddling into a science that is still in its infancy is understandable, it is also important to take steps to forestall any potential damage to human health or the environment, however remote that possibility may seem.

3.2. PROHIBITION, MORATORIUM AND THE "GREY GOO" SCENARIO

At the other end of the regulatory spectrum is the prohibition of nanotechnology research, development and commercialization. While there has been no outright call for a ban on nanotechnology, there have been calls for "the ban's temporary cousin", namely a moratorium.[112] The Action Group on Erosion, Technology and Concentration, a Canada-based activist organization, has demanded an immediate stop to the commercialization of nanoproducts. Friends of the Earth and Greenpeace have also called for a moratorium to be imposed.

A ban on nanotechnology research was first proposed in the light of the hypothetical "grey goo" scenario, in which uncontrolled self-replicating nanobots would fill the biosphere. That scenario was one of the first headline-grabbers in the debate on the management of nanotechnology. Fears relating to the "grey goo" scenario have been exacerbated by concerns relating to another hypothetical scenario involving the advance of nanotechnology-enabled artificial intelligence. That scenario, which envisages a future in which computers with super-human intelligence make humans irrelevant and position themselves as humanity's overlords, was elaborated in an essay by Bill Joy entitled "Why the future doesn't need us", which was published in Wired magazine in 2000. Joy proposed that research should be halted in order to prevent that scenario from coming true. A 2004 report by the United Kingdom Royal Society and Royal Academy of Engineers downplayed the "grey goo" scenario and dubbed it "a distraction from more important issues". Other commentators see the intensive focus on the hypothetical scenario as "an unfortunate tendency" that has had a disproportionate impact in the debate on nano-regulation.[113, 114] The scientific community has, moreover, reassured the public that, for the foreseeable future at least, there is no cause for concern that the hypothetical grey goo scenario could come true.[115]

110 Kathy Wetter (2006).

111 Upendra Baxi, The future of human rights, (second edition) (Oxford University Press, New Delhi, 2004).

112 David Guston, Nanoscale: Issues and Perspectives for the Nano Century, Nigel Cameron and Ellen Mitchell, eds., The Center for Nanotechnology in Society at Arizona State University (Hoboken, Wiley and Sons, 2007).

113 UNESCO, The ethics and politics of nanotechnology, (Paris, UNESCO, 2006).

114 Ahson Wardak, "Nanotechnology and regulation: a case study using the Toxic Substances control Act", paper presented as part of the Scholars Foresight and Governance Project, Woodrow Wilson International Centre for Scholars (2003). Available at www.environmentalfutures.org/nanotsca_final2.pdf.

115 Robin Wilson (2006).

Though not enjoying as much attention as it once did, the "grey goo" scenario has not completely disappeared from scientific discourse and it should be underscored that efforts to discredit the scenario "do not constitute a blanket disproof of the feasibility of [molecular nanotechnology enabling the scenario]."[116]

Although the chances of computers eliminating humans or the biosphere becoming crammed with nanodevices are at present remote, resources are needed to prevent any abuse of the technology in the near to mid-term. The "double life" of technology, a phenomenon analysed in science and technology studies, is a term that encompasses the use of technology for purposes other than those originally envisaged by its creators.[117] The use of the most powerful and beneficial technology ever created, namely nanotechnology, for destructive purposes is by far "the greatest danger",[118] and examples of the double life of nanotechnology and its nefarious uses abound, particularly in military applications.

Regulating the abuse of nanotechnology is an unprecedented challenge that is compounded by the peculiar attributes of the technology itself, namely its relative inexpensiveness and its invisibility, micro-locomotion and self-replication.[119] The dangers posed by the abuse of nanotechnology requires, as Drexler and others have put it, "a level of political control far beyond that which most nations know how to exercise."[120] While prohibition may not be the ideal or even a practicable way to address the risk of technology abuse, neither is disregarding that risk entirely. Indeed, "ignoring technological risk can clearly be detrimental."[121]

Proposed bans on nanotechnology research and development and suggestions that "the genie must be kept in the bottle" are, at this point in time, irrelevant, not only because the genie is already out of the bottle but also and primarily because Governments and societies should strive to tame nature for beneficial purposes, and in order to safeguard and preserve ecosystems for posterity. Calls for bans and voluntary moratoriums should not therefore be pursued as policy choices for regulating nanotechnology.

3.3. STATUS QUO VERSUS REGULATORY OVERHAUL

There is no regulatory framework at present that applies exclusively to nanotechnology. Instead, the trend has been to apply existing regulations to nanomaterials while treating them as new substances. In the United States of America, nanomaterials are regulated by the Toxic Substance Control Act, while the Environmental Protection Agency (EPA) applies Significant New Use Rules for Existing Chemicals to nanomaterials. In the European Union, nanomaterials are categorized as new substances under the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation. However, because it is not nano-specific, REACH may not cover all nanotechnology products effectively.[122] It should be noted that China has drawn on the REACH regulation in the formulation of its chemicals regulation regime.[123]

116 Chris Phoenix, "A Technical Commentary on Greenpeace's Nanotechnology Report" (2003). Available at www.crnano.org/Greenpeace.pdf.

117 David Bell, Science, Technology and Culture (Maidenhead, Open University Press, 2006).

118 Alexander Arnall, Future technologies, today's choices: nanotechnology, artificial intelligence and robotics; a technical, political and institutional map of emerging technologies (London, Greenpeace Environmental Trust, 2003).

119 Robert Pinson, "Is nanotechnology prohibited by the biological and chemical weapons conventions?" in Berkley Journal of International Law, vol. 2 (2004).

120 Eric Drexler and others, Unbounding the Future: The Nanotechnology Revolution, (New York, William Morrow and Company, Inc., 1991).

121 Gregory Mandel, "Regulating Emerging Technologies", in Law, Innovation and Technology, vol. 1, (2009), p. 75. Available at: http://ssrn.com/abstract=1355674.

122 Quasim Chaudhry, Carolyn George and Richard Watkins, "Nanotechnology regulation: developments in the United Kingdom" in New Global Frontiers in Regulation: The Age of Nanotechnology, Graeme Hodge, Diana Bowman and Karinne Ludlow, eds. (2007).

123 Sally Dalton-Brown, "Global ethics and nanotechnology: a comparison of the nanoethics environments of the EU and China", in NanoEthics, vol 6 (2012), pp. 137-150.

States have attempted to apply existing regulatory regimes to nanomaterials while also recognizing nanotechnology as an emerging policy issue. An exception is the International Organization for Standardization (ISO), whose technical committees and working groups are currently striving to formulate specific standards and nomenclature for nanomaterials. However, recommendations of ISO are only issued as guidelines and are not binding.[124]

Nanotechnology is also high on the agenda as an emerging policy issue under the Strategic Approach to International Chemicals Management (SAICM), a policy framework that is overseen by UNEP. SAICM is the only multilateral international framework on chemicals management.[125, 126] Decisions taken under SAICM are not mandatory but member countries have a responsibility to develop their respective national plans with due attention to those decisions. The International Conference on Chemicals Management (ICCM) has, moreover, passed resolutions recognizing nanotechnology as an emerging policy issue that should be addressed under SAICM. Nanotechnology has been on the agenda of ICCM since 2009. At the fourth session of the Conference, held in 2015, a resolution calling on all relevant stakeholders to conduct awareness raising, capacity building and information sharing activities was adopted. Although this has kept nanotechnology in the spotlight within the context of global chemicals management, it is unlikely that voluntary processes such as SAICM will lead to robust nanotechnology oversight, and the framework has so far proven unable to achieve consensus among its members on the need for regulation of the sector.

Although some parties claim that nano-specific regulation is not needed and that existing regulatory frameworks are sufficient, that position is untenable, as nanomaterials have new properties and functionalities even though, in terms of their chemical composition, they are identical to their macro counterparts.[127] For example, the chemical composition of graphite and carbon nanotubes is identical: both are made of carbon atoms. Indeed, the metrological indices and parameters employed in the regulation of macro-substances are simply not applicable to nanomaterials. The novel properties of nanomaterials do not depend on mass, volume or other ratios such as percentage-by-weight, by which standardization agencies determine the toxicity of substances.[128, 129]

The application of existing regulatory systems to nanomaterials with the clear knowledge that they are not designed with nanomaterials in mind is destined to fail. In a slightly hyperbolic analogy, Kimbrell argued that "[t]rying to solve these problems through regulatory adjustments and increases in agency resources and expertise alone is somewhat akin to shuffling deck chairs on the sinking Titanic."[130] Oversight of nanotechnology clearly requires innovative approaches.

124 Quasim Chaudhry, Carolyn George and Richard Watkins (2016).

125 Hailemichael Demissie and others (2017).

126 Ndeke Musee and others, "Social and environmental implications of nanotechnology development in Africa", (South Africa Council for Scientific and Industrial Research, Latin American Nanotechnology and Society Network, International POPs Elimination Network, 2012).

127 Ahson Wardak (2003).

128 UNEP, "Emerging challenges: nanotechnology and the environment", in GEO Year Book 2007: An Overview of Our Changing Environment, (UNEP, 2007).

129 Commission of the European Communities, Communication from the Commission: Towards a European Strategy for Nanotechnology, (Brussels, May 2004).

130 George Kimbrell (2009).

Those who have argued against new nano-specific regulation are rapidly changing their views, however, and calls for specific regulation are gaining momentum as more information on the uniqueness of the technology and its impact becomes clear. [131, 132, 133]

A number of countries are reviewing existing regulations with a view to preparing the ground for the specific regulation of nanotechnology. In the European Union, for example, amendments to REACH have been proposed in order to more effectively regulate nanotechnology, and Belgium has tabled a proposal for the labelling of nanomaterials and for a new nanomaterials specific registry to be added to REACH. Some European Union members are designing their own specific registries and France, Belgium and Denmark have already developed their own nano-inventories.[134]

In the United States of America, a draft bill to amend the Toxic Substance Control Act, which singles out nanomaterials, has been submitted to lawmakers.[135] Other countries, international organizations and special interest groups are also calling for the adoption of specific regulatory frameworks on nanomaterials.

Regulatory overhaul often implies government command and control regulation, which is neither appropriate nor practical.[136] The regulatory regime should, instead, also embrace industry and allow some measure of self-regulation with appropriate oversight.

3.4. SELF-REGULATION AND THE TRANSITION FROM REGULATION TO GOVERNANCE

One argument downplaying the need for a regulatory overhaul is that concerns about the risks of the technology are overblown.[137] Thus far, research has drawn contradictory conclusions on nanotoxicity. Some therefore suggest that industry self-regulation is a more appropriate regulatory approach than government regulation.

Industry self-regulation is said to have many advantages: some claim that it is more effective and efficient than government regulatory systems, which are often accused of "regulatory creep" and of being overly bureaucratic.[138] It is also argued that governmental regulation is tantamount to "throwing amateur wrenches to fix a highly technical field".[139]

Self-regulation is also considered a more effective way to engage with the technology, since it is already in place or can be easily arranged. Governmental regulation should, at present, be kept to a minimum because of the inflexibility of legal regulatory frameworks: once a legal regulatory system is in place, its subsequent adaptation to changing developments is likely to be a protracted process. Indeed, the development of appropriate legislation is unlikely to keep pace with the rapid progress that is taking

131 Mark Duvall and Alexandra Wyatt, "Regulation of nanotechnology and nanomaterials at EPA and around the world: recent developments and context" (Washington D.C., Beveridge and Diamond, P.C., 2011).

132 Diana Bowman and Graeme Hodge, "A small matter of regulation: an international review of nanotechnology regulation" in Columbia Science and Technology Law Review, vol. 8 (2007).

133 Gregory Mandel (2009).

134 SAICM, "Emerging policy issue update on nanotechnologies and manufactured nanomaterials" (note by the secretariat, presented at the International Conference on Chemical Management, Fourth session, Geneva, 2015). Available at: www.saicm.org/Portals/12/documents/meetings/ICCM4/inf/ICCM4_INF19_Nano.pdf.

135 Mark Duvall and Alexandra Wyatt (2011).

136 Gregory Mandel (2009).

137 Diana Bowman and Graeme Hodge (2007).

138 Julia Black, "Tensions in the regulatory state" in Public Law, Maurice Sunkin, ed. (Sweet and Maxwell, Spring, 2007), pp. 58-73.

139 Glen Reynolds (2003).

place in the nanotechnology field. By its nature "the public policy apparatus does not move quickly."[140] Many argue that an absence of legislative regulation is preferable to entrenched regulation that can only be amended with difficulty, as the latter could impede progress in the area of nanotechnology. [141, 142]

It is also argued that self-regulation is preferable to legislative regulation because it facilitates the adoption of appropriate reactive regulation mechanisms. Those believing in the suitability of such mechanisms argue that "the normal scheme of events is to regulate after the fact".[143] If an unfortunate incident occurs, all relevant facts are already known and it is easier to design an effective regulatory framework addressing all the factors that gave rise to the incident in question. Reactive regulatory responses would therefore postpone the regulation of nanotechnology until such a time as a need for regulation is demonstrated.

This is far from an ideal approach to the regulation of technologies, and balancing the need to encourage the development of the technology and the need to forestall potential hazards will remain of paramount importance in the design of regulatory frameworks on nanotechnology.

Governments therefore face a dilemma: while tempted by the potential economic rewards of nanotechnology, they also have a duty to protect the public. Many Governments have, in effect, chosen to ignore calls for legislative action to regulate nanotechnology and instead have proposed non-binding mechanisms such as public dialogue, voluntary reporting, and other forms of self-regulation. The relinquishment by Governments of their regulatory powers in favour of voluntary self-regulation by industry is viewed with some scepticism as there are many cases in which self-regulation by industry has proven inadequate. People worldwide are right to question whether entrusting the regulation of powerful technologies such as nanotechnology to private bodies is not tantamount to "entrusting the fox to guard the hen house".[144, 145]

Those in favour of self-regulation and the reactive regulation of nanotechnology claim that they wish to remove regulatory impediments to the development of the technology. The promotion of the technology is, however, more effectively achieved through the adoption of regulatory legislation. Indeed, it is more important to build and maintain public trust in the technology than it is to try to remove any regulatory hurdles. Regulation by Governments will reassure the public that the authorities are closely monitoring developments in the nanotechnology field.

Government regulation of nanotechnology should not be viewed as premature meddling but rather as long overdue intervention. Risk issues can no longer be pushed aside on the excuse that scientific evidence does not warrant a nano-specific regulatory framework. For a world that has seen the likes of Bhopal and Chernobyl, issues such as environment, health and safety hazards and industrial accidents should certainly remain a major concern in the debate about nanotechnology regulation. If current approaches to regulation continue and Governments fail to take action, it is likely that the public will

140 Philip Bond, "Vision for converging technologies and future society", in Annals of the New York Academy of Sciences, vol. 1013 (2004), pp. 17-24.

141 Gary Marchant and Douglas Sylvester, "Transnational models for regulation of nanotechnology", in Journal of Law, Medicine and Ethics (Winter 2006).

142 Roger Brownsword (2004).

143 Robin Wilson (2006).

144 Tim Little, Sanford Lewis and Pamela Lundquist, "Beneath the skin: hidden liabilities, market risk and drivers of change in the cosmetics and personal care products industry" (Investor Environmental Health Network and Rose Foundation for Communities and the Environment, 2007).

145 Surveillance Studies Network, "A report on the surveillance society", presented to the United Kingdom Information Commissioner (September 2006). Available at: https://ico.org.uk/media/about-the-ico/documents/1042390/surveillance-society-full-report-2006.pdf.

become increasingly concerned about the possibility of a catastrophic accident taking place.[146] Once the technology is entrenched in the market, it will prove extremely difficult and costly to take remedial action, as has been the case with genetically modified organisms.[147] As Mandel advises "[a]n appropriate degree of government oversight is particularly necessary to maintain public confidence in emerging technologies as many people often are largely unaware of them."148

4. FROM REGULATION TO GOVERNANCE

Self-regulation has become a feature of the "new regulatory State" and the apparent tension between self-regulation and governmental regulation is explained away by the notion of a "regulatory regime", namely "a set of interrelated units that are engaged in joint problem-solving to address a particular goal".[149] [150] The shift of focus from State regulation to "governance" also underscores a recognition that the State should not enjoy a monopoly on regulatory systems at the expense of non-State bodies.

Nevertheless, even when conducted under the slogan "self-regulation", regulation remains a public function and the final say rests with national authorities.[151] Furthermore, maintaining public trust in government regulation necessitates a greater, rather than less prominent role for regulatory mechanisms. The reasons for the public's preference for governmental binding regulation are clear: governmental regulation makes technological development far more transparent and shifts the debate into the public arena and out of the secretive world of academic and company research and development departments.

However, national authorities cannot be expected to bear all responsibility for regulating nanotechnology by themselves, and co-regulation might therefore be an appropriate approach to that issue.[152] In the United States, EPA has endorsed that recommendation, stating that "partnerships with industrial sectors will ensure that responsible development is part of initial decision-making".[153]

In the absence of legally-prescribed guidelines, industry will wield significant power in nanotechnology oversight and in the shaping of rules that will govern the sector for years to come.[154] To address that state of affairs, a more active governmental role in the regulation of nanotechnology is needed. As stated by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2006, a "serious discussion of self-regulation is probably due".[155]

Governments are at the moment encouraging self-regulation for various reasons. Some use it as a fact-finding mechanism to gather evidence which can then be used as a basis for governmental regulation, while for other Governments it embodies their approval of the unfettered development of nanotechnology. Over the short term, self-regulation might be an acceptable step, but the weakening of the regulatory role of national authorities, either as a result of the persistence of self-regulation or because of undue influence from industry and their partners in academia in the debate on how nanotechnology should

146 UNEP (2007).
147 Gary Marchant and Douglas Sylvester (2006).
148 Gregory Mandel (2009).
149 Julia Black, "The emergence of risk-based regulation and the new public risk management in the United Kingdom", in Public Law (Autumn 2005), pp. 512-549.
150 Julia Black (2007).
151 Peter Cane, "Tort Law as Regulation", in Common Law World Review, vol. 31 (2002).
152 Jason Wejnert, "Regulatory mechanisms for molecular nanotechnology", in Jurimetrics, vol. 44 (2004).
153 United States Environmental Protection Agency (EPA), Nanotechnology white paper (Washington D.C., EPA, 2007).
154 Michael Mehta, "Nanotechnology", in Encyclopaedia of Globalisation, Roland Robertson and Jan Scholte, eds. (Routledge, 2006).
155 UNESCO (2006).

be regulated, will have serious repercussions in terms of those authorities' legitimacy, accountability and transparency.

The call for a more proactive government role in the regulation of nanotechnology and limits on private sector regulation is justified because regulation is a public function and should be carried out in the public sphere. It is unwise, however, to discount the changes that industry has undergone in recent years, including its growing responsiveness to public concerns. That responsiveness and other changes in corporate behaviour have not come as part of some benevolent gesture, however, but in order to secure and retain the loyalty of environmentally-savvy consumers, to limit the impact of criticism by non-governmental organizations with regard to child labour and unfair trade practices, and to forestall potential lawsuits. Those changes to corporate behaviour, which have now become institutionalized as "corporate social responsibility",[156] underscore just how much could be achieved if steps are taken to involve industry in the regulation of nanotechnology.

Besides Governments, the public and industry, other actors shaping the evolving regulatory frameworks include non-governmental organizations, international organizations, social science researchers and ethicists. Governance structures should be as inclusive as possible to ensure that no powerful stakeholder or group of powerful actors exerts undue influence. Multinationals pursuing the technology have various motives for engaging in nanotechnology oversight, ranging from the desire to lock-in the benefits accruing from the technology to the neo-Luddite tendency to stifle its development in order to perpetuate existing production and market patterns. Only State authorities can wield power matching that of the corporate behemoths. However, not all Governments are able to wield such power and some, particularly in the developing world, may fall victim to pressure exerted by multinationals. For this and other reasons, the regulation of nanotechnology will only be fully effective if it is implemented at the global level.

4.1. NATIONAL VERSUS INTERNATIONAL REGULATION

The regulatory issues of nanotechnology are so wide ranging that no single country can address them all effectively.[157] Regulation must be comprehensive and global in scope if it is to have any credibility. Experience with biotechnology has demonstrated that national regulation is easily undermined by "regulatory arbitrage" among jurisdictions, which, over the long term, tends to weaken regulatory standards.[158] The race to the bottom in regulatory standards has gathered pace as lax regulations have been used by certain countries to gain a competitive advantage. The development of cancer treatment technology in China is often cited as an example of how the purposeful exploitation of weak regulatory frameworks can give countries a competitive edge.[159]

The nature of nanotechnology is such that it requires regulation that is global in scope. Regulation, especially if it is a ban, is unlikely to be successful unless it is universal and it has, in fact, been argued that 99.999 per cent regulation is as good as no regulation at all.[160] International action must therefore be taken because, as stated by one expert, "if you are planning to guide the development of nanotechnology across the entire planet, local regulations may be worse than useless." [161]

156 Ibid.

157 Meridian Institute, "International Dialogue on Responsible Research and Development of Nanotechnology", (Alexandria, United States, 2004).

158 Roger Brownsword (2004).

159 The development in China of cancer treatments involving gene therapy that are unavailable in the West has raised fears about an erosion of regulatory hurdles. See "Biotech Cancer Therapy Gets Approval in China", New York Times, 17 November 2005.

160 Glen Reynolds (2003).

161 Ralph Merkel, "The Risks of Nanotechnology" in Nanotechnology: research and perspectives: papers from the First Foresight Conference on Nanotechnology, B. C. Crandall. and James Lewis eds., (Cambridge, Massachusetts, MIT Press, 1992).

A consensus on the need for international regulation is slowly emerging. Calls for international cooperation are being made in reports by Governments and international organizations.[162] Despite those calls, no steps have so far been taken to draft legislation at the international level. However, efforts by non-governmental organizations in that regard continue to drive that process forward and, as early as 2004, the Meridian Institute, a non-governmental group, convened a gathering of government representatives from over 25 countries.[163] Such events have inspired parallel developments at the more formal intergovernmental level and a flurry of activity by key United Nations agencies and regional intergovernmental organizations, including UNESCO, UNEP, the United Nations Development Programme (UNDP), the United Nations Industrial Development Organization (UNIDO), the World Health Organization (WHO), the United Nations Institute for Training and Research (UNITAR) and the International Labour Organization (ILO), which have all addressed nanotechnology in publications, conferences, consultations and other initiatives.

As previously mentioned, ICCM has become an important international platform in the area of nanotechnology regulation and has established a non-binding multi-stakeholder policy framework. Although that framework is voluntary, it is an important governance instrument whose recommendations should be taken into account by countries when drawing up their national nanotechnology policies. SAICM has, moreover, provided a forum for interested parties to voice and register their concerns and developing countries, in particular, have used that forum effectively to underscore that development of nanotechnology cannot proceed if their needs are not addressed. African countries have played a prominent role in shaping the global debate on nanotechnology oversight.[164] However, more needs to be done to mitigate pressure exerted by more powerful stakeholders, particularly as certain industrialized countries and the chemical industry have successfully blocked the adoption of a number of decisions, including on the adoption of the precautionary principle as a rule of nanotechnology governance.

5. HOW TO REGULATE? THE PRECAUTIONARY PRINCIPLE

The potential risks of nanotechnology are, at present, largely speculative. Dupuy and Grinbaum suggest that the expression "hypothetical risk" is a more fitting expression and should be used when describing those risks, as "potential risk" designates a risk waiting to be realized, whereas a "hypothetical risk" designates a risk that is only a matter of conjecture.[165] In such uncertain circumstances, the precautionary principle in international law is often invoked as an appropriate principle to guide scientific endeavour. Activists have, in fact, been calling for the application of a version of the precautionary principle that seems rather like an inversion of a criminal law principle, namely that everyone is innocent until proven guilty.[166] Organizations such as Greenpeace, the Action Group on Erosion, Technology and Concentration and Friends of the Earth have all called for the adoption of the precautionary principle under which materials are initially assumed to be hazardousness. Indeed, "these materials should be considered hazardous until proven otherwise."[167] The precautionary principle has been invoked in national and international legislation for decades. Principle 15 of the Rio Declaration on Environment and Development of 1992 provides one of the most quoted formulations of the principle:

162 See, for example, UNESCO, 2006, p.13; Commission of the European Communities, 2004, p.22; and EPA, 2007, pp.17 and 112.

163 Meridian Institute, 2004.

164 Hailemichael Demissie and others (2017).

165 Jean-Pierre Dupuy and Alexei Grinbaum, "Living with Uncertainty: Toward the Ongoing Assessment of Nanotechnology" in Techné, vol. 8, No. 2 (Winter 2004).

166 International Risk Governance Council (IRGC), White paper on nanotechnology risk governance, (Geneva, 2006).

167 Gary Marchant and Douglas Sylvester (2006).

> In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

The interpretation and implementation of the precautionary principle has not, however, been consistent. Its ambitious normative power has been undermined by its inconsistent application, despite the claim made by some that it has attained the status of international customary law.[168, 169]

Those calling for the regulation of nanotechnology believe that the application of the principle is more than justified given the scientific uncertainty in the nanotechnology field. What is not properly addressed by the principle, however, is the massive interest in exploiting the technology for economic and, more importantly, environmental purposes.

In fact, one of the more interesting promises of nanotechnology relates to environmental restoration. Nano-led economic growth will not be the kind of growth that has depleted the Earth's resources at the expense of the environment and there is a convergence between goals of the nanotech revolution and those expressed by environmental movements. Promising clean and ubiquitous energy, wasteless production, and little or no dependence on raw materials, nanotechnology could be used to restore environments that have been adversely affected by other technologies. The precautionary approach will be self-defeating if, because of scientific uncertainty, it is applied in such a manner that it hampers the environmentally beneficial development of the technology.

This inability to predict the future can result in numerous compromises being made in the application of the precautionary principle and, to date, applications of the principle have been only "a little more than a glorified version of a "cost-benefit" analysis."[170]

However, reducing the precautionary principle to a form of cost-benefit analysis would encourage the continuation of nanotechnology research and development, which runs counter to the expectations of those who, in invoking the principle, have called for such research and development to be halted. A cost-benefit analysis is likely to conclude that the benefits of the technology far outweigh its costs, given that, at present, there are only potential and/or hypothetical risks associated with that technology. Consequently, it is unlikely that a moratorium or prohibition would be imposed.

The precautionary principle is believed to be too restrictive to serve as a basis for a global nanotechnology regulatory regime[171] and, in view of the strong objections to its application expressed by major nanotech stakeholders, it has rarely been invoked. The principle, as defined in the Rio Declaration on Environment and Development, was initially invoked in the early stages of the process to draw up the SAICM framework. However, at the second session of the International Conference on Chemicals Management (ICCM2), held in 2008, the principle was abandoned due to pressure from developed countries and the chemical industry.[172]

The principle has not been adopted widely not only because of opposition from industrialized countries, but also because of the widespread belief that the principle would prove inadequate in the face of the

168 Sustainable Development Law, Marie-Claire Segger and Ashfaq Khalfan, eds. (Oxford, Oxford University Press, 2004).
169 Gary Marchant and Douglas Sylvester (2006).
170 Jean-Pierre Dupuy and Alexei Grinbaum (2004).
171 Gary Marchant and Douglas Sylvester (2006).
172 Ndeke Musee and others (2012).

inevitable development of nanotechnology. Indeed, the principle is viewed as insufficiently robust to serve as a normative basis for the regulation of nanotechnology and other emerging technologies.[173] Given the fact that nanotechnology is incredibly promising to society and the planet, subscribing to the "technology-freezing" canons of the precautionary principle would be a gross miscalculation.

5.1. ALTERNATIVES TO THE PRECAUTIONARY PRINCIPLE

In 2004, having dismissed the precautionary principle as incapable of "dealing with the kind of uncertainty that the new technological wave generates", the researchers Dupuy and Grinbaum called instead for "a novel concept of prudence" and a "methodology of ongoing normative assessment" The two researches saw that methodology as "a practice" and "a way of life", and defined it as:

> [A] matter of obtaining through research, public deliberation, and all other means, an image of the future sufficiently optimistic to be desirable and sufficiently credible to trigger the actions that will bring about its own realization.

The researchers stressed the need to live with an uncertain future while continuously re-evaluating it. Continuous and incremental evaluation is the hallmark of their proposal, which is supported by other authors, including Douglas and Wildavsky, who suggest that, as paraphrased by Black, "we do not know the risks we face, but we must act as if we do".[174] The researchers Guston and Sarewitz also elaborated on the issue of ongoing assessment and, in their "Real-Time Technology Assessment" model, they argued that:

> Society's capacity to plan despite an uncertain future shows that the alternative to prediction is not inaction or reaction, but incremental action based on synchronous reflection and adjustment. What is necessary … is to build into the research and development enterprise itself a reflexive capacity that … allows modulation of innovation paths and outcomes in response to ongoing analysis and discourse.[175]

Mandel also suggests that "emerging technology governance" mechanisms should be used to regulate new technologies.[176] In order to address the challenges of "the combination of vast potential benefits and uncertain risks" that emerging technologies such as nanotechnology present, Mandel proposes a governance model similar to those outlined above that stresses the role of a range of stakeholders and moves away from traditional command and control regulation mechanisms.

A discussion of the nuances of the precautionary principle is beyond the scope of this report. Suffice to say that the various interpretations of the principle have made its application difficult for regulators. Among the twenty or more interpretations of the principle currently available, there are versions that incorporate the methodologies proposed by the aforementioned experts. Further efforts are needed, however, to complete the formulation of more effective and workable approaches that can be used as alternatives to the principle.

173 Jean-Pierre Dupuy and Alexei Grinbaum (2004).

174 Julia Black (2005).

175 David Guston and Daniel Sarewitz, "Real-time technology assessment" in Technology in Society, vol. 24. (2002). Available at: cspo.org/legacy/library/1104071235F63583901WV_lib_GustonSarewitzRe.pdf.

176 Gregory Mandel (2009).

6. SOCIETAL ISSUES AND REGULATION

The debate surrounding the regulation of nanotechnology focuses, primarily, on hazard prevention. Even in that area, the scope of the debate is limited to the first stages of the development of nanotechnology and insufficient thought is being given to potential future developments in the field. Currently, we are at a stage where systems of nanosystems and molecular nanosytems are being developed, which is characterized by advances in robotics, next generation information technology and nanobiotechnology, and the construction of molecular and atomic devices. With the exponential advance of technology, it is predicted that, within a few years, humanity may enter an age of "technological singularity" in which "solutions to most of today's problems, including material scarcity, human health, and environmental degradation can be solved by technology."[177] Technology will assume its own accelerated momentum and computers with superhuman intelligence will be capable of solving problems far more complex than those that humans can solve with their biological brains.

These developments have been dismissed as visionary and science-fictional or derided as "urban myths" and hence not worthy of consideration in the debate on regulation.[178] However, it will prove impossible to regulate such developments by continuing to think of nanotechnology regulation as merely the regulation of chemicals and materials, with a particular focus on their toxicity or carcinogenicity; attention will need to be given, more broadly, to the need to prevent any "abuse" of the technology, which could, in fact, pose a much greater danger.

However, in the current debate on the regulation of nanotechnology "abuse", however it is understood, is often overlooked, and is considered less important than "ethical, legal and societal implications". The debate on those issues has to be approached with urgency, despite the seemingly remote science-fictional aura of aspects of the technology.

With the convergence of economic, political and social values with scientific and technological progress, countries increasingly believe that science can play a crucial role in development. Science now plays a critical role in national economies and government policies on civil and military affairs. Ziman has in fact noted that science provides crucial support to the economy, to government policy, to the military, and is a decisive factor affecting international hegemony, competitive edges and military superiority or inferiority.[179] Science today, and nanotechnology in particular, is "unashamedly focused on applications rather than fundamental understanding".[180] This has led some to use a clever pun to refer to nanotechnology as "political science"- not in the sense of a social science discipline but as science that has become political. The need to redirect science to promote human welfare should be the core objective of nanotechnology, which should be viewed as "a socio-political project". As Guston observed in 2013, nanotechnology provides an opportunity to focus on policy, institutional and governance change, the role of stakeholders holding a wide range of opinions and beliefs, and key concepts such as responsibility.[181]

177 Joseph Kennedy, "Nanotechnology: The Future Is Coming Sooner than You Think" in The Yearbook of Nanotechnology in Society, Eric Fisher, Cynthia Selin and Jameson Wetmore, eds., vol. 1 (2008), pp. 1-21.

178 Emilio Mordini, "Nanotechnology, society and collective imaginary: setting the research agenda" in New Global Frontiers in Regulation: The Age of Nanotechnology, Graeme Hodge, Diana Bowman and Karinne Ludlow, eds. (2007).

179 See Fabrice Jotterand, "The Politicization of Science and Technology: Its Implications for Nanotechnology" in, Journal of Law, Medicine and Ethics, vol. 34, No. 4 (2006), pp. 658-666.

180 Richard Jones, "Nanotechnology: "Privacy will be a quaint obsession"", in "20 Predictions for the next 25 years", The Guardian, 2 January 2011. Available at: www.guardian.co.uk/society/2011/jan/02/25-predictions-25-years.

181 David Guston, "Introduction to the special issue: nanotechnology and political science", in Review of Policy Research vol. 30 (2013), pp. 439-446.

There is little disagreement that a debate on the ethical and societal implications of the technology is long overdue. Unlike the situation of genetically modified organisms, which entered the public sphere without adequate debate, societies still have an opportunity to conduct an informed debate on nanotechnology. That opportunity should not be squandered. In fact, the aforementioned report by the United Kingdom Royal Society and Royal Academy of Engineers on nanoscience argues that public engagement on emerging technologies should be organized "at a stage when it can inform key decisions about their development and before deeply entrenched or polarised positions appear".[182] Furthermore, early public debate on critical issues are vital in that respect as "they could become "showstoppers" before there is a show to stop".[183]

That public debate will undoubtedly be wide-ranging and complex in view of the fact that the societal impacts of nanotechnology are likely to be diverse and multidimensional. As the technology delivers on its promises, challenges will arise in connection with the distribution of its benefits and its impact on people's livelihoods. Social equity within countries and equity among countries will be a major theme that will shape the development of the technology itself. Public acceptance of the technology will determine the pace at which it advances and such acceptance will largely depend on the outcome of the debate on the distribution of nanotechnology's benefits and the risks it poses. The benefits of nanotechnology to developing countries and the risks posed to their populations should, moreover, figure prominently in that debate.

7. CONCLUSION

The exponential advance of nanotechnology is giving rise to opportunities and challenges much sooner than was initially envisaged. Society remains largely unprepared to address those challenges. Although the developing world will be particularly affected by the advance of nanotechnology, the rest of the world cannot simply enjoy nanotechnology's benefits and will also need to address its undesired repercussions. The fair and even distribution of the benefits of nanotechnology is a universal imperative driven by the exigencies of sustainability. The emphasis on inclusivity articulated in the 2030 Agenda for Sustainable Development and expressed in the slogan "Ensuring that no one is left behind" stems from the realization that the world should not be only "partially" better off and that promoting the welfare of all humanity is in everyone's interest. The primary objective of nanotechnology regulation should therefore be the achievement of sustainable development, particularly as advances in the technology are already facilitating the achievement of numerous sustainable development objectives. The global community must now ensure that the technology is used in a responsible and equitable manner so that societies are not further divided into "haves" and "have nots".

182 United Kingdom Royal Society and Royal Academy of Engineers (2004).

183 David Guston and Daniel Sarewitz (2002).

CHAPTER 4.

NANOTECHNOLOGY RESEARCH AND INNOVATION IN SOUTH AFRICA

1. INTRODUCTION

South Africa is a developing country with a rapidly growing nanotechnology sector. Its Government believes that economic growth, poverty alleviation and an enhanced quality of life can be achieved through the development and exploitation of nanotechnology. The country's National Nanotechnology Strategy, adopted in 2005, draws upon the strengths of the country's National System of Innovation and sets forth the following four priority objectives: the establishment of national multi-user nanomaterial characterization centres; the creation of research and innovation networks to encourage and strengthen inter-disciplinary research at both the national and international levels; the promotion of human capacity development; and the launching of flagship nanotechnology projects. Achievements to date include the establishment of centres of innovation and excellence as well as laboratories that can fabricate state-of-the-art nanostructures. The two national nanotechnology innovation centres, namely those run by the Council for Scientific and Industrial Research (CSIR) and South Africa's national mineral research organization (MINTEK) collaborate with universities and industry in key research fields related to poverty reduction and industrialization.

2. NANOTECH ETHICS AND A CODE OF CONDUCT

Nanotechnology and biotechnology are emerging technologies that promise new and exciting possibilities for the developing world. However, in order for these promises to be realized, a collaborative effort involving the private sector, the investment of significant financial resources and synchronized, well-thought-out policies will prove crucial. South Africa must position itself strategically as a knowledge economy, but this can only be achieved if the country develops a robust research agenda and strengthens its National System of Innovation so that it can effectively address the country's developmental needs. At the same time, the risks posed to human health and the environment by those emerging technologies necessitate the adoption of a transdisciplinary approach to research and development: the development and roll out of nanotechnology applications must take place in tandem with studies on nanotoxicity and nano-ethics, while the development of biotechnology must take into account bioethical considerations and the potential dangers of genetically modified organisms.

Challenges arise, however, when advances in technology fail to take place in a holistic manner. The development of nanotechnology, for example, has far outpaced the development of nano-ethics, and this poses potential risks for human health and the environment. Those conducting nanotechnology and biotechnology research and designing real-world applications of those technologies must take into account the context in which these technologies are being developed. Efforts must also be made to address the needs of as many people as possible and collaboration among government departments, the private sector and research institutions should be encouraged.

Since 1994, numerous plans and policies have been formulated with a view to addressing historical injustices and inequality and promoting development, including in the areas of science and technology. A white paper published in 1996 set forth a road map for science and technology policy reform and provided for the launch of the country's National System of Innovation. The paper emphasized the need to exploit technology and promote innovation in order to foster development and economic growth.

In subsequent years, the country adopted specific policies on nanotechnology and biotechnology. The National Biotechnology Strategy, launched in 2001, was less effective than had been hoped, and, in 2014, it was superseded by the Bio-economy Strategy. The National Nanotechnology Strategy was launched in 2005 and, since then, a number of nanotechnology characterization centres, research and innovation networks, and capacity-building programmes have been established. Regrettably, however, very few of those initiatives have moved beyond the research phase and delivered tangible outcomes. The Ten-Year Innovation Plan was launched in 2008 to help transform South Africa into a knowledge-based economy in which knowledge drives economic growth and human development. The plan aims to support the development of the National System of Innovation and address pressing socioeconomic challenges facing the country. It acknowledges that much more needs to be done if South Africa is to develop a knowledge-driven economy and commercially exploit its scientific breakthroughs.

3. PUBLIC AWARENESS-RAISING INITIATIVES BY THE SOUTH AFRICAN NANOTECHNOLOGY INITIATIVE AND THE SOUTH AFRICAN AGENCY FOR SCIENCE AND TECHNOLOGY ADVANCEMENT

The Nanotechnology Public Engagement Programme is an initiative funded by the Department of Science and Technology and implemented by the South African Agency for Science and Technology Advancement, which is overseen by the National Research Foundation. The Programme, which is based on the National Nanotechnology Strategy, was launched in early 2008, and aims, in particular, to improve people's lives by raising public awareness of nanotechnology research and promoting informed decision making on nanotechnology by policymakers and stakeholders from industry.

As is the case with any emerging technology, public acceptance of nanotechnology will prove crucial if commercially developed nanotechnology products and services are to be successful. It is inevitable that perceptions of, and attitudes towards, nanotechnology will be shaped by the news and information that the public receives about that technology and efforts must therefore be made to educate people about the technology to enable them to make informed decisions in that regard.

The National Nanotechnology Strategy National Strategy therefore encourages open and frank debate on the technology and engagement with the public to explore its potential impact on society. The Strategy identifies four target audiences, namely learners in schools, scientists, stakeholders from industry and the general public.

The South African Nanotechnology Initiative was established in 2002 to lay the ground work for nanotechnology development in South Africa. The Initiative brings together academics, researchers and engineers from universities, the private sector, industry, research councils and government bodies, and seeks to raise awareness of nanoscience and nanotechnology and to identify potential market opportunities. The Initiative organizes annual student symposiums and biennial international conferences that provide an opportunity for students, university researchers and industry professionals to share their experiences in nanoscience and nanotechnology and discuss future trends.

4. HUMAN CAPITAL DEVELOPMENT FOR NANOSCIENTISTS

Establishing a highly-competent human resource base with requisite research and development expertise will facilitate the private sector development of nanotechnology-based products and services. Emerging markets in that area will, in turn, promote societal development, particularly in the areas of education and job creation. Government and private sector actors should, in particular, provide financial support to the following: final year undergraduate and postgraduate students in order to spur a massive increase in human resources with appropriate skills in the areas of nanoscience and nanotechnology; training programmes and internships to bolster the skills of those wishing to enter the nanotechnology field; interdisciplinary and inter-institutional postgraduate programmes in nanoscience and nanotechnology to encourage collaborative research and development; and initiatives aiming to establish strategic national and regional nanotechnology research support networks.

Although the commercial development of nanotechnology products and services is beyond the scope of the National Nanotechnology Strategy, several industrial partners have formulated strategies to that end. Their commitment to the Strategy has already been demonstrated through cost-sharing initiatives and many have made pledges to promote the commercial development of nanotechnology at the earliest opportunity.

5. INCREASING THE AVAILABILITY OF HIGH THROUGH-PUT NANOTECHNOLOGY INSTRUMENTS

To position South Africa as a key player in the rapidly advancing science and technology field, the National Nanotechnology Equipment Programme is supporting the acquisition, upgrade and development of advanced research equipment for the analysis and characterization of nanomaterials that help researchers design, synthesize, characterize, model and produce nanomaterials. The primary objectives of the Programme are to:

(a). Stimulate and support nanotechnology research by investing strategically in research equipment for the characterization of nanomaterials with a view to advancing the National Nanotechnology Strategy;

(b). Build human resource and infrastructure capacity in the area of nanoscience and nanotechnology;

(c). Promote regional, national and international collaboration among nanoscience and nanotechnology researchers;

(d). Enhance access by postgraduate students to equipment used in nanotechnology research and training;

(e). Support the creation of new and innovative mechanisms for the application of nanotechnology in various areas; and

(f). Support and strengthen the strategic objectives of the National Nanotechnology Strategy.

6. FLAGSHIP PROJECT FUNDING

To highlight the potential benefits of nanotechnology, South Africa should support the implementation of a number of nanotechnology flagship projects that address areas where the country stands to gain the most from the development of the technology, namely water, energy, health, chemical and bioprocessing, mining and minerals, and advanced materials and manufacturing.

Such flagship projects can be grouped into two development clusters: namely an industrial and a social cluster. In the industrial cluster, mining and minerals, chemical and bioprocessing, and materials and manufacturing could benefit tremendously from the country's expertise in nanotechnology. As for the social cluster, benefits would arise from new developments in the provision of clean and purified water, affordable and renewable energy and improved primary health-care services.

7. RESEARCH INNOVATION NETWORKS

Collaboration among traditional disciplines, research teams and institutions is critical if we wish to understand the characteristics of nanomaterials and develop nanotechnology applications. Collaborative research and innovation networks should initially be established in key areas of nanotechnology research, such as research into the characterization of non-carbon-based nanoparticles, nanosynthesis techniques and nanoparticle modelling. In the South African academic and research spheres, it is also important that collaborative networks seek to address research capacity gaps between historically white and historically black institutions. South Africa should also cooperate in the area of nanotechnology with the wider Southern African region and the African continent as a whole through its engagement with institutions such as the Southern African Development Community (SADC) and NEPAD. Efforts should also be made to engage with networks of nanotechnology researchers that that have been established in other parts of the world, including those established in Brazil, Europe and India.

8. LESSONS LEARNED FROM THE REPUBLIC OF KOREA

The Republic of Korea has established a government agency that supports the development and patenting of nanotechnology products and services by universities and research institutions. To effectively exploit the commercial potential of nanotechnology developed in Africa, South Africa and other African countries should likewise support nanotechnology patenting.

CHAPTER 5.
DEVELOPING A NANOTECHNOLOGY RESEARCH AND INNOVATION BASE: THE EXPERIENCE OF MAURITIUS AND THE CREATION OF AN AFRICAN NANOTECHNOLOGY ALLIANCE

1. BUILDING A NATIONAL NANOTECHNOLOGY KNOWLEDGE BASE AND PROMOTING NANOTECHNOLOGY RESEARCH AND DEVELOPMENT

The University of Mauritius Centre for Biomedical and Biomaterials Research, established in 2011, has been instrumental in the country's efforts to strengthen its human resources and promote research and development into biomedical applications of nanotechnology, including, in particular, the use of biomaterials to promote tissue regeneration. The Centre has allowed research institutions and companies from Mauritius and abroad, including research groups from Kenya and the French overseas department of Reunion to use its facilities and specialized equipment. Since its establishment, the Centre has significantly reduced its dependency on the analytical facilities provided by its international partners. An interesting parallel can be drawn with Brazil, which, in 2008, established the National Nanotechnology Laboratory for Agriculture, which later became the Brazilian Nanotechnology National Laboratory. This has led to a significant increase in the number of researchers in the country active in the area of materials science.

1.1. STRENGTHENING REGIONAL AND INTERNATIONAL COLLABORATION

Ph.D. and postdoctorate student exchanges with the Mayo Clinic medical centre in the United States of America, the University of Siegen, Germany and CYROI, the cyclotron and biomedical research platform in Reunion have allowed the Centre for Biomedical and Biomaterials Research to reduce its dependency on external collaborators and develop its own teams of trained researchers. The Centre has also established partnerships with Edith Cowan University in Australia, Zhejiang Sci-Tech University in China, the University of Witwatersrand in South Africa and Northeastern University in the United States of America.

1.2. CREATION OF A JOINT REGIONAL RESEARCH AND INNOVATION PLATFORM WITH REUNION

The regional research and innovation platform, which receives financial support from the Mauritian Government and the European Union, has facilitated the sharing of complementary facilities and expertise and has enabled the Centre to create a multidisciplinary team that includes polymer chemists, biochemists, veterinary experts and molecular biologists.

1.3. CONTRIBUTION OF THE CENTRE TO NATIONAL DEVELOPMENT

With the financial support of the European Union, the Centre has, to date, organized two workshops that were attended by some of the country's prominent scientists: a workshop held in 2013 that aimed to lay the groundwork for the establishment of national biobased industries, and a workshop held in 2014 entitled "Analysing the National Innovation System", which sought to identify national strengths and weaknesses in the area of innovation.

The Ministry of Technology, Communication and Innovation is actively supporting the establishment of a national nanotechnology industry and provided financial support for the purchase by the Centre of a scanning electron microscope (the only such microscope in the region). Furthermore, in April 2016, the Cabinet of Ministers approved a concept note on the development of a nanotechnology industry and is encouraging small and medium enterprises to develop nanotechnology-based products. Efforts are now being made to raise awareness among relevant national stakeholders, including the Chamber of Commerce and Industry, the Chamber of Agriculture, the Mauritius Manufacturing Association, Enterprise Mauritius, the Board of Investment and the Small and Medium Enterprises Development Authority, on the opportunities provided by nanotechnology. Areas identified for the development of new industries include the following:

(a). Energy and the environment: nanotechnology could facilitate the generation of energy from renewable energy sources, thereby strengthening the country's energy independence and helping to safeguard the environment. The establishment of the country's smart cities also provide opportunities for nanotechnology-based development;

(b). The health sector: Nanotechnology could revolutionize the field of medicine by radically improving the performance of medical materials and devices;

(c). Water resources: To address the country's increasing water requirements and in the light of unpredictable rainfall patterns, Mauritius could develop low-cost nanomembranes for use in seawater desalination plants;

(d). Nanotextiles: The Mauritian textile industry should strive to develop innovative nanotextiles and smart materials that could strengthen the competitiveness and exportability of their products.

1.4. SUPPORT PROVIDED BY THE EUROPEAN UNION

Thanks to financial support provided by the European Union in 2017, the Government of Mauritius has been able to upgrade the University of Mauritius Centre for Biomedical and Biomaterials Research, so that it can more effectively promote innovation, skills development and the creation of small and medium enterprises. To that end, the Centre aims, inter alia, to:

(a). Develop a master's degree course in nanotechnology and its applications as well as professional training courses that address the needs of industry;

(b). Work with small and medium enterprises and industrial stakeholders to identify critical areas for nanotechnology research and development that will promote the emergence of a knowledge-based economy in Mauritius;

(c). Create a platform for nanotechnology knowledge dissemination, to be called the "Nano-Forum", to enhance the innovation capacity of small and medium enterprises, and promote collaboration among those enterprises and nanotechnology research institutions.

1.5. BUSINESS OPPORTUNITIES

For small countries like Mauritius, the development of nanomaterial-based products is an expensive process that poses significant financial challenges. To help offset costs, it is important to identify potential markets both at home and abroad. In addition, those countries must develop their capacity to both produce and exploit nanomaterial-based products and should endeavour to conclude trade agreements that will support their sustained economic growth. In that regard, the Centre will strive to provide newly-established small and medium enterprises with appropriate analytical support in order to reduce their nanotechnology product development and production costs.

2. THE WIDER AFRICAN CONTEXT

In 2005, the University of Toronto Joint Centre for Bioethics asked 63 specialists from around the world to identify areas for nanotechnology research and development that would be particularly beneficial for developing countries. The top 10 areas identified by those specialists were:

(a). Energy storage, production and conversion;

(b). Agricultural productivity and enhancement;

(c). Water treatment and remediation;

(d). Disease diagnosis and screening;

(e). Drug delivery systems;

(f). Food processing and storage;

(g). Air pollution and remediation;

(h). Construction;

(i). Health monitoring;

(j). Vector and pest detection and control.

Today, 15 years after the study by the 63 specialists, the African continent should:

(a). Prioritize areas for industrial nanotechnology application development;

(b). Consider the creation of an African nanotechnology alliance, possibly with ECA oversight, that would establish country focal points to promote research and training in specific areas of nanotechnology;

(c). Provide support through the African Development Bank for nanotechnology development;

(d). Establish a database of researchers in the fields of nanoscience and nanotechnology.

Apart from providing access to its research and development facilities and providing training to researchers from other countries in the African region, the University of Mauritius Centre for Biomedical and Biomaterials Research is keen to collaborate with universities across Africa on the design of nanoscience and nanotechnology curricula. Indeed, if it is adequately funded, the Centre can play a key role in coordinating efforts by a wide range of stakeholders in the area of nanotechnology training and research.

3. NANOTECHNOLOGY AND THE PROMOTION OF SUSTAINED DEVELOPMENT IN DEVELOPING COUNTRIES.

Every developing country should identify a particular niche area of nanotechnology in which to specialize. By doing so, developing countries can develop their own network of nanotechnology users and providers with skills and expertise that reflect the needs and particular economic circumstances of their countries and who are thus able to effectively address the concerns of the populations of those countries and enhance their quality of life. The establishment of an African nanotechnology alliance would pave the way for achieving that goal.

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