UNIVERSITY OF TURKU
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# Expectations for nanotechnology

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Nanotechnology is said to be the transforming technology of our era, representing a completely new level of understanding of the world. Manipulating atoms and molecules at the nanoscale, nanotechnology enables advancements in materials and devices. However, many nanotechnology visions are still waiting for breakthroughs in research or applications for commercialisation. Expectations play a pivotal role in the evolution of emerging technologies such as nano. New technologies are brought into society through expectations. Expectations for emerging technologies are real-time representations of future capabilities of the technology. They have a central role in building the momentum for technological and scientific innovation.

This study delves into the expectations of experts for nanotechnology. Knowing these expectations will help to focus on the relevant aspects now and to build the desired futures. The research questions are: 1) What is the role of expectations in the development of nanotechnology? 2) What is the current stage of nanotechnology development and how is it expected to develop? 3) What are the current expectations for nanotechnology?

The study begins with a literature review on technology life cycles and the role of expectations in their formation. Next, it traces the development path of nanotechnology and the evolving expectations along it. Empirical data is gathered through a Delphi expert panel and complementary interviews. Delphi was attended by 14 experts from different fields of nanotechnology, and six of them also participated in thematic interviews. The results were analysed using content analysis.

The results section describes the expected changes in the different fields of nanotechnology, the main obstacles to commercialisation, guiding megatrends, societal impacts, the development phase, and long-term visions. Nanotechnology is in a state of divergence and stability, with some fields already reaching maturity and mainstream acceptance, while others remain in early developmental stages. Significant changes are expected in the fields of energy, information technology, medical applications, and materials science. Obsolete laws and regulations and safety concerns continue to hamper the commercialisation of nanotechnology although green transition and digitalisation create new needs for it. Nanotechnology remains one of the most promising technologies, with a current focus on ensuring its safety for health and the environment. Interest in nanotechnology is growing as it is anticipated to offer solutions for a more sustainable society. The synergy between nanotechnology and other emerging technologies, along with the potential for hybrid solutions, is increasingly recognised.

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Nanoteknologian sanotaan olevan aikamme käänteentekevää teknologiaa, joka edustaa aivan uudenlaista ymmärrystä maailmasta. Atomien ja molekyylien manipulointi nanomittakaavassa mahdollistaa edistysaskeleet materiaaleissa ja laitteissa. Monet nanoteknologian visiot odottavat kuitenkin yhä läpimurtoja tutkimuksessa tai sovelluksia kaupallistamiseen. Odotuksilla on ratkaiseva merkitys nanon kaltaisille kehittyville teknologioille, sillä uudet teknologiat tuodaan yhteiskuntaan odotusten kautta. Odotukset kehittyvistä teknologioista ovat reaaliaikaisia representaatioita teknologian tulevaisuuden kyvyistä. Niillä on ratkaiseva rooli teknologisten ja tieteellisten innovaatioiden momentumin rakentamisessa.

Tämä tutkimus pureutuu nanoteknologian asiantuntijoiden odotuksiin. Näiden odotusten tunteminen auttaa keskittymään olennaisiin asioihin nyt ja rakentamaan toivottuja tulevaisuuksia. Tutkimuskysymykset ovat: 1) Mikä on odotusten rooli nanoteknologian kehittymisessä? 2) Mikä on nanoteknologian kehityksen nykyinen vaihe ja miten sen odotetaan kehittyvän? 3) Mitkä ovat nykyiset odotukset nanoteknologiaa kohtaan?

Tutkimus alkaa kirjallisuuskatsauksella teknologioiden elinkaaresta ja odotusten roolista niiden muotoutumisessa. Seuraavaksi se kuvaa nanoteknologian kehityspolkua ja vaihtuvia odotuksia sen varrella. Empiirinen aineisto kerätään Delfoi-asiantuntijapaneelin ja sitä täydentävien haastatteluiden avulla. Delfoihin osallistui 14 nanoteknologian eri alojen asiantuntijaa, joista kuusi osallistui myös teemahaastatteluihin. Tulokset analysoitiin sisällönanalyysin avulla.

Tulososiossa kuvataan nanoteknologian eri osa-alueiden odotettuja muutoksia, tärkeimpiä kaupallistamisen esteitä, kehitystä ohjaavia megatrendejä, yhteiskunnallisia vaikutuksia, kehitysvaihetta ja pitkän aikavälin visioita. Nanoteknologia on eriytyneessä ja vakaassa tilassa. Jotkin nanoteknologian alat ovat kypsempiä ja jo valtavirrassa muiden alojen ollessa vielä varhaisemmassa kehitysvaiheessa. Merkittäviä muutoksia odotetaan erityisesti energian, tietotekniikan, lääketieteellisten sovellusten ja materiaalitieteen aloilla. Vanhentuneet lait ja määräykset sekä turvallisuushuolet haittaavat edelleen nanoteknologian kaupallistamista, vaikka vihreä siirtymä ja digitalisaatio luovat nanoteknologialle uusia tarpeita. Nanoteknologiaa pidetään edelleen yhtenä lupaavimmista teknologioista, ja sen nykyinen painopiste on turvallisuuden varmistamisessa niin terveyden kuin ympäristönkin kannalta. Kiinnostus kasvaa, koska nanoteknologian odotetaan tarjoavan ratkaisuja kestävämpään yhteiskuntaan. Nanoteknologian ja muiden kehittyvien teknologioiden välinen synergia sekä hybridiratkaisujen mahdollisuudet tunnustetaan yhä vahvemmin.

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# 1 Introduction

Futures studies aim to reveal alternative futures. Knowing what the future will be is impossible, but futures studies methods enable to anticipate and act on the preferred futures (Dator, 2019). One of the interests of futures studies are emerging technologies because of their potential disruptive effects on society. This study is about expectations for emerging technologies based on the case example of nanotechnologies. Nanotechnology is stated to be the transforming technology of our time. After the hype at the beginning of the 2000 century, there has been a lot of development in the separate branches and novel innovations but many of the visions are still waiting for breakthroughs in research or tools for mainstream commercialisation. Current challenges in green transition and digitalisation create new demands and again increase the significance of nanotechnology.

Nanotechnology refers to the technology in a nanoscale (one billionth of a meter) of molecules and atoms, which provides unique opportunities for developing materials and devices (Salerno, Landoni & Verganti 2008). It draws on the scientific knowledge of biology, physics, chemistry, and materials science (Glenn, 2006). Nanotechnology is used in this study as a collective term, encompassing its various branches. A more detailed definition is given in the next section.

Nanotechnology has already been around for decades but has not yet redeemed all its promises. Some of the promises hold key solutions for our decade's biggest challenges such as the energy crisis, material scarcity, and climate change. At the same time, technology opportunism is seen as a thread while people wait for innovations to solve problems without a need to change anything.

Expectations have a decisive role with emerging technologies like nano. They possess power since new technologies are brought to society through expectations. Expectations transform into actions in a current time for example in funding and strategies. (Borup, Brown, Konrad & Van Lente 2006). This study aims to find out what has been the role of the expectations in the development of nanotechnology and what are the current expectations.

My interest in nanotechnology was sparked throughout my husband's business related to insulative nanomaterials. I was intrigued by the bold visions for nanomaterials but surprised by the fact of how slow the commercialisation seems to be. During my studies in futures research and technology foresight in particular, I got interested in the development of emerging technologies and the role the expectations play in it. As my background is in human sciences, education, and psychology, expectations offered a natural perspective for me to perceive the development of nanotechnology. Technology expectations emerge at a societal level rather than an individual. While society is transforming more and more future-oriented because of the fast phase of the changes, expectations become an interesting research domain.

The study begins with a literature review on the development and expectations of emerging technologies. It moves then to describe the development path of nanotechnology and the expectations along it interpreting the past development of nanotechnology and orienting to the current state. Understanding the past explains our current beliefs and expectations for the future (Bell 1997, 88-90). After, the focus turns to the future ten years ahead. The study is interested what are the experts' expectations for nanotechnology. Knowing those expectations helps focus on relevant aspects now to thrive for the preferred outcomes. The empirical data is collected through a Delphi expert panel supplemented by interviews. The data is analysed using content analysis. The results will reveal some expectations for nanotechnology for the next ten years and beyond and describe the role of the different drivers.

The report is divided into four sections. The first part describes the research objects and the theoretical background. It defines nanotechnology and explains the common theories of the development cycles for emerging technologies. It introduces the main theories of expectations and their role within emerging technologies. The first section ends with an outline of the development path of nanotechnology and various expectations along it. The second section discusses the research process introducing the methodology and adaptation of Delphi and interviews used to gather empirical material and explains how the content analysis is utilised. The third section presents the results and compares them to theory and previous studies. It first describes the experts' expectations of the impact of nanotechnology on its different fields and the role of the obstacles and trends. Then it discusses the current stage and the future of the development cycle of nanotechnology. After that, it presents some societal implications and longer-term future visions. The fourth section observes the quality of the study, forms conclusions, and discusses further research needs.

# 2 Nanotechnology and the role of the expectations

This paragraph presents the main research objects and the theoretical background used in this study. It begins with a description of nanotechnology: definition, characterisation, development, and current state. After that, the theories of the development cycles of emerging technologies are outlined and compared to the development of nanotechnology. Then the framework of expectations is displayed, focusing on the expectations for emerging technologies. Finally, the results of the literature review are presented in the form of a table which shows how the expectations have changed along with the development of nanotechnology. In qualitative research, theory can be used as a tool to produce interpretations or as a goal when single observations can be turned into generalisations (Eskola & Suoranta 2008, 81-83). This study utilises theory to describe the study object.

## 2.1 Nanotechnology

Nanotechnology is introduced here briefly to give an idea of its uniqueness, but not described in technical detail. Nanotechnology refers to the technology in the nanoscale of molecules and atoms, which provides unique opportunities for developing materials and devices (See, for example Dannemand Andersen, Rasmussen, Strange & Haisler 2005; Salerno et al. 2008). In the International System of Units (2019), the prefix "nano" means one-billionth and a nanometer is one-billionth of a meter. Nanotechnology is in some arenas understood more as an approach to engineering which is based on the scientific knowledge of biology, physics, chemistry, and materials science (Dannemand Andersen et al., 2005). Nanotechnology can be divided into top-down structural technology, where nanotechnology is used to update existing items and more challenging bottom-up molecular technology designing completely new materials (Lele, 2009; Kumar, Kumar & Luthra 2023).

As the technology has such a wide range of applications its multifunctionality makes it difficult to categorise. The definition of categories shapes perception and attitudes and influences decision-making about regulation, adoption, and investment in technology (Kim, Shim, Moon, Kwon, Kim & Son 2014). Nanotechnology can be divided into three major sections: nanotools, nanostructured materials and nanodevices that are utilised across multiple application fields. Nanotools include supramolecular chemistry, synthetic methods, surface science, nanolithography, analytic tools and computer simulations. Nanostructured materials are nanoparticles, nanowires, carbon nanotubes, quantum dots, fullerene, graphene, nanocomposites, thin solid films and nanolayers, nanopatterned surface and supramolecular systems. Examples of nanodevices include nanoelectronics, spintronics, nano-optoelectronics, nano-sensors and drug delivery systems. (Kumar et al. 2023.)

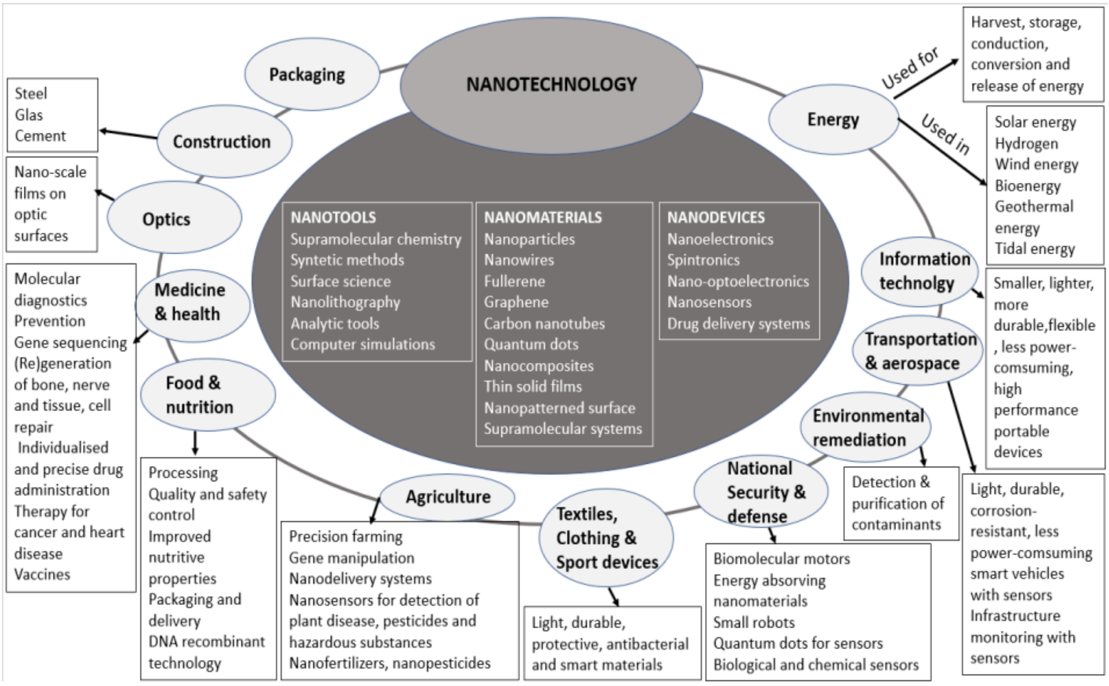


Figure 1 Fields of nanotechnology

(Inspired by Kumar et al. 2023 and elaborated by the author and colleagues in a Technology Foresight course at the University of Turku 2023)

Foresight studies on nanotechnology have used different categorisations. Salerno et al (2008) used application based categorisation adapted from the categorisation used in EU: 1. materials science (characterization, materials by design, functionalization); 2. medical applications (diagnostic and therapeutic); 3. nano-electronics (photonics, magnetism and, in a broader sense, information elaboration processes); 4. energy production and storage; 5. metrology and development of instruments; 6. food, water and environment; 7. manufacturing processes; 8. security (both passive and active); 9. robotics.  This study utilises the categorisation from Salerno et al. (2008) updated by the latest divide based on applications from National Nanotechnology Initiative (NNI 2023).

The peculiarities of nanotechnology are the interdisciplinarity- crossing the boundaries of traditional science - and pervasiveness - effecting all industries. These peculiarities offer a variety of commercial applications revolutionising many products and ways of manufacturing them (Salerno et al. 2008; Munari & Toschi 2014.) Nano is often referred to as a general-purpose technology, as it touches on nearly all aspects of society, is a source of a variety of innovations, and has high potential to improve many solutions (Dewick, Green & Miozzo 2004; Youtie, Iacopetta, & Graham 2008).

Nanotechnology research began already in the 1950s but came to the knowledge of a wider public in the 1980s (Munari & Tuchi 2014). Nowadays nano is the key emerging technology, one of the defining technologies of the 21st century (Bachman, Holtmannspötter, Korte & Zweck 2001) and called even the most promising technology of the future (Salerno et al. 2018). The development path of the technology from its early years to its current stage is described in chapter 2.4.

## 2.2 Development cycles of emerging technologies

Emerging technologies refer to technologies that are still at the development stage and have the potential to shape a variety of industries, society and economy. There are various ways to define the emerging technology. Rotolo, Hicks & Martin (2015,1828) name five attributes in their study overlooking these different definitions: (i) radical novelty, (ii) relatively fast growth, (iii) coherence, (iv) prominent impact, and (v) uncertainty and ambiguity. Nanotechnology is considered to be an emerging technology because its biggest impacts are still foreseen (Munari & Toschi, 2014). Lots of studies have shown repeating patterns in the development of emerging technologies. This chapter presents the most common theories of these development cycles. It begins with an introduction of the big shifts in industry and society called Kondratieff waves. Then it defines the development cycles of emerging technologies presenting macro curve and S-curve. After that it describes Gartner's hype cycle, which highlights the role of expectations in the development of emerging technologies.

Kondratieff cycles or long waves describe big shifts in the economy and industry lasting several decades. The latest cycle starting in the 1970/1980s is called the information technology wave including microelectronics, software, and internet development. Before that were the railroads, steel, and oil waves. According to some experts, the next wave will be determined by biotechnology and nanotechnology dedicated to the manipulation of organisms, information and material. (Dewick et al. 2004.) Nanotechnology being a significant part of the next technology wave reflects the high expectations this study will describe later.

Taylor & Taylor (2012) studied various definitions and models for technology life cycles and emphasis the two most used types of technology life cycles in their literature review, macro and S-curve. In the macro cycle innovation creates discontinuation, which is followed by competition and then the evolution of the winning technology until new innovations create again discontinuation. Additionally, the S-curve model highlights the performance over time. The performance typically first emerges slowly because of the uncertainties, then accelerates as the technology is ready, and at some stage declines after the full potential has been reached. Critiques for the S-curve claim the development is not so straightforwardly smooth. Sometimes x- and y-axis are replaced with effort and diffusion. In some cases, multiple S-curves can occur simultaneously and even compete against each other. Apart from macro and S-curve approaches, they identified various other technology lifecycle theories, which focused for example on collaboration practices, strategical choices, a societal level or recognising relevant courses of action in different stages. They argue that technology life cycles should focus on applications rather than specific artefacts since it describes the development only with very simple products. Their model is based on concepts of applications (what is the technology used for) paradigm (technological approach used to solve the problem) and generation (variation of technologies used). In this viewpoint, the S-curve can be perceived from different levels. Also, Dewick et al. (2004) recognise the sectoral differences depending on the nature of technology (product or process), the way it's generated, and the level of radicality. As nanotechnology is multidisciplinary and has applications in various fields, the application-focused model offers useful viewpoints.

Since this study is about expectations, Gartner's hype cycle theory gives valuable perspectives. Gartner's hype cycle describes expectations at different phases of the technology development drawing a pattern of hope, hype, disappointment, differentiation, and steady development. The hype cycle begins with an innovation trigger when a new promising technology penetrates the news even when there are no ready products available. This sparks a peak of inflated expectations when both success stories and failures are published. Still, only a few companies act on the new possibilities. The next phase is called disillusionment as interests decline when some experiments fail. This is a critical point to improve the product to ensure further investments. After that follows the slope of enlightenment when the idea becomes more widely understood and next-generation products are revealed. The final phase is called the plateau of productivity where mainstream market applications are available. (Borup et al. 2006; Gartner 2024.) Critics say that the Gartner's hype cycle is too simplified and general to describe the sociotechnical change. The hype cycle gives too linear picture and fails to involve path dependencies and ongoing reconfigurations that are part of the development. (Borup et al. 2006.) Since nanotechnology has been around for many decades and includes various technologies there is a lot of oscillation and multiple hype cycles occurring simultaneously and even new curves emerging. Expectations play a key role in the hype cycle as explained in the next chapter. Development cycles are used in this study to observe nanotechnology's development path and to understand the role of expectations in it.

## 2.3 The role of expectations

This paragraph describes the definitions of expectations, how they are constructed, and what is their impact. The descriptions start from psychology and then focus on expectations' role in technology development. In addition, some related concepts are described briefly to underline the specific role of the expectations. This study is particularly interested in expectations' role in the development of emerging technologies.

### 2.3.1 Definitions of expectations and related concepts

Expectations are a highly studied topic in psychology explaining human behaviour. Psychological research focuses on expectations mostly at the individual level. Expectations define how people interpret information and how they decide to act.

Expectations are conditional beliefs about the future that modify our perception, motivation, cognition, decision making and behaviour. They guide us towards successful behaviour as they help to anticipate the behaviour of others and the environment we live in. Expectations are tight to basic concepts of human cognition. People have certain schemas, meaning representations about the world, which are the base for expectations. Schemas are modified based on new information and experiences. Expectations are constantly maintained and updated through new information and experiences either confirming or violating the dominant expectations. (Panitz et al. 2021.) As this study is especially interested in the expectations about emerging technologies the perspective differs from classical psychology. Expectations in economics focus on consumer behaviour and pay more attention to rational expectations where expectations are assumed to be something that can be calculated (Borup et al. 2006). Expectations in behavioural science are not tied to technology and are not tied only to the preferred future.

In futures studies, expectations are one of the many concepts describing future-oriented thinking. The concepts are partly overlapping but highlight different aspects. Next, the concepts most overlapping with expectations are described.

Gustafsson, Kuusi and Meyer (2015) differentiate between anticipation and expectation. They define anticipation as a vision with a long-term perspective, more uncertain and vaguer. Whereas expectations are more specified and connected to capacity and performance within the near future. Gustafsson et al. (2015,181) introduce also another concept, leitbild or guiding image. Guiding images can be formed based on expectations or anticipations. Guiding image is a more general anticipation of the future and can obtain various visions. In this study, expectations are seen from a wider perspective – not distinguished from anticipation.

Images of the future are one of the main concepts in futures studies as they are the base for societal change. Bell and Mau (1971,23-24) define an image of the future as an expectation about the future state of things. Expectations present a variety of possibilities. Images of the future may be considered for individuals or groups, on specific subjects or wide aspects, on long-range or near future. Images of the future may be pessimistic or optimistic and people may consider their role towards the future active or passive. The viewpoints define actions and the actual realised future. Schick (2021) approaches images of the future with a modern perspective discussing how artificial intelligence has affected our understanding of anticipating the future. As computers are more and more efficient and can calculate highly relevant forecasts, one might think we are closer to being able to see the future. Still, futures studies is not about predicting and counting probabilities but widening the viewpoint and acknowledging the alternatives. We should not let AI alone imagine the futures but be active future makers ourselves. The future images of AI should be taken seriously and consciously build strategies to utilise them to our advantage.

The line between different concepts is blurred. Often images of the future are seen as more holistic and may include various expectations. On the other hand, images of the future refer more to individual perspectives while expectations represent collective views. The list of future-oriented concepts is not exhaustive and could have been expanded for example with visions and promises. However, this study focuses on the expectations concerning emerging technologies and the next chapter describes expectations in that context.

### 2.3.2 Expectations and emerging technologies

Expectations have a psychological background as they are fixated on motivation and intention Selin (2007). Expectations in general refer to looking forward but expectations on technology are real-time representations of the future capabilities of certain technology. It is impossible to know how the technologies will turn out to be and the expectations are the only truth we have. (Borup et. al. 2006.) Knowledge of emerging technologies is often based on the expectations of future performance rather than current performance (Alkemade & Suurs, 2012). Studying expectations for emerging technologies is essential to understand the change. Expectations are a bridge between boundaries and levels as they bring together different actor groups and link together technological and societal aspects. (Borup et al. 2006.) Expectations give the shared vision and motivation for development.

Konrad (2006,431) divides expectations into individual and collective. Collective expectations refer to widely accepted expectations, not only inside certain groups but expectations mediated in general societal discussions. Individual expectations are based on specific positions and interests but are also affected by collective expectations. Widely agreed expectations can even become obligatory, like promises of the future (Borup et al. 2006) or normative, guiding the development (Konrad 2006). Expectations inform the stakeholders even though they are not automatically approved by all (Bakker, Van Lente & Meeus 2011).

Borup et al. (2006, 286) define expectations as wishful thinking and acknowledge that fears of risks have an equally important effect on technological change. In comparison, Alvial-Palavicino & Konrad (2019, 193) describe expectations as statements about the future including both promises and concerns. Expectations can be both positive underlining the advantages or negative focusing on assumed risks. This study perceives expectations concerning both hopes and fears.

Emerging technologies exist only in the expectations, which shape their potential as they shape activities, investments, and regulations (Borup et al. 2006). Expectations have the biggest role at the beginning of the development cycle attracting the interest of experts and funders and overcoming uncertainties (Bakker et al. 2011; Alkamade & Suurs 2012; Hielscher & Kivimaa 2019). Still early expectations describe badly the future of technology. However, expectations at a later stage are often connected to niches or specific aspects of the technology. The changing role of expectations during the development path of emerging technologies was described also in the earlier chapter when describing Gartner's hype cycle. Expectations create a mandate for continuing the development of the technology (Bakker et al. 2011). Expectations hold power since new technologies are brought to society through them. Expectations transform into actions in a current time for example in funding and strategies. Expectations define if technology is peaking or sinking. Expectations have a crucial role in building momentum for technological and scientific innovations. (Borup et al. 2006; Hielscher & Kivimaa 2019.)

Expectations impact also the governance of emerging technologies (Budde & Konrad, 2019; Hielscher & Kivimaa 2019). Hielscher & Kivimaa (2019) studied the role of expectations for emerging technologies related to policymaking using smart meters as a case example. They observed governance through expectations, focusing expectations on the policy design phase. The interest was both in governance by expectations (how they impact planning and legitimating innovation processes) and governance of expectations (how expectations are realised). Expectations describe the future and can be governed through systematic futures visioning. Governing expectations aims also to distribute the power. The research showed the importance of studying expectations not only in the early emergency of new technologies but also later in the implementation phase when the regulations are made. Nanotechnology at this moment is undergoing a lot of regulations, which makes observing expectations highly topical.

Expectations play a meaningful role in the relations between different actors. They are not personal visions but created in discourses of the future and define what translation of the technology survives. (Selin 2007.) Expectations often differ between stakeholder groups, especially between scientists and the public, according to the closeness of the issue, access to information, and feeling of ability to affect (Borup et al. 2006). Bakker et al. (2011, 153) studied arenas of expectations, which represent places where ideas about future technological options are presented and evaluated. Arenas of expectations have an important role in the processes of variation and selection of emerging technologies. Multiple arenas may co-exist as expectations are tested on economic and societal aspects. Different actors express and formulate expectations in a debate for legitimacy. If the expectations are approved the innovation continues. They identified differences between two groups in these arenas, scientists with positive expectations who wanted the funding to continue and industry representatives with more reservations wanting to compare and test expectations.

Alvial-Palavacino and Konrad (2019) studied the role of the different arenas of expectations in anticipatory practices building the graphene (carbon nanostructure) hype. Findings highlighted the importance of appreciated publications as one of the arenas of expectations as well as the ability to reach the wider public and new fields of science. Expectations impacted on public funding mechanism reflecting economic and societal implications. The study described a pathway of expectations from scientists to funding and further to the markets. Expectations actuated networking and channeled funding. The basic ideas of the expectations were shared but different stakeholder groups highlighted different aspects. Also, the way the expectations were produced varied between the arenas. This study examines experts' expectations which are assumed to be more realistic compared to laymen.

Alkemade and Suurs (2012) have studied patterns of expectations for sustainable emerging technologies. They argued that sustainable technologies cannot count only on market forces but are part of larger societal transformation and technological change. The specific role of sustainable technologies affects also expectation patterns. They made an event history analysis for new sustainable transportation options (biofuels, hydrogen, and natural gas). Based on the findings, the government's role in creating expectations is specifically important for emerging sustainable technologies. The same hype cycles occur as analysed with other emerging technologies, but the difference was the highlighted importance of the government and the lack of consensus on the expectations. The government's role is emphasised by investments, regulations, and subsidies. Sustainability-related innovations are very complex because of risks, long development time, large investments, regulations, policies, and involvement of many actors. Nanotechnology offers a variety of solutions for sustainability transition, for example energy storage and material scarcity (Leinonen & Kivisaari 2010), and can be counted among sustainable emerging technologies. This study is interested in how strongly nanotechnology is seen as a sustainable technology and how it may shape expectations.

## 2.4 Literature review: Development path of nanotechnology and the expectations during the lifespan

The starting point for a foresight action is to familiarise with the subject. The purpose is to have an overview, to understand the history, and to perceive the current trends to anticipate possible futures. To study the expectations for nanotechnology, the first thing was to sketch the development path of the technology and combine it with the various expectations along the way. The process showed variations in the expectations and helped to draft questions for the nanotechnology experts. This section first describes the process of gathering information about the steps of the development. Secondly, it tells the narrative of the nanotechnology development path and the expectations rising along it. Thirdly, it concludes the main points relevant to this study and sets goals for the empirical data gathering.

### 2.4.1 Information gathering

The literature review started with going through academic articles in futures studies and social studies journals. The search was done using nanotechnology and expectations as search words together and separately. The overview showed that most of the futures research articles on nanotechnology were written between the years 2000 – 2010. After that period only a few articles on nanotechnology were published in the field of social studies or articles focused on the specific domains of nanotechnology, for example, graphene or nanomedicine. The finding suits well on the typical development curve of emerging technologies. During the hype, interest is wide but later technology is distributed to specific domains and the research focuses on those domains instead of the general technology.

The search produced only a couple of studies on expectations for nanotechnology (Selin 2007; Anderson 2007; Karaca & Öner 2015; Alvial-Palavicino & Konrad 2019). On the other hand, studies on expectations for emerging technologies in general were published regularly over the years. The most relevant studies were selected to perceive the role of expectations and to learn if the expectations for nanotechnology were unique. The search also produced some studies on the development path of nanotechnology.

The literature review was widened to scan national and international nanotechnology strategies, roadmaps, and initiatives. The aim was to test the hypothesis on the stage of nanotechnology development and to gather more data on the expectations for nanotechnology. The scan started with listing strategies, roadmaps and initiatives already mentioned in the scientific articles selected during the literature review and continued with a Google search focusing on nanotechnology and technology development institutions' and research centres' publications. The search ended with an overview of the nanotechnology strategies in 15 countries around the world, plus a European Union-wide strategy. The search was limited only to 15 countries since widening the search did not seem to produce new findings and data saturation was reached. After all, the strategies were only supplementary background information in this study. The findings supported the earlier observations. Most of the strategies were published during the hype and after that, publications were roadmaps for specific nanotechnology domains or nanotechnology was only mentioned among other emerging technologies. Search also revealed various nanotechnology reports which were scanned and considered in cases where they described the development path or expectations. More references were discovered later during the study and used to supplement the description of the key concepts, development path, and expectations.

Table 1 Summary of the literature review
(Created by the author)

| **Data** | scientific articles in the field of futures studies and social studies | nanotechnology strategies, roadmaps, initiatives, and reports |
|---|---|---|
| **Source** | scientific article database | internet search |
| **Search words** | nanotechnology, emerging technologies, expectations | nanotechnology strategy/roadmap/initiative |
| **Outcome** | 55 scientific articles | overview of nanotechnology strategies in 15 countries (+EU wide strategy) and various reports |

### 2.4.2 The Nanojourney

The nanojourney, the development path of nanotechnology and the expectations rising along it, was created based on the literature review of scientific articles, nanotechnology initiatives, roadmaps and strategies, and various reports. The nanojourney gives an overview and tells the narrative of the development of nanotechnology rather than giving quantitative statistics or specific steps of the development. The journey was written by collecting the important events, milestones in technology development, data on funding, publications and patents combined with expressions on expectations towards future progress. The description of nanojourney is part of the results of this study. The overview of the previous development and evolution of expectations forms the basis for current expectations.

-1970

The science that underlies nanotechnology can be traced to the beginning of the 19th century (Kostoff, Koytcheff & Lau 2007). Even though nanotechnology has been mentioned in academia earlier it came strongly to the awareness of wide public in the 1970s. The famous speech "There is plenty of room in the bottom" by Feynman 1956 is seen as an important event for nanotechnology presenting the idea of controlling matter at the atomic level. (Selin 2007.) There was slow growth in funding, research, academic publications, and patents (Daim, Monalisa, Dash & Brown 2007; Munari & Toschi 2014; Arranz, Arroyabe & Schumann, 2020). Nanotechnology was considered to be a wild dream. It was seen as a new technological domain (Selin 2007) and even transformative technology (Kostoff et al.2007).

1980–1990

At the beginning of the 1980s, the IBM microscope was able to see and manipulate a single atom and it helped to perceive the possibilities of nanotechnology concretely and strengthened the expectations for nanotechnology as the next big thing (Salerno et al. 2008). Nano contains various fields of science such as chemistry, physics, material science, and biology and all these fields had their own nano applications. Research focused on chemistry and physics (Fogelberg & Sandén 2008) but during the late 1990s, the branches started to merge (Islam & Miyazaki 2009). Growth in funding, research, academic publications and patents continued (Daim et al. 2007; Munari & Touchi 2014; Arranz et al. 2020).

Engineer Eric Drexler published the book "Engines of Creation: The Coming Era of Nanotechnology" in 1986, where he presented his far-looking visions of molecular manufacturing and nanobots. Drexler's arguments attracted a lot of attention to nanotechnology and created wild expectations of molecular machinery. At the same time, the scientists feared the field would lose its credibility. (Selin 2007.) Nanotechnology was considered the next big thing (Salerno et al. 2008). Even visions of utopian “Grey Goo”, where self-replicating nanobots rule the world were shared (Leinonen & Kivisaari 2010).

2000–2010

The years between 2000–2010 were an active time for governments to conduct national nanotechnology initiatives. The US started with the famous National Nanotechnology Initiative (NNI 2000) and others followed trying to compete in the new, exciting field. (Fogelberg & Sandén 2008). Rising interest increased national investments in nanotechnology (Salerno et al. 2008). The first articles on nanotechnology in futures studies were published as nano was seen as a key emerging technology. The fast growth of scientific articles on nanotechnology started already 1990 but accelerated at the beginning of 2000 century (Kostoff et al 2007; Arranz et al. 2020). The amount and the phase of articles varied between countries, US heading, Japan and Germany being pioneers, but China quickly overtooking them (Kostoff et al. 2007). The research on funding, publications, and patents is somehow controversial and varies across nations but follows the normal pattern, where first the amount of funding and articles start to grow, and patents will follow. The beginning of 2000 showed a heavy increase in funding and publications of academic articles, but growth in patents was much more decent.

Renn & Roco (2006) described four overlapping generations of nanotechnology products and processes expected to evolve between 2000–2020 starting with passive nanostructures, active nanostructures, nanosystems and ending with molecular nanosystems, where molecules are used as devices and novel functions will emerge from self-assembly. The hype on nanotechnology was high and it was considered to be one of the most promising technologies (Salerno et al 2008) and was predicted to even create the next Kondratieff cycle (Wonglimpiyarat 2005). Leinonen & Kivisaari (2010) studied laymen's expectations for nanotechnology and noticed high hopes for nano changing the world fundamentally and offering help to burning challenges. At the same time, there were ethical concerns about nanodivide between rich and poor countries and fears of safety threats to humans and the environment. Tegart’s (2004) scenarios for nanotechnology recognised the potential for pervasive technology and new manufacturing styles but foresee a lack of big innovations and challenges in regulation. Instead of significant societal disruption where nano changes everything, it is more likely to see changes in one sector or technology at the time and co-existing of the old and new technologies.

2010–2020

Nanotechnology was seen as a natural continuation of technological development. Lots of education programs were created to ensure a skilled workforce and research continuation. Nanotechnology connected different scientific fields (EC 2013) and enabled the development of other technologies bringing multidisciplinary to traditional industries. The focus was on convergent technologies. The amount of funding, research, and patents continued to increase but the peaks were not so high. There is no easily available data since the numbers were no longer reported under nanotechnology, but rather under the singular branches of it. The amount of national nanotechnology strategies decreased as the differentiation of nano branches continued.

Trust in nanotechnology was still high. It was expected to tackle future challenges and add quality to every aspect of life (EC 2013). It's assumed to solve global problems in economics, ecology, and material scarcity (Vishnevskiy & Yaroslavtsev 2017). There was hype especially around one nanotechnology, graphene (Alvial-Palvacino & Konrad 2019).

Present

During the 2020s, the focus has been on safety and health regulations as the commercialisation of nanotechnology has finally reached higher volumes in some applications.  Not all technology reports mention nanotechnology as such anymore, but rather different branches of it, quantum most often. Publication of futures studies' articles on nanotechnology is rare. Expectations for nanotechnology are still high. Nanotechnology is expected to bring economic relief and offer new applications for various fields. Yet it is considered only one of the promising technologists which alone cannot provide all the solutions.

Table 2 Nanojourney

(Created by the author)

| TIME | ACTIONS | EXPECTATIONS |
|---|---|---|
| -1970 | • Feynman's speech 1959<br>• slow growth in funding, research, publications, and patents | • wild dream<br>• transformative technology<br>• new technological domain |
| 1980 | • Drexler's article 1981<br>• microscope able to see and manipulate a single atom<br>• slow growth in funding, research, publications, and patents | • risks and new possibilities<br>• molecular machinery - Grey Goo<br>• the next big thing |
| 1990 | • fast growth in funding, research, publications, and patents | • rising star<br>• nanobots rule the world vs no need for fear<br>• enabling vs disruptive technology |
| 2000 | • rapid growth in funding, research, publications, and patents<br>• increase in foresight articles<br>• separate branches of nano united as a multidisciplinary research field<br>• national nanotechnology initiatives | • hype -may change the world fundamentally<br>• general purpose technology vs might not penetrate markets<br>• enables the development of other technologies<br>• safety risks for humans and the environment<br>• ethical dilemmas, nanodivide |
| 2010 | • not much comparable data about funding, research, publications, and patents for nano in general<br>• differentiation and steady development in different branches<br>• focus on convergent technologies<br>• opening of commercial market<br>• education programs<br>• decrease in national strategies for nano<br>• some foresight articles | • slow development continues<br>• safety risk<br>• human mastery of molecules and atoms<br>• interdisciplinarity creates innovations<br>• solution for societal problems<br>• key enabling technology vs niche applications<br>• solving global problems<br>• nano part of green transition |
| 2020 - | • focus on safety and health regulations<br>• decrease in foresight articles<br>• commercialisation of nano | • one technology among others<br>• brings economic relief<br>• increases the quality of life in every area |

Selin (2007) aptly describes the role of the expectation during the development of nanotechnology. She reveals how the narrative of the early years of the emergence of nanotechnology demonstrates the power of expectations. It was a battle between imaginary visioners and traditional scientists. The development curve of emerging technology is an arena for debates about futures. Richard Feynman kept his famous speech "There's Plenty of Room at the Bottom" in 1959, where he introduced the possibilities of nanotechnology. A couple of decades later, in 1986, enthusiastic engineer Eric Drexler published the book "Engines of Creation: The Coming Era of Nanotechnology", where he presented his far-looking visions of molecular manufacturing and nanobots. Drexler's arguments attracted a lot of attention to nanotechnology and created wild expectations. At the same time, the scientists feared the field would lose its credibility. Some expectations have power, and others are more superficial, lacking an impact on material, social, or institutional actions. Drexler's vision was catchy but didn't last for debates. (Selin 2007). Both kinds of expectations are needed. Visioners who look far away, inspire, and imagine. And a scientific approach to keep the relativism and make the groundwork. When studying expectations, it is important to consider all the arenas of expectations. Despite which expectations finally materialised, this narrative proves the power of expectations.

Based on the literature review, the development of nanotechnology appears to be stable. Nanotechnology has moved from a hype stage to an integrated development in various fields. Interest has increased somewhat due to the demands of the green transition. Progress is continuous but does not make spectacular leaps. Expectations were wild at first. Now expectations are more modest, although nano has not yet reached its full potential and can still change many industries and have a huge impact on society. Revolutionary no longer seems revolutionary when change happens slowly.

The search for nanotechnology strategies was not conducted systematically or comprehensively. It provided a wider perspective on the development of nanotechnology and confirmed the hypothesis rising from the scientific articles. Describing the development path of nanotechnology and expectations along it could have been a topic for the thesis alone. In this study, the nanojourney served as a starting point for exploring the present expectations. The description of nanojourney finetuned the research questions and created the ground for formulating statements for the expert panel. The Delphi panel was set to test the hypothesis of the nanojourney and collect more detailed observations.

# 3 Research questions and research process

This section presents the research process of this study. First, it introduces the research questions and explains how they were formulated. Then it describes the research process reasoning the meaning of each step. Finally, it presents the data gathering and data analysis in more detail. Opening the research process increases the transparency and through that the reliability of the study. Reasoning the choices of a researcher and reflecting on the research project is essential in qualitative research (Eskola & Suoranta 2008, 219–221).

## 3.1 Research questions

The study started with an interest in the development of emerging technologies, nanotechnology particularly, and focused on the role of expectations. The research questions have evolved during the process. The literature review and scanning nanotechnology strategies revealed the focal issues and laid the ground for defining research questions. The test panel of experts reinforced and finetuned the questions during the first part of data gathering. The time horizon for the study, the next ten years, was selected considering the fast changes in the field.

The main research questions are:

1. **What is the role of expectations in the development of nanotechnology?**

2. **What is the current stage of nanotechnology development and how it is expected to evolve?**

3. **What are the current expectations for nanotechnology?**

   3.1 How will nanotechnology impact the different fields of industry?
   3.2 How will the current obstacles to commercialisation impact the development of nanotechnology?
   3.3 How will the current megatrends impact the development of nanotechnology?
   3.4 How will nanotechnology shape society?

Salerno et al. (2008) identified specific demands for foresight studies on nanotechnology based on its peculiarities. They identified a demand for global studies, a need for quantitative data, and ideally mid or long-term time horizon. There is a demand for gathering knowledge from various fields and from a wide range of experts as well as other subgroups and to consider societal impacts. This study partially answers the call since the perspective is broad focusing on nanotechnology in general rather than specific fields and the scope is global.

## 3.2 Research process

The research onion presented by Saunders & Lewis (2018, 105-136) describes the versatile aspects of the research process. It begins with the philosophy and theories behind the research and then moves to methodologies and techniques. The strength of this model is the ability to describe different layers of the process. Describing the research from philosophy to practicality is part of ethicality. This study is based on critical realism as it is interested in underlying structures that shape the actions. The focus is on revealing the expectations that modify the development of technologies.

Academic research can utilise theory in different ways. The deductive, data-driven approach begins with describing the theory and then gathers data to test the theory. On the contrary, the inductive approach moves from specific observations to generalisations and defining theories. Between these approaches, the abductive approach moves between theory and data along the study. (Saunders & Lewis 2018, 111-114.) This research follows abductive tradition as it moves back and forth between theory and empirical data using theory to formulate data gathering and explain the findings. The approach gives room for surprising findings and is open to including new theories. Research can also be categorised as exploratory or explanatory. Exploratory studies focus on finding information on the subject and explanatory studies describe why something is happening (Saunders & Lewis 2018, 115-118). This study combines both elements as it describes expectations for nanotechnology but also aims to understand their role.

The research process started with defining the preliminary research questions and framing the study objects. It continued with a literature review to acquire the relevant theories. The focal points were the theories about expectations and development cycles for emerging technologies. The aim of the literature review was also to familiarise with earlier futures studies on nanotechnology. The traditional literature review was supplemented with scanning the nanotechnology initiatives and strategies to perceive the development path of nanotechnology and the previous expectations. The findings were summarised as a description of the nanojourney presented in chapter 2.4.

After gathering the knowledge on the subject, the next step was to gather empirical data. The data was collected first through a Delphi expert panel and supplemented with interviews. Results of the Delphi were summarised before the interviews to be able to confirm the findings and widen the perspective. Finally, the data from the Delphi and the interviews were analysed and compared to theory and earlier studies. The process was not linear but progressed in cycles, always returning to the earlier stages to check the direction. Qualitative research is seldom executed linearly but gathering the data, analysis and reporting intertwine (Hirsjärvi & Hurme 2000). An important part of the process was writing the report during every stage of the study and reflecting on the reliability and validity of the whole study.

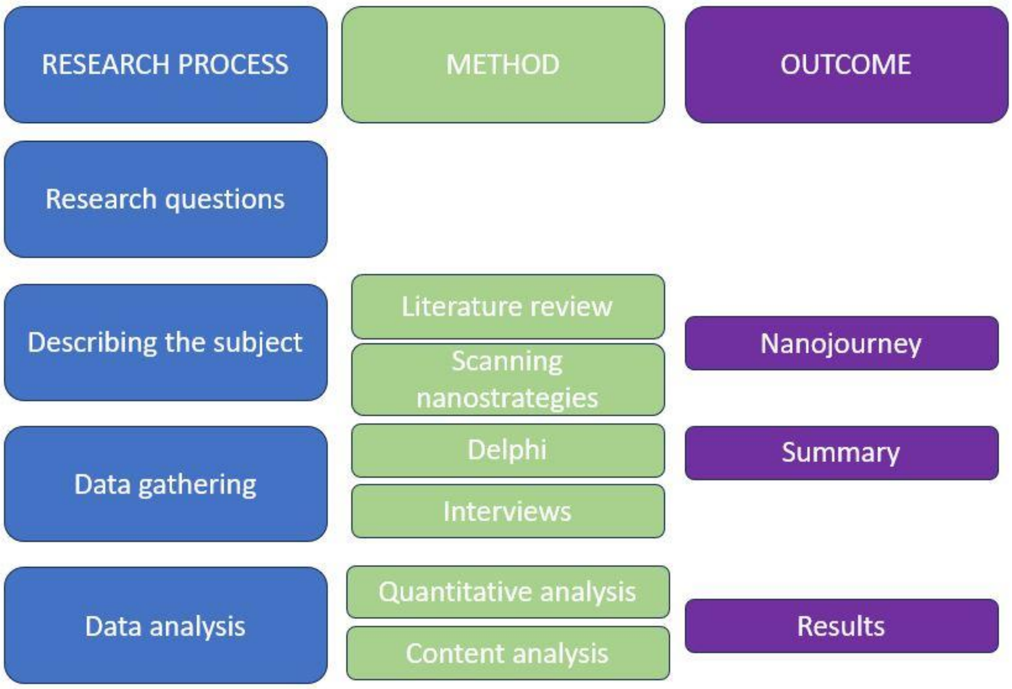


Figure 2 Visualisation of the research process
(Created by the author)

Expectation patterns are more studied retrospectively and the impact of current expectations has drawn less attention (Gustafsson et al. 2015). Dynamics of expectations can be recognised for example by observing shared research agendas, collective learning agendas, and emerging mutual dependencies (Jørgensen, Jørgensen & Clausen 2009). Usually, expectations are studied based on documents, reports, news, or conversations.

In this study, previous expectations were studied from scientific articles and nanotechnology strategies and initiatives and current expectations by asking directly from experts. It is assumed that experts can articulate their expectations, but acknowledged that some expectations can be subconscious.

### 3.3 Expert panel

This chapter describes the assembly and structure of the expert panel since reflecting principles for data gathering increases the quality of the research (Saunders & Lewis 2018, 137). Data gathering started with creating an expert panel. Traditionally technology foresight relies on the knowledge of experts. The validity of the research is based on the idea that experts possess more valid information than laymen. On the other hand, experts might have very narrow knowledge and laymen's expectations can be as valid in some situations. Public opinion holds power over which emerging technologies peak which makes also laymen's expectations interesting (Karaca & Öner 2015). Visions can even be seen as privileges and focusing on the expectations of certain groups creates an imbalance of power (Sand 2019). On the other hand, nanotechnology is very abstract and difficult for laymen to grasp. This study is interested especially in experts' ideas since they have specific knowledge and may better visualise the futures based on their knowledge.

One of the cornerstones of the Delphi method is the expertise of the panellists. Gathering the experts is a crucial aspect of the study since the results depend on the knowledge and cooperation of the participants (Gordon 2009b). Building an expert panel started by defining who is an expert in this study. The domain of nanotechnology is very wide and includes a variety of different fields and technologies. The study aimed to get a broad picture, not detailed knowledge of a specific field. In this case expert must be someone who observes the development of nanotechnology from a wider perspective. This means for example directors of research centres, people with versatile careers, people from companies working in many fields of nanotechnology, board members of nanotechnology associations, and futurists dealing with emerging technologies. Previous Delphi studies on nano and other emerging technologies have identified the challenge that experts are not familiar with all fields of nanotechnology (Su, Lee & Yuan 2010). Finding people with a broad view of nanotechnology was challenging in this study as well.

The selection of the experts is a crucial part and should aim for a heterogeneous group consisting of both academics and stakeholders of different organizations and ensure high commitment (Belton, MacDonald, Wright & Hamlin 2019). To have a holistic view, the intention was to gather experts from all actor groups. Arranz et al. (2020) define a nanotechnology network consisting of universities, industries, research centres, and governments.

Gathering the experts started in the early stage of the study. Experts were collected during the literature review among the writers of the articles. It continued throughout the scanning of nanotechnology strategies and roadmaps. The experts were picked up from the reports and the institutions drafting them. Also, speakers from the most recent nanotechnology conferences were contacted. For the industry sector, the internet search was utilised to find the biggest nanotechnology firms as well as the promising start-ups. The goal was to have experts with long-term experience from the big companies and novel, new ideas from the start-ups.

Data gathered is often a sample of the wider population. The sample is assumed to represent the population and still be manageable (Saunders & Lewis 2018, 138-139). The sample was selected narrowing to experts with a broad view. The sample is based on non-probability sampling, meaning that not all population members have the equal opportunity to participate (Saunders & Lewis 2018, 144). The method used was purposive sampling supplemented by snowball sampling. Purposive sampling means that the researcher actively selects appropriate members for the study (Sanders & Lewis 2018, 145-146). Many of the experts were found throughout the snowball technique meaning that one contact led to another (Peltoniemi, Kess, Haapasalo & Alasaarela, 2004). Recommendations from other experts were valuable but snowball sampling can lead to homogeneous groups since people usually recommend people similar to them (Saunders & Lewis 2018, 147). This was avoided by checking the suitability of all recommended candidates according to the same criteria (wide perspective, long work experience). Heterogeneous of the panel was guaranteed using an expert matrix. The aim was to have a global balance, experts from various fields of nanotechnology, and representation of different stakeholder groups.

Altogether 98 experts were invited to participate. The biggest group (49) were scientists. List of the scientists could have been much longer, but the interest was on the scientists who have worked in the field for some time and perceived nanotechnology from a wider perspective than just their focal research area. In the end, eight scientists agreed to participate in the Delphi. In addition, 23 invitations were sent to experts presenting industry sector. Those were directors, and research and development leaders in nanotechnology companies. Finding experts from the business was challenging since it was difficult to find information about the expertise of the staff and the contact details. After all, three experts from the business sector agreed to participate. Finally, 26 invitations were sent to experts in associations and governments, and some futurists focusing on emerging technologies. Out of them, six volunteered. This mixed group was created to ensure the anonymity of the participants. Altogether 17 experts promised to participate in the Delphi panel. The aim was to create an expert panel of over 20 people and 15 was set to be the minimum to guarantee a representative sample. Finally, 14 of the participants completed the Delphi and six of them gave also an interview.

Experts were contacted mostly by email explaining the study and the reason why they were selected. Some contacts were also made through contact forms and LinkedIn messages. Besides individual contacts, some inquiries were sent to companies, universities, associations, and research centres to indicate suitable candidates.

In qualitative research, the size of the empirical material varies related to the research question and the context. It depends on whether the aim is to find generalisable results or samples. Reasonable coverage has been reached when the sample is representative, but it can mean different things in different studies. Saturation of the material is one way to measure suitable size. Saturation means that no more new perspectives arise. Eskola & Suoranta (2008, 60-67.) The size of the sampling group could have been bigger to cover more perspectives and present a wider range of stakeholders and nanotechnology fields. However, in a qualitative study, the researcher aims to describe certain phenomena in a specific context rather than making wide generalisations (Eskola & Suoranta 2008, 18).

Table 3 Expert panel
(Created by the author)

| | |
|---|---|
| **DELPHI** | |
| **Stakeholder group** | academy 7, industry 2, other 5 |
| **Country** | Finland 8, Netherlands 2, Italy 1, Portugal 1, USA 1, Slovenia 1 |
| **Field** | energy, environment, information technology, manufacturing, materials sciences, medical applications, metrology, nanosafety |
| **Experience** | 5-10 years: 2 participants<br>10-15 years: 5 participants<br>over 15 years: 7 participants |
| **INTERVIEWS** | |
| **Stakeholder group** | academy 5, other1 |
| **Country** | Finland 4, Italy 1, Portugal 1 |
| **Field** | medical applications, materials science, nanosafety |

## 3.4 Data gathering

Empirical data was collected in two steps starting with the Delphi expert panel followed by interviews. Triangulation of methods enabled to use of scales and open questions, qualitative and quantitative analysis, independent and cooperative reasoning, and testing and reframing of the hypothesis, which all increased the validity of the study. The next chapters first introduce the methods and then illustrate how those were utilised in this study.

### 3.4.1 Delphi method

The Delphi method was developed in the 1960's to collect experts' insights. It was based on the notion that experts who agree are more likely right than non-experts. The ambition was to repeal challenges in teamwork and create a perfect debate that bypasses participants' skills in speaking, pedagogy, and personality traits and gives equal weight to all opinions. (Gordon 2009a.) The Delphi method is still widely used in futures studies to gather expert opinions. The basics of the Delphi method were originally the anonymity of the participants, controlled feedback, a summary of the results, and iterative rounds (Rowe & Wright 1999). The Delphi method consists of various steps. First, the experts chosen for the panel answer the given statements anonymously. Then they receive a summary of all responses and have an opportunity to modify their answers. The rounds of questions and revised answers are repeated after the consensus is reached or results show notable dissensus. (Belton et al. 2019.) Delphi is mostly used for making judgments, supporting decision-making, and forecasting (Rowe & Wright 2011). Instead of statistically significant results, Delphi seeks to collect unique views of the particular group (Gordon 2009a). Originally, Delphi studies aimed to find a consensus among the experts. Nowadays most argue that Delphi is not only a method to find a consensus (Linstone & Turoff 2011; von der Gracht 2012; Winkler & Moser 2016).

There are lots of variations of the Delphi method. The Real-time Delphi used in this study is an ongoing study where argumentation happens at once instead of multiple rounds. The participants can answer the statements, see the summary of the answers, participate in argumentation, and revise their judgments on a certain platform during the predetermined time. There are no second or third rounds, but participants are asked to visit the platform more than once to revise their judgments and participate in the argumentation. In a way, those multiple visits represent the multiple rounds. (Gordon 2009b.) The benefits of the Real-time Delphi are saved time and resources, flexibility, efficiency, increase in availability and commitment of participants, and transparency (Gordon 2009b; Gnatzy, Warth, von der Gracht & Darkow 2011). The Real-time Delphi enables individual answers, changes in judgments, and argumentation in one single round. Technology makes it easy to collect answers anonymously, gather the data, and share it. According to Gnatzy et al. (2011) the Real-time Delphi follows the principles of traditional Delphi (anonymity, controlled feedback, summary of the results, and multiple rounds) even though the process and rhythm of the study are different, and participants have an opportunity to immediate reactions. The Real-time Delphi does not give significantly different results compared to the traditional way.

Delphi is ideal for collecting multiple views on complex subjects. The advantages of Delphi are the anonymity and the multiple rounds which together permit participants to modify or change their opinions and learn from each other without being embarrassed or submission to group behaviour. (Tapio, Rintamäki, Rikkonen & Ruotsalainen 2017.) Multiple rounds of questionnaires and anonymity separate Delphi from other methods and may help to build stronger reasoning. Expectations are constructed together in certain groups (usually experts when the focus is on emerging technologies) throughout the discussions, debates, and predictions. Delphi offers an opportunity for closed conversations to formulate expectations cooperatively. Delphi is often used to perceive future events and their timescale in the technology field (Andersen 2023) and was selected as the main method for this study to observe how experts perceive the future of nanotechnology.

### 3.4.2 Conducting the Real-time Delphi

**The Statements**

Creating the statements for the expert panel started already during the literature review gathering interesting viewpoints and relevant insights. The statements were formulated according to the good practices introduced in the Delphi methodology guidelines and adopted from other Delphi studies on nanotechnology and other emerging technologies. Delphi statements were written following the best practices: use simple language, be concrete, no emotions, use numbers or very clear wording on amounts, avoid anchoring bias, rely on the given information, no lengthy explanations, compact (Andersen 2023). Typically, participants are asked to evaluate the probability and the desirability of certain events. Since this study is about the expectations the focus was instead on impact.

When setting up the Delphi process, it is advised to make pilot rounds to test the clarity of statements and scales (Belton et al. 2019). The first draft of the Delphi was commented on by two nanotechnology experts in short interviews, one representing the academy and the other representing the business. According to Gordon (2009a) interviews before the Delphi may help reveal the topical issues on the field. The purpose of the commentary round was also to ensure that the interpretation of the current stage of nanotechnology development was correct and that the statements were relevant and topical. Since I am not an expert in nanotechnology, I found this step crucial. One of the challenges in the questionnaire was dividing nanotechnology into different fields and the commentary round gave valuable feedback.

The Delphi was divided into three different sections according to the research questions: 1) Impact on the different fields of nanotechnology, 2) Obstacles to the commercialisation and 3) Impact of the megatrends. At the beginning of each section, the context and the reasoning for the question were explained briefly. Respondents were asked to estimate the magnitude of the impact and then give the reasoning and/or comment on the statement. For background information respondents were asked to tell their field of expertise, the type of institution they worked in, years of experience in nanotechnology, and the country they were currently working in.

In the first section, participants were asked to estimate the impact of nanotechnology on eight fields (energy, environment remediation, information technology, manufacturing, material science, medical applications, metrology, security) over the next ten years selecting on five scales from no impact to transformative impact. Nanotechnology is a very broad field and can be categorised in a variety of ways. The categorisation used in this study was adapted from previous futures studies on nanotechnology (Salerno et al. 2008) and from the European Commission (EC 2004) and the United States National Nanotechnology Initiative (NNI 2023). The approach is based on different applications of nanotechnology. After each field participants were encouraged to leave comments. At the end of the section, they had an opportunity to name new fields if they felt that all branches of nanotechnology weren't covered.

In the second section, participants were asked to estimate the impact of the obstacles to the commercialisation of nanotechnology over the next ten years selecting from a six-point scale from no impact to very high impact. The selected obstacles to commercialisation were recognised during the literature review and were 1) health risks 2) environmental risks, 3) expenses 4) laws and regulations, 5) public opinion, 6) challenges in cooperation between science and business, and 7) lack of skilled workforce. Again, participants were also asked to explain the impact and their reasoning and indicate other possible obstacles.

In the third section, participants were asked to estimate the impact of the four megatrends on the development of nanotechnology in the next ten years on a seven-point scale from very high negative impact to very high positive impact and explain the impact and the reasoning. Megatrends are long-term trends affecting all aspects of society and the estimated megatrends were the ones assumed to have the most impact on the development and use of nanotechnologies (Megatrends Hub 2022; Sitra 2023). The selected megatrends were 1) green transition, 2) digitalisation, 3) circular economy, 4) uncertain political atmosphere. Participants were also asked to explain the impact and their reasoning and indicate other possible megatrends relevant to nanotechnology. (See the Appendix 1 Delphi questionnaire.)

**The Real-time Delphi**

The Delphi panel was held online on the eDelphi platform (https://www.edelphi.org/). The accurate format for the Delphi should be chosen according to its easiness for participants, resources of the researchers, and the impacts on the validity (Belton et al 2019). eDelphi enabled participants to answer at the best time suitable for them. It allowed the researcher easily to follow the answers and send instructions and reminders. However, eDelphi format set some limitations to the formulation of the statements. It was predetermined how many aspects per one statement participants could evaluate and when there was room for open comments.

During the first week, participants answered the statements individually and only saw their own answers. At the beginning of the second week, the answers and the comments were revealed anonymously to all participants. The participants were encouraged to return to the platform to revise their answers and comment on each other’s responses. The planned duration of the panel was extended once, lasting altogether three weeks to give time for everyone to answer and comment. Finally, 14 out of the 17 participants answered the questions in the panel. According to Belton et al. (2019) one of the challenges in Delphi is preventing panellists drop-out. The long process demands commitment, and incentives like social rewards and ongoing communication with panellists are shown to be effective. With eDelphi it was easy to communicate with the participants. They received regular messages during the panel about the state of the panel and what they were expected to do.

Two branches of nanotechnology (medical applications and metrology) were accidentally missing during the first week of the panel. Participants were asked to answer them when they returned to see the other participants' answers but only 11 answered on those fields. The mismatch is considered in the analysis. The most common and significant cognitive biases in Delphi studies according to Winkler and Moser (2016) are framing, anchoring and desirability biases. To avoid framing bias the given background information should be a short, neutral overview, which gives room for own ideas. Still, participants may interpret the statement differently, especially because of different roles and backgrounds. Examples of estimates and statements tight together may increase the risk of anchoring bias. In this study, each statement was separate from the previous one. However, the scales for each statement were different, which may have created confusion. The risk for desirability bias rises when things are in the far future and touches especially people with low knowledge on the topic. In this study, most questions were about midterm future and participants had an opportunity to skip any statement if they were not familiar with the topic. Winkler and Moser (2016) state that expertise and heterogeneity of the group are best practices to mitigate these biases.

Besides answering the statements participants were asked to leave open comments and comment also other's answers. Most of the panellists revisited the eDelphi after the answers and comments of others were revealed. All the questions received comments but the communication between participants was remote. It is a common challenge in the Real-time Delphi to get participants to re-visit the questionnaire and engage them in serious debate with each other. Lacking these may threaten the feedback principle of the method. (Gordon 2009b.) The most common cognitive biases in the feedback and revision phase are the bandwagon effect and belief perseverance. The bandwagon effect refers to the tendency to agree with the opinion of others and believe perseverance in contrary is the inability to change opinion. (Winkler & Moser 2016.) The argumentation was not vivid and there were no strongly disagreeing arguments. In the Real-time Delphi the researcher doesn't see if the participants changed their answers after re-visiting the survey. To mitigate these biases, participants had the opportunity to skip the statements not familiar to them.

**Summary of the Delphi**

Providing carefully formulated feedback for the panellists is a demanding task since it can influence the answers in the next round and the number of rounds needed before satisfactory stability. Medians and inter-quartile rates are often convenient and adding qualitative rationales can increase quality. When analysing and presenting the data, it must be formulated for a certain audience. (Belton et al. 2019.) The results from the Delphi were gathered and summarised both quantitatively and qualitatively. Answers for the scaled questions were presented as tables and open comments were categorised and summarised. The summary of the Delphi is presented in the next section together with the results of the Delphi and the interviews. (See Appendix 2 Summary of Delphi.) The summary was sent to all participants followed by an invitation to the interviews where participants will have an opportunity to comment on the results and reason their views in more detail.

Before starting to gather the summary of the Real-time Delphi it was not clear yet how to proceed with the study. There were three different options planned. The first option was that the Real-time Delhi gives enough data to answer the research questions. However, it was quite sure that the Delphi would not give enough in-depth knowledge as it turned out. The other option was to continue the Delphi and ask participants to evaluate and comment on the summary and add some follow-up statements to the same eDelphi platform. Based on the common challenges of Delphi and the experiences of this study, the Delphi was not the right platform to collect in-depth information as it worked best for evaluating clear statements. The third option was to continue with interviews as in some Delphi processes panel discussions or interviews are used as an option for a new Delphi round. Individual interviews seemed the best solution for this study since the aim was to collect the reasoning and insights of the experts coming from the different fields of nanotechnology.

### 3.4.3 Thematic interviews

An interview as a research method relies on the fact that when we want to find out what people think about a certain subject, people themselves can tell best (Eskola & Suoranta 2008, 85). Interviews were used in this study to deepen the knowledge already gathered in the Delphi. The aim was to find out the reasons behind the answers and allow experts to explain their views in more detail. The summary of the Delphi showed the expectations and how different fields, obstacles, and megatrends compared to each other. The interviews sought insights behind the views and aimed to widen the perspective on societal impacts and development trend of the technology. Interviews are often used to explore the state of a certain topic or identify general trends and combined with other methods can reveal the meaning of statistical findings (Saunders & Lewis 2018, 159).

The interviews in this study were semi-constructed, thematic interviews. A semi-structured interview is constructed around the topics the researcher has chosen beforehand. The order and form of the questions do not have to be identical, and some questions can be left out or added, depending on the participant. (Saunders & Lewis 2018, 158-159.) In thematic interviews, the themes are set before the interviews, but the interviewer can ask about them in a different order and at variable depth depending on the interviewee (Eskola & Suoranta 2008, 86). The themes of the interviews followed the summary of the Delphi with some additions. The semi-structured form of the interviews fitted well for the purpose as it allowed to focus on the specific themes the interviewees found important but ensured that all relevant aspects were covered (Hirsjärvi & Hurme 2000, 35). Choosing the themes can narrow down the discussion. On the other hand, the themes should be broad enough to allow diverse discussion. The themes can be deepened according to the interests of the researcher and the interviewees. The thematic interview is quite open and leaves room for discussion. The themes are operationalised in an interview situation, which allows the researcher to find out how the interviewees understand the key concepts. (Hirsjärvi & Hurme 1982, 14–18, 35–37.) Interviews allow the gathering of in-depth knowledge about the phenomenon being studied. During the interview, it is possible to refine and deepen the answers. The interviewee should be seen as an active subject creating meanings to allow the interviewee´s voice to become well heard.

### 3.4.4 Conducting the interviews

Invitations to the interviews were sent to all experts who participated in the Delphi panel. Together with the invitation they received the summary of the Delphi results and privacy and data protection notice. (See Appendix 4 Privacy and data protection notice.) The invitation mentioned that the focus of the interview was to comment on the results, explain their views, and discuss the development trajectories and societal impacts of nanotechnology.

The interviews began by presenting the summary of the Delphi and asking for comments on the results and reasoning their own answers. The structure of the interviews followed the same order as the Delphi. In the first theme, the participants were asked to comment on the Delphi summary about the impact of nanotechnology on the different fields. The participants had an opportunity to comment if they agreed or disagreed with the findings and if they noticed something surprising or especially interesting. They had an opportunity to explain their reasoning and ideas in general or in more detail on the fields most familiar to them. They were also asked about alternative futures for the fields.

In the second theme, the participants were asked to comment on the Delphi summary about the obstacles to commercialisation. They had an opportunity to comment if they agreed or disagreed with the findings. They were asked the most relevant obstacles in their most familiar field of nanotechnology. As public opinion received the most controversial answers in Delphi, participants had an opportunity to explain the reasoning behind that answer.

In the third theme, the participants were asked to comment on the Delphi summary about the impact of megatrends. They had an opportunity to comment if they agreed or disagreed with the findings and name the most relevant megatrend in their most familiar field of nanotechnology.

The fourth theme dealt with development cycles of emerging technologies. The findings of nanojourney presented in chapter 2.4 were introduced to the participants and they had an opportunity to share their ideas on the development phase of nanotechnology. They were asked to focus on the field most familiar to them or comment on nanotechnology from a more general viewpoint. They were also asked if they identify any peculiarities in the development curve of nanotechnology compared to other emerging technologies.

The fifth theme concerned societal impacts. Society adapts to the development of technologies and the focus was on the possible impacts nanotechnology might have on everyday life during the next ten years. The participants were asked to consider also the ethical aspects.

Finally, the participants were asked to shift the timeframe from ten years to twenty years and beyond and describe their future images. They were asked to imagine what role nanotechnology might then have and name some possibilities and threats. They were encouraged to envision also alternative futures. This question aimed to peek into the long-term future and release the thinking from current realities. (See the Appendix 3 Interview structure)

Altogether six experts participated in the interviews. The interviews were held online via MS Teams. Two of them were held in English and four in Finnish. All the participants worked as nanotechnology experts in Europe, four of them in Finland. Participants presented different nanotechnology domains: medical applications, materials science and nanosafety. They came from research institutions, universities, and industry backgrounds. It was not an ideal heterogenic mixture, but the aim was not to gather information covering all domains of nanotechnology.  Interviews were about the insights from individual experts on the general perspective. Still, the results might be biased since there were no experts for example from the energy or IT sectors which are developing quickly at the moment. The length of the interviews were approximately 30 minutes. On the consent of the participants, the interviews were recorded and transcribed.

Interviews went smoothly, and the Teams platform worked well. Interviews in Finnish were easier to carry out when they were conducted in the native language of both the interviewer and the interviewee. The interviews held in English were more challenging. In these cases, it was very useful to have the transcript. The transcript option made it easier to concentrate on the discussion knowing the possibility to specify the notes later. According to Eskola & Suoranta (2008, 142) in qualitative research and social research, language is part of the research object. Language is a way to build societal reality. When the language used is not native the cultural hints and small details might not be noticed. Another challenge was my limited knowledge of nanotechnology. My background is not in nanotechnology and even though the aim of the study was not to understand specific technical details of certain technology but to understand the role of expectations, still some basic knowledge of nanotechnology was required to be able to conduct the expert panel and the interviews. The participants were experts in certain domains of nanotechnology and sometimes they referred to technical properties or processes I was not familiar with. At some points, it prevented me from asking specifying questions and understanding all the concepts they referred to.

Table 4 Summary of the data gathering
(Created by the author)

| **Data** | **Literature review** | **Delphi** | **Interviews** |
|---|---|---|---|
| **Time** | June 2022–November 2023 | February 2023 | March–April 2023 |
| **Statistics** | 55 scientific articles<br>15 nanostrategies | 98 experts contacted<br>17 experts agreed<br>14 completed the Delphi<br>20 statements and 115 qualitative comments | 6 experts interviewed<br>30 minutes per interview |

## 3.5 Analysis process and methods

The analysis is reflective, theoretical thinking where the researcher creates new (Eskola & Suoranta 2008, 148). The analysis process started already at the literature review: choosing suitable theories and defining the key concepts, making interpretations, and choosing valuable statements for the Delphi questionnaire. Analysis continued while building the development path for nanotechnology and the changing expectations along it. This chapter however focuses on the analysis methods and process of the empirical data gathered throughout the Delphi and the interviews.

The chapter first describes the quantitative analysis of the Delphi. Then it moves to describing the qualitative summary of the Delphi. After that, it presents the content analysis of the Delphi and the interviews.

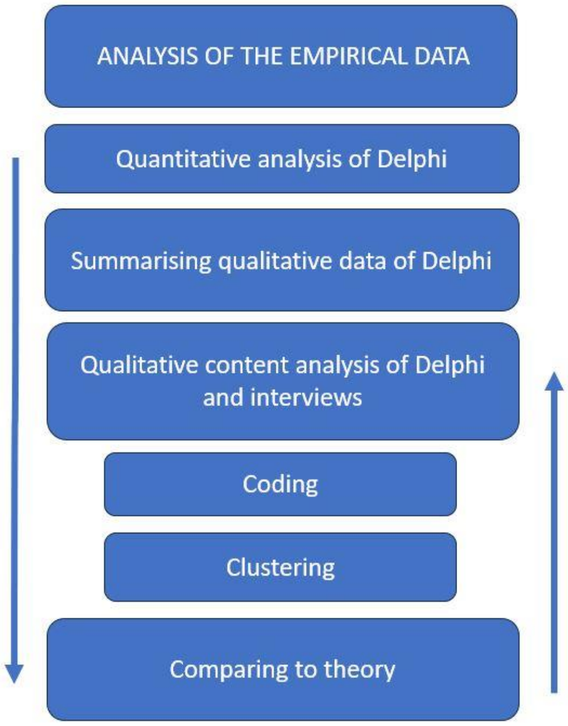


Figure 3 Analysis of the empirical data
(Created by the author)

### 3.5.1 Quantitative analysis of the Delphi

The results from the Delphi were analysed first throughout the quantitative data. The figures from the eDelphi program were extracted into an Excel program. The interest was in average and median and finding out which field/obstacle/trend was evaluated to have the most or least impact. The results were presented as a percentage of answers per category. Percentages were selected over the number of answers to interpret the results more easily and to make the different fields comparable since not all participants answered all statements. Then it was investigated how strong was the consensus of the answers or if there was a lot of dispersion. After that, results were analysed based on how high the expected impact was and results were organised in decreasing order. The data was also analysed by comparing answers based on the background of the participants.

### 3.5.2 Content analysis of Delphi and interviews

Analysis of the qualitative data from Delphi and interviews was done following the content analysis method and thematic analysis. Seven classical steps for qualitative content analysis are: stating the research questions, selecting the data for analysis, deciding the categories used in the analysis, planning the coding process, ensuring the reliability of the process, and finally analysing the results (Kaid 1989, according to Hsieh & Shannon 2005, 1285).

The content analysis aims to interpret the meanings of the text data utilising a systemic process for recognising themes. Content analysis can be done in three different ways: conventional analysis based on open-ended questions and relaying on the content and letting content define the themes; direct analysis based on theory and summative analysis observing the frequency and usage of certain words or content. (Hsieh & Shannon 2005.) This study follows the direct analysis, which relies on earlier research. It aims to verify and enrich already existing theories and research. The literature review is used as a reference point for the analysis. The literature review determined the themes used in Delphi, which also formed the base for interview questions and the frame for the content analysis. Direct content analysis may be biased for seeing mainly supportive arguments for previous research (Hsieh & Shannon 2005). The bias was mitigated by being loyal to the empirical data and avoiding making too much interpretation. It was also important to highlight the themes arising from the material outside the pre-determined themes.

After gathering the empirical data, it needs to be coded to easily handled form and then organised before it can be further analysed (Eskola & Suoranta 2008, 150). The qualitative data from Delphi meaning the written comments from Delphi were extracted from the eDelphi platform and first summarised for the participants. The summary was made categorising and clustering the comments. For the impact on different fields, the data was categorised according to the eight fields of nanotechnology and creating a new category other for the other fields mentioned. Comments on every field were then divided under drivers, technologies, and doubts. These three categories were created based on the data. Drivers were the issues participants assumed to cause the future utilisation of nanotechnology. Most of the comments also included specific nanotechnologies relevant to the future development. Doubts were the category for the issues that might decrease or even replace the use of nanotechnology. For the obstacles and trends the data was categorised according to the seven obstacles and four megatrends already determined for the Delphi questionnaire and the category other was added for the topics experts felt missing. The data was organised according to obvious themes rising from the material. Later the comments from the Delphi were coded together with the interview transcripts and analysed together.

The material must be unpacked and analysed as soon as possible after collection, while it is still fresh in mind (Hirsjärvi & Hurme 2000, 135–136). The first impressions were saved right after each interview. It is important to acknowledge the atmosphere and the initial thoughts and to go back to the feelings during the interview (Hirsjärvi & Hurme 2000, 185). Then the transcripts were cleaned of typing errors and misinterpretations the MS Teams program has made and irrelevant content, for example small talk at the beginning, was erased. Interviews were anonymised by deleting the names of the people, companies and associations. The reliability of the material improves if the quality of the recording is good, the transcription takes place immediately after the interview and the transcription is systematic (Hirsjärvi & Hurme 2000, 185).

The accuracy of the transcription is determined by the research question and research method (Hirsjärvi & Hurme 2000, 139). The pauses or tone of voice were not marked to transcripts since the interest was in the opinions rather than the way the participants presented their ideas. The unit of data was a sentence or group of consecutive sentences. All the data from the interviews and qualitative data from the Delphi were coded using NVivio program under the themes used in the interviews. In thematic interviews, the themes form naturally the base for coding the data (Eskola & Suoranta 2008, 152).

The coding process determines the quality of the analysis and it must be systematic, logical and scientific (Hsieh & Shannon 2005). The analysis started with the themes presented already at the Delphi, impact on different fields of nanotechnology, obstacles to commercialisation and megatrends. The data from the interviews was compared to the data from the Delphi and observed if it was reinforcing the findings or contradicting them. The analysis continued to the themes presented only at the interviews. Experts' ideas on the development trajectories of nanotechnology were grouped with similar ones and examined based on the theories of development cycles of emerging technologies. The thoughts about societal impacts were compared to the societal impacts of nanotechnology highlighted in the literature review. The ideas were categorised using PESTEC (political, economic, social, technological, environmental, cultural) matrix often used in futures studies as it gives a 360-degree perspective. Future images for a longer time perspective were clustered to possibilities and threats naturally rising from the data.

Trusting the initial coding and analysis of the data is important but for the validity of the study the readiness to create new categories as they arise is also crucial (Hsieh & Shannon 2005). The analysis process was about balancing between determined categories from theory, new and novel viewpoints from experts, and finding links between theory and empirical data.

# 4 Results

This section presents the results of the analysis of the Delphi and interviews and compares them to the theories of the development of emerging technologies and expectations as well as to the previous studies on nanotechnology. The results are presented according to the research questions. The section ends with a summary of the results and the conclusions of the findings.

The quotations from the empirical material are marked with “”marks. Some of the quotations are translated freely from Finnish to English by the author. Inside the quotations … means that the text is cut. The ensure the anonymity of the participants, the quotations are marked with acronyms respondent I1-I6 meaning interviewee 1-6 and Delphi meaning that the citation is from the Delphi panel.

## 4.1 Impact on the different fields of nanotechnology

Nanotechnology is said to be a general-purpose technology changing almost all fields of industry. Impact of the nanotechnology still varies in different fields. It has changed some fields dramatically and some use it among other technologies. Experts were asked to estimate how much nanotechnology will impact the different fields during the next ten years. The categorisation of nanotechnology into eight fields is based on different applications of nanotechnology.

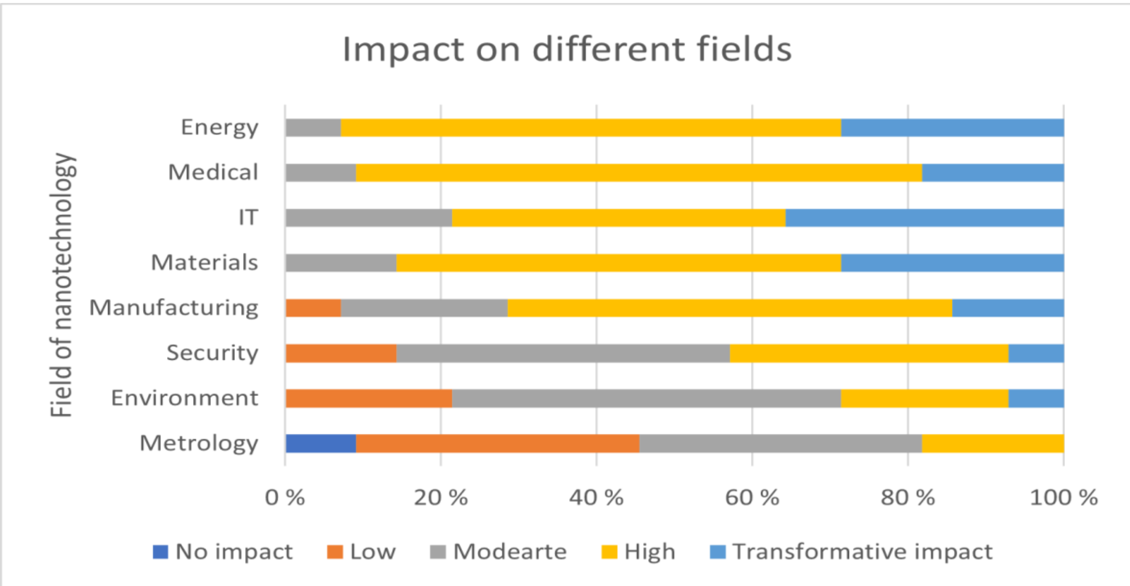


Figure 4 Impact of nanotechnology on the different fields
(Created by the author)

Among the fields, the impact of nanotechnology over the next ten years was evaluated to be high in the fields of energy, medical applications, information technology, materials science and manufacturing and moderate in the fields of security, environmental remediation and metrology. The impact was evaluated to be highest in the field of energy and almost as high in medical applications, information technology, materials sciences, and manufacturing.

Next, each field was observed more closely. First, it was investigated how strong was the consensus of the answers or if there was a lot of dispersion. Half of the fields had a quite clear consensus (high impact on energy, medical applications, information technology and material science) and the rest half had more variation in the answers.

Next table presents the summary of the experts' reasoning behind the expected impacts on the different fields dived into drivers, technologies and doubts.

Table 5 Delphi results
(Created by the author)

| **Energy** | Consensus on high impact |
|---|---|
| Drivers | Nanotechnology has the potential to move towards a renewable energy-based economy and low carbon society. It can make solutions smaller, more effective, and more efficient. |
| Technologies | Especially the role of new energy storage technologies and the development of batteries were highlighted. Also, solar energy solutions, hydrogen production and fuel cells were mentioned multiple times. |
| Doubts | It was questioned if ten years is enough for remarkable changes in industrial implementation and manufacturing processes as well as lowering the costs. It is valid to notice that also other promising technologies compete in this sector. |

| **Environmental remediation** | Moderate impact with variation in estimates |
|---|---|
| Drivers | Achievements to consider environmental issues and biodiversity loss increase the interest in utilising nanotechnology in remediation. Seeking for more efficient solutions and reducing the need for raw materials achieved by nanotechnology help indirectly environmental remediation. |
| Technologies | The most mentioned potential future solutions were related to water purification. Also, catalysts and reactive nanomaterials were mentioned as well as advanced sensing technologies for detection. |
| Doubts | Nanotechnology will offer solutions for this sector but at the same time pose risks. Safety regulations slow the implementation of solutions and there is scepticism about the large-scale solutions. Other technologies are needed alongside nano to find solutions. |

| **Information technology** | Consensus on high impact |
|---|---|
| Drivers | The digitalisation and constant need for fast, reliable, sustainable and low-energy devices and systems accelerates the development. |
| Technologies | Quantum computing was seen as the most promising in the field, but also spintronics, and printable and wearable electronics were mentioned. |
| Doubts | There were some doubts if quantum computing can meet all the expectations. It was also mentioned that high energy consumption may hamper development. |

| Manufacturing | High impact with variation in estimates |
|---|---|
| Drivers | Nanotechnology has the potential to solve current problems in manufacturing. It can increase efficiency and produce new nano-based materials and components. |
| Technologies | Manufacturing effects both the process and material design. Processes such as distributed sensing and manufacturing metamaterials were mentioned. |
| Doubts | Participants expressed that the field was difficult to evaluate since the concept of manufacturing is so broad and the impacts on different fields vary a lot. The transition from nanotechnology innovations to full-scale production has been slow and remarkable changes may not occur in the next ten years. |

| Materials science | Consensus on high impact |
|---|---|
| Drivers | Materials science is one of the key areas of nanotechnology. There is potential to increase knowledge of the characteristics of materials, improve material functionality, find tailor-made solutions and create completely novel materials. Aiming for efficient and environmentally friendly materials and solutions to use less material to produce material. |
| Technologies | New materials will be strong, flexible, smart or biobased and will have for example self-cleaning and healing properties and optical characteristics. Materials for robotics is a growing field. |
| Doubts | Nanotechnology alone is no longer enough but the future lies more in developing advanced materials together with other technologies. The high costs and difficulties with scalability hinder the development. |

| Medical applications | Consensus on high impact |
|---|---|
| Drivers | Nanotechnology will have a remarkable contribution to health and have major economic and social gains by improving diagnosis, gaining better impacts with less amount of chemicals, better detection and better targeting with treatments and medicines. |
| Technologies | Promising development in various sectors from prevention to testing and diagnosis to new kinds of medicines and drug delivery solutions, for example personalised medicine, DNA technology and genetic surgery, vaccinations, self-healing and self-repairing materials, sequence technology and engineering proteins. |
| Doubts | The safety of nanotechnology was highlighted in this field. The slow approval processes will delay the implementation of new innovations. |

| Metrology | Moderate impact with variation in estimates |
|---|---|
| Drivers | There is a continuing need to improve accuracy, reliability and efficiency when creating new applications. |
| Technologies | Metrology is especially valid in the medical field, material science, and quantum technology. |
| Doubts | Nanotechnology is one tool among others to study the properties of materials and metrology for nano is already well developed. |

| Security | Moderate impact with variation in estimates |
|---|---|
| Drivers | The defence sector is constantly utilising and looking for new technologies. The goal is to increase sensitivity, reduce power consumption and obtain energy autonomy. |
| Technologies | Most mentioned nanotechnology areas were sensors, robotics, cyber safety solutions and nanomaterials like fading materials. |
| Doubts | Because of the secrecy of the development, the defence industry might already be ahead of commercial applications. |

When asked about the missing fields, participants mentioned agriculture and food, transportation and space. Some participants found it difficult to answer statements about manufacturing since it was considered to be so broad. A few passed the field of metrology because of not being familiar with the field. Some considered that the field of security should have been more specified if it refers to security, safety, defences or other. When asked about the information technologies not all were sure if it included quantum computing. This illustrates well the complexity of defining nanotechnologies.

Interviews confirmed the results of the Delphi. Experts thought that the results were in line with current conversations as energy, information technology and medical applications are currently most affected by nanotechnology. Also based on the literature review these fields are the most topical since they were best presented on articles, strategies and reports searches. There is no comparable data from previous studies on the expectations for each nanotechnology field. The relatively high consensus of the answers confirms the collective nature of expectations on emerging technologies. Individual expectations are based on specific positions and interests but are also affected by collective expectations (Konrad 2006).

The Delphi panel gathered 11–13 comments per field but for security only 9 and for metrology 6 comments. Participants explained they were not familiar with these fields. Those were also at the end of the first part of the questionnaire. In the interviews, most of the comments were on materials science and medical applications. That is mostly explained by the background of the interviewees. The bigger group of experts and experts with even wider perspectives may have increased the volume and quality of comments.

At the interviews, experts were asked to also describe some alternative development paths for these fields. Some mentioned that the exploitation of natural biometrics for material production and combining it with nanotechnology might be an option. Others thought it is impossible to anticipate since most of the scientific innovations are almost coincidences. A few mentioned that other technologies might replace nano and then the role can be very different from current expectations. Others were convinced that further development of nanotechnology is essential for humankind and therefore there are no other paths. Experts found it difficult to imagine alternative paths. Emerging technologies exist only in the expectations which are often so widely agreed they become almost obligatory, like promises of the future (Borup et al. 2006).

> No alternative paths. Our society needs materials. Nano is the only option. Operating on nanoscale makes it possible to reduce the amount of materials. (Respondent I1)

> Nano may become a feared monster if we aren't able to solve the threats to the health of nanotechnology. Then it may be that it is displaced and then we'll go for other alternative routes then to make the materials. (Respondent I3)

> Most of the real breakthroughs in science comes from almost serendipity. So it's very difficult to predict. But something completely and totally new.... Maybe already done in five years from now, someone discovers something new, perceptually new, that will lead the field changing completely the landscape. (Respondent I6)

Expert comments show that there are still high expectations for nanotechnology, and it is still considered to be even the most promising technology of the future (Salerno et al. 2018). On the other hand, the utopian visions of nanorobots ruling the world (Leinonen & Kivisaari 2010) were missing. In some fields, the expectations of nanotechnology alone offering the solutions were rather low and the hope was more on combining different technologies.

## 4.2 Obstacles hindering the commercialisation

The commercialisation of the findings in nanotechnology has been slow at least in some fields. Studies on nanotechnology have recognised some obstacles typical for emerging technologies and some peculiar to nanotechnology. Participants were asked to evaluate the significance of the typical obstacles in the next ten years.

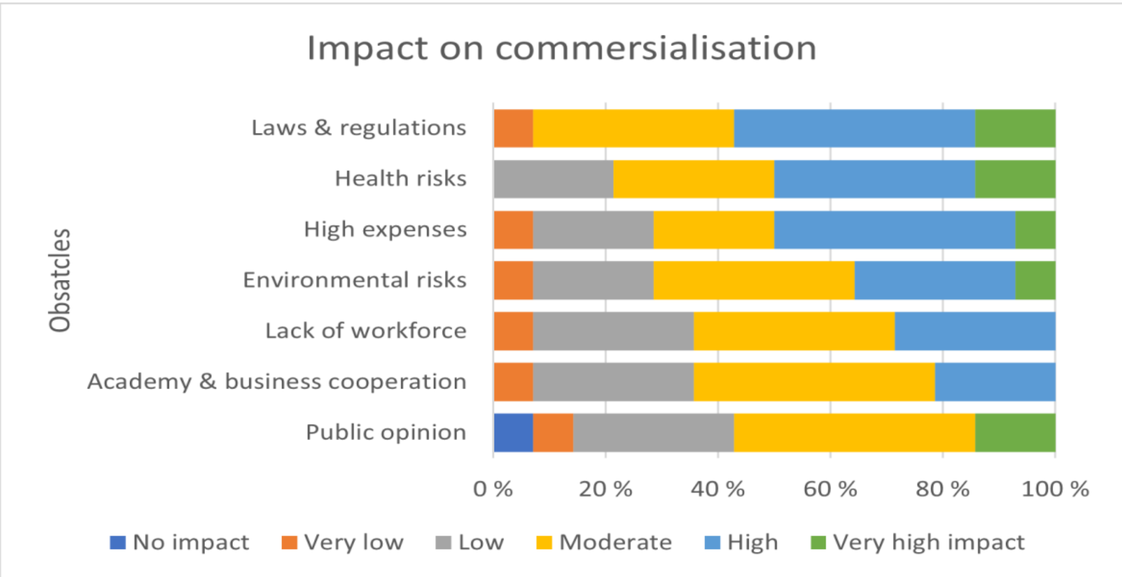


Figure 5 Impact of the obstacles on the commercialisation of nanotechnology
(Created by the author)

The experts estimated that laws and regulations as well as the health risks will have the biggest impact on the commercialisation of nanotechnology in the next ten years. Expenses and environmental risks were also evaluated to have a high impact. This confirms the findings from the literature review as during the 2020s the focus has been on safety and health regulations as the commercialisation of nanotechnology has finally reached higher volumes in some applications. All interviewees agreed with the Delphi results. The biggest variety in the answers was about the impact of public opinion as it was seen varying a lot between the fields.

**Laws and regulations**

Experts highlighted that legislation is not up-to-date and does not cover all aspects of nanotechnology. It can hinder the innovation of novel solutions. It will also impact the investments since the uncertainties make investments too risky. Differences in laws and regulations between countries and regions will create uncertainty and disturb cooperation. As the majority of the participants were from Europe, it was not possible to compare the effects in different parts of the world. On the other hand, if in the future all the fields of nanotechnology will have to follow the same laws and regulations, it might also unnecessarily slow down commercialisation as in some fields the risks are smaller and the materials simpler. At the same time, experts emphasised that until clear classification models for nanomaterials have been developed, the commercial introduction will be slow. The generation and adoption of new laws and regulations is slow, and the related uncertainties are expected to slow down the commercialisation of nanotechnology over the next ten years.

> The different approaches to nanotechnology in the legislative frameworks of different countries and regions also create uncertainty, which makes it difficult for companies to operate and increases costs. (Delphi)

> Sometimes technological developments are so fast that the safety aspects of nanomaterials are neglected. Current legislation does not take into account the "out of the box" properties of nanomaterials. (Delphi)

The responsible development of nanotechnology has been a key factor since knowledge of the technology has deepened. Besides safety for humans and the environment, responsible development also considers ethical, legal, and societal implications as well as inclusion, diversity, equity, and accessibility (NNI 2021, 11-12). During uncertain geopolitical times, the differences in regulations have a big impact on global trade and the independence of economic areas. Expectations impact the governance of the emerging technologies and should be studied especially in the implementation phase when the regulations are made (Hielscher & Kivimaa, 2019).

**Health risks and environmental risks**

Health and environmental risks were asked separately but because of the major overlap in the comments, the results are presented together. The lack of information on safety for humans and the environment will continue to be one of the biggest obstacles. The long-term effects of nanotechnology are still mostly unknown and could be irreversible and severe if not taken seriously. Methods for life cycle assessments are currently developed to measure the health implications. It will be necessary to evaluate not only the nanomaterials humans are in direct contact with but also evaluate the whole life cycle of nanoparticles. In some fields, nanosafety is already very high, for example in industry work, but safety will have to be ensured in all fields in the coming years. Small changes can turn health effects upside down. There is a need to create a categorisation of safe and harmful materials to avoid evaluating every nanomaterial individually. Individual evaluation will halt new applications and keep the costs high. Strict safety standards and evaluation criteria in other countries and looser in the others may temp to move production to countries with less strict rules. It is essential to do proper research before nanosolutions are in production. Society should be better prepared not to repeat the mistakes previously made with some other chemicals.

> Small changes to some of the chemistry or functionality of the material can turn its health effects upside down. There is no way to classify them yet. That is why, at the moment, practically every new nanomaterial that one wants to put into a consumer product, has to be evaluated separately. And then it's expensive and it's slow. (Respondent I4)

> Some of these nano-objects are difficult to control once they are widespread in the environment. Before releasing, we have to be extremely careful. That's the point. This is already happened. I mean, think about the chemical industry or other type of nuclear waste. We did a lot of mistakes. I will say this time is better to wait a little bit longer. Understand exactly and then move on. (Respondent I6)

The literature review revealed that during the 2020s, the focus of research has been on safety aspects as the commercialisation of nanotechnology has finally reached higher volumes in some applications. There are multiple ongoing projects to increase nanosafety by OECD and EU (STM 2022, 97). These are commonly used approaches in various fields of industry but are still quite new in nanotechnology. Safe by Design - concept promotes assessing safety already in the early stages of the innovation process. The concept aims at an iterative process where safety assessment is integrated into product development. Safety in this context means safe materials and products, safe production, and safe use and waste stage (EC 2021.) Safe and Sustainable by design, SSbD-concept is a holistic approach that combines the safety, recyclability, and functionality of chemicals, materials, products, and processes throughout their life cycle, while minimizing their environmental footprint (EC 2022).

**High expenses**

The high expenses of using nanotechnology were seen as relevant only for some applications. A lot of nanotechnology applications are still in the development stage and continue to be expensive until they become mainstream. More efficient methods for categorisation were seen as one possibility to lower the costs in the future.

> It (nanotechnology) will be used in such fields where the value of that market is high, as medical applications and energy technology, if the price which has been invested in testing can be returned. (Respondent I4)

**Lack of workforce**

Even though the lack of workforce was estimated moderate it was not considered to be typical only for nanotechnology. It was mentioned that currently there are lots of academic education options in nanotechnology to ensure future needs. The importance of education and workforce development to the entire nanotechnology ecosystem is recognised as one of the goals in the National Nanotechnology Initiative Strategic Plan (NNI 2021) also related to increasing support for STEM (sciences, technology, engineering and math) education. Nano2all report highlights the need to create a lifelong participatory culture in science and society through accessible education material on nanotechnology and other emerging technologies (Nano2all 2019, 9–11).

**Public opinion**

Lack of information and transparency can lead to a negative public perception and the term nanotechnology is often misunderstood. Impact of the public opinion was asked specifically in the interviews since it received the most controversial estimates in the Delphi panel. The impact of public opinion will vary depending on the field. Some fields are already used to nanotechnology, and it is not seen as a threat but other areas such as medical applications will trigger more public attention and suspicion. The divide between the ones who are excited and the ones who are concerned will continue. The focus should be on how the safety standards of nanotechnology are brought to public attention. More knowledge on nanotechnology still needs to be shared with the public since nano is a complex and multidisciplinary field and hard to grasp.

> Some people are really excited and some people are scared. That seems to me that there are two divisions in public opinion. But then how to communicate to wider population and increase awareness? That is a good question. (Respondent I3)

Expectations often differ between the scientists and the public, according to the closeness of the topic, access to information and sense of agency (Borup et al. 2006). The wider public has to approve the expectations constructed by experts to continue the development (Bakker et al. 2011; Alvial-Palvacino & Konrad 2019). The widespread adoption of innovations needs society´s approval. Communication plays a central role in addressing potential consumer concerns. It should be balanced, based on scientific knowledge, and focused on dialogue and transparency about the advantages and disadvantages of nanomaterials. (STM 2022.)

**Cooperation between academia and industry**

Lack of communication between the academy and business was evaluated to have a moderate impact on the commercialisation in the next ten years. The development of nanotechnology requires a deep understanding of various sciences, and it can be difficult to reason the benefits of new applications to the representatives of the manufacturing industry. Nanotechnology has the potential to find solutions for some of our most topical challenges. Cooperation is needed to speed up the new applications. The focus cannot be only on wins for one party but the benefits for the whole planet. The need for global networking and cooperation was obvious as building barriers will slow down the potential innovations. Nanotechnology has its national strategies but there are hints that the multinational cooperation is increasing.

> There is definitely lack of sufficient communication and co-operation between science and business. Development of nanotechnologies requires high understanding in chemistry, physics, engineering etc. and it can be difficult to reason the benefits of these new applications to the representatives of manufacturing industry. (Delphi)

Because of the limited number of participants, it was not possible to compare the expectations between different stakeholder groups and analyse if the scientists expressed more positive expectations than industry representatives as in the study by Bakker et al. (2011).

**Other obstacles**

Besides the obstacles recognised during the literature review, experts mentioned also a couple of more factors that may hinder the development of nanotechnology. One of them being the different orientations of societies. In Asia, nano is a label for high technology while in Western countries it attempts to raise more concerns. We will need the strengths of each country: money, hard workers, competence and knowledge, and regulations. Another concern was that nanosize needs completely new ways of doing and planning things.

> When you go to the nano size, it means that you go beyond your environment. You have to reduce by more than 1000 times the way how you manipulated the things. We have to find the new tools, and it's completely different to make one device in the laboratory than up scaling them. (Respondent I1)

It was also mentioned that since part of nanotechnology is still quite new, the development is always first very challenging and slow. It takes enormous effort before research findings turn into commercial applications and you must consider countless issues like risks and manufacturing.

Obstacles to commercialisation intertwine but the key factor seems to be the lack of communication between fields of nanotechnology, countries, academia and businesses, experts, and the public. Nano2all (2019) report emphasises the need for tight cooperation between all stakeholders to ensure safety in nanotechnology development. Interaction between different stakeholders, different fields, and different countries is very much needed, and sharing and building on existing frameworks is encouraged.

## 4.3 Megatrends shaping the development

The globalised world is driven by trends shaping societies. Trends are the trajectories of long-term development and megatrends are the most obvious trends observed in almost every field of society (Sitra 2023; Megatrends Hub 2023). The participants were asked to evaluate how the current megatrends will shape nanotechnology in the next ten years.

Megatrends selected here are assumed to have the most impact on the development of nanotechnology according to the literature review.

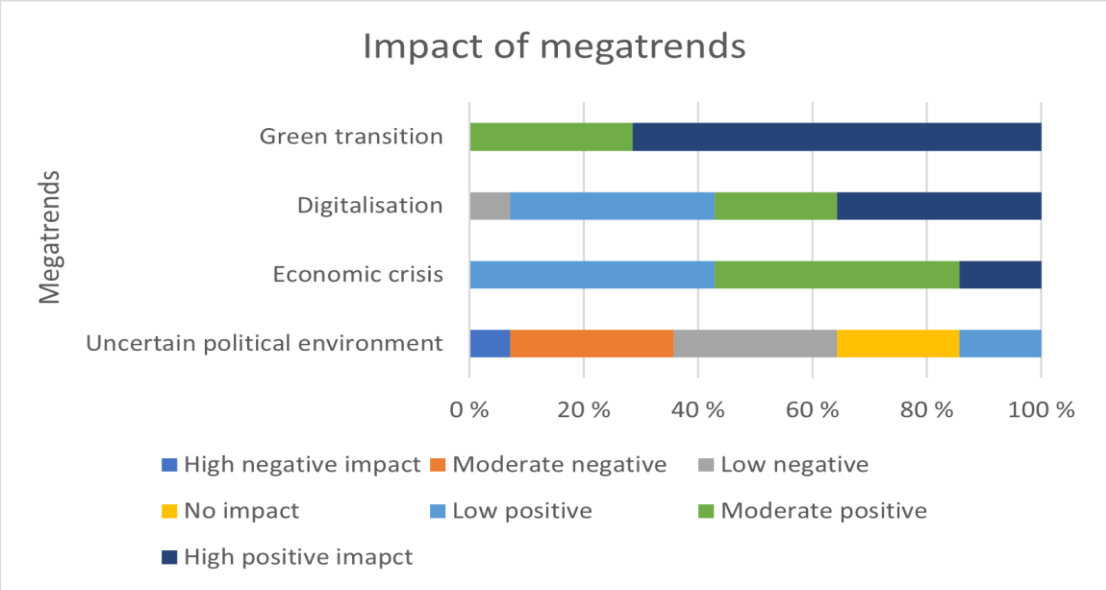


Figure 6 Impact of the megatrends on the development of nanotechnology
(Created by the author)

The expert panel evaluated the impact of the green transition clearly as the highest. Digitalisation was also expected to have a high positive impact. The impact of the circular economy was estimated to be moderate, and the uncertain political environment was evaluated to have a negative impact but the estimates had a lot of variation. According to the experts, nanotechnology is highly needed to support the green transition. Nanotechnology can offer new materials and even new systems. The scarcity of raw materials can be partially solved by utilising nanoscale.

> Without materials you cannot do too much… I need to use less materials, so it means that while I'm using in the range of microns, I have to go for the range of nanometers. It does not mean that I am saving all, but I at least postpone all the problems. (Respondent I1)

The nanoscale solutions must be easily recyclable and produced with less energy. Focus on all development will continue to be in ecological aspects. The need from society is high but it can also shift easily according to the challenges faced in the future. Green transition creates the push for applications promoting sustainability. However, competition is high, and some other technology might replace nano.

According to experts, nanotechnology is highly needed to support digitalisation. Quantum computing and the new IT technologies are typically those where nanotechnologies have a big impact. Increased interest in quantum computing was observed also during the literature review. The impact of the circular economy was evaluated to be low but positive. Nanotechnology is needed to reduce the need for rare materials and energy consumption. Moving on to the circular economy creates pressure to develop sustainable nanotechnology.

> The circular economy itself is not as strong a driver, although it can play a role in stimulating the development of new production and business models, which might include the application of nanotechnology. (Delphi)

The uncertain political environment was evaluated to have a moderate negative impact but created a lot of dispersion among the answers. An uncertain political environment may hinder the development as focus and investments are steered elsewhere. Increasing tension between countries may impair cooperation. Aim for independence may be a driving force for the development. For example in Europe, knowledge, competence, critical materials and manufacturing are scattered and mostly moved to Asia. In the future, it is needed to bring back to Europe. It was pointed out that the political atmosphere can change quickly and may differ a lot during the next ten years. Regardless of the uncertain politics, cooperation in some areas is expected to increase. Global cooperation is vital for science and science is vital for the future of humankind to encounter challenges.

> The uncertain global political situation could have a negative impact on the development of nanotechnology in the near future, as investment is diverted more elsewhere and tensions between countries increase and cooperation becomes more difficult. (Delphi)

All the interviewees agreed with the Delphi results. Besides megatrends mentioned in the questionnaire, finding solutions for energy generation to solve the energy crisis and health needs of the growing aged population combined with the poorer life conditions were mentioned as factors that accelerate the development of nanotechnology.

The impacts of the megatrends are interlinked, which is typical in all fields. It is not a surprise that the green transition and digitalisation were estimated to have the biggest impact also to the development of nanotechnology since they are currently the most well-recognised drivers of change globally. These two transitions are observed to have many interlinkages and for example EU has set the twin transition as its main goal. The digital transition is needed to achieve a fair and just green transition. The integrated approach is essential to avoid pushing two agendas separately and linking them could bring benefits from noticing synergies and managing the risks. (Muench, Stoermer, Jensen., Asikainen, Salvi & Scapolo 2022.) Nanotechnology should also be observed from the perspective of the twin transition.

### 4.4 Stage of the development cycle

Interviews with the experts confirmed the interpretation made based on the literature review of steady and differentiated development. Nanotechnology has diverged into specialised branches and the development has multiple phases. Some fields of nano are still in an uncertain phase, others accelerating and some are declining. As the technology has various applications in diverse fields of industry, the variation of the S-curve from Taylor & Taylor (2012) focused on applications fits best to describe the development of nanotechnology. The model considers the purpose, paradigm and variation/generation of the technology. Experts recognised the cyclicity of the development. Applications are at different stages of the hype cycle, others in disillusionment and others in the slope of enlightenment (Gartner 2024).

> Therefore, the field more than flat has been divided in many different branches. In some of them there is still quite hype in the sense that this developing some others have shown that maybe they are not so important. So, I would say that the nanotechnology as a tool is mature. Now the technology, as the application is still infancy. (Respondent I6)

All agreed on a moderately steady stage. Even though some argued that technology is still in a transition period and needs more proof to get to a steady stage. Steady development continues as moving from laboratories to manufacturing takes time to adapt the processes and is still slow.

> Yes, I would agree with that conclusion. I remember when it (development of nanotechnology) was like on a terrible curve. Now it's sluggish. And then it will go up a little bit again. Now it's a maybe levelled up, little bit at standstill. (Respondent I3)

Some of the experts believed that a breakthrough had not yet come, and the promises were not yet fulfilled. Research methods have evolved, and new discoveries will come as understanding the nano level gets better. However, others were more sceptical if such breakthroughs would ever occur for nano. It may be that the promises of nano will not be reached.

> I think at some point there's going to be a little bit of a bigger breakthrough…I think it's going to be like some kind of hybrid solution to be able to combine nanotechnology with something and it's going to be some kind of bigger thing. (Respondent I2)

> The more we understand the matter at the nano/molecular level, the higher are the chances to make ground-breaking discoveries. (Delphi)

Some experts highlighted that nano is already merged with other technologies and there is a lot of potential for hybrid solutions. Nanotechnology is connecting different scientific fields and the focus is on convergent technologies (EC 2013). Others see nanotechnology as the key enabling technology of the future. However, some believe nano will lose some attention and move out of the spotlight which is a sign of maturity, not negligence.

> It's already merged at some level. We talk a lot about hybrid materials, for example EU has focused on advanced materials, and it (nanomaterials) would be one subclass there. It would not be like the only solution and nothing else is not needed. It´s like one technology there among others. (Respondent I2)

Others thought nano doesn’t differ from other emerging technologies while others the novelty is in the interdisciplinary, pervasiveness, and the way it has changed the way we think about chemistry and physics, all features observed also by Salerno et al. (2018).

### 4.5 Societal impacts of nanotechnology

One goal of the interviews was to discover more expectations about societal impacts. Experts were asked what societal impacts nanotechnology will have in the next ten years. They were asked also to consider possible ethical concerns and the role of responsible nanotechnology. The majority of the answers dealt with health issues and ecological aspects focusing on sustainability. Experts stated that nano will offer solutions for prevention, diagnosis, and cure for diseases and improve the quality of life. However, it was mentioned that nanoproducts may increase or decrease life expectancy and wellbeing depending on how the development is executed. Nanotechnology will also bring solutions for the circular economy, support the improvement of the environment, and introduce safer products for the whole ecosystem.

Only a few ethical concerns were raised. Most of the current ethical challenges with nanotechnology focus on the unequal distribution of its benefits, involuntary exposure and not having enough information on the technology (Harthorn 2017,1550). From these, the safety of humans and the environment was mentioned. The concern was not significant since nowadays the volume of nanosafety research is very high. Responsible nano is already a reality as lifecycle analysis and other safety protocols are adopted as discussed in chapter 4.2. There is still a need for scientific evidence of the long-term consequences of nanotechnologies. Safety measures will increase expenses but repel the mistakes made with other innovations. It was not possible to compare the ethical concerns in the different fields of nanotechnology because of the small sample in this study.

The answers concerning societal impacts remain quite narrow and few. More structured questions on the topic might have helped as societal impact is a broad and abstract issue. On the other hand, many answers to other questions touch on the subject as it will be explained in the results summary.

### 4.6 Long-term future images

To widen the perspective, the interviewees were asked to describe also more long-term visions for nanotechnology. This was also an open question at the Delphi. The time range was stretched to 20 years ahead. The aim was to encourage participants to use more imagination and let go of the current realities.

Participants stated that nano will stay as a key enabling technology and keep developing even though it is not in the spotlight. The focus will be on advanced materials in general and nanotechnology will have an important role combined with other technologies. To ensure further development education in the field is essential. Basic science is expected to still make new remarkable findings which will lead to groundbreaking discoveries. Even some wild visions of multiverse and simulation theory were mentioned. Future images included both opportunities and threats that nanotechnology might create.

At the core of the possibilities lies the quest for sustainable materials, which serve as the building blocks for the circular economy and drive affordability through scaled-up manufacturing processes. Some materials will be inspired by nature and engineered for multifunctionality, not only minimizing waste but also fostering a regenerative relationship between humanity and the planet. Innovations in healthcare will improve wellbeing and reduce inequalities, leverage technology to enhance accessibility and preventive care. The environment can be manipulated in a manner that will no longer create risks for diseases, which also improves equality. Nano holds the potential for a safe and sustainable high-technology society even with aspects of the artificial world. It was also mentioned that nanotechnology may bring a completely new way of perceiving the world.

> All the process all the technologies that we know are additive processes. I have to add materials. I have to add components in order to integrate and make what I want to do. But I can also look at it in a different way – no need to add new material in order to create something. (Respondent I1)

For threats, experts raise the lack of cooperation, bad policies, and impractical or too loose regulations that can steer production to countries with lax oversight. In addition, insufficient investments and public apprehension due to concerns over nano-toxicity and pollution can hinder progress. The recycling of hybrid materials may also become a big obstacle. Transitioning from laboratory breakthroughs to scalable production remains a daunting task, and some visions may never be realised. Overselling of nano-products erodes public trust. Alternative technologies may also develop quickly and take the lead over nano.

The expectations towards 10 or 20 years didn't differ significantly. The number of possibilities and threats expressed was balanced.

## 4.7 Summary of the expectations for nanotechnology

The data was also analysed by comparing answers based on the background of the participants. There were no significant differences in the answers regarding the organisation they came from, the field of nanotechnology, the country they worked in, or the years of experience. In some cases, the sample was too small to do the comparison.

To perceive an overview of the identified expectations for nanotechnology, the results were summarised and visualised in Figure 7 below following PESTEC (political, economic, social, technological, environmental, cultural) categorisation. The summary presents the whole empirical coded data divided according to these aspects. The overview gathers expectations on different fields, obstacles, trends, development paths, and future images both in a ten-year and twenty-year time range. It does not indicate the popularity or relevance of the expectations but draws an overview of all expectations.

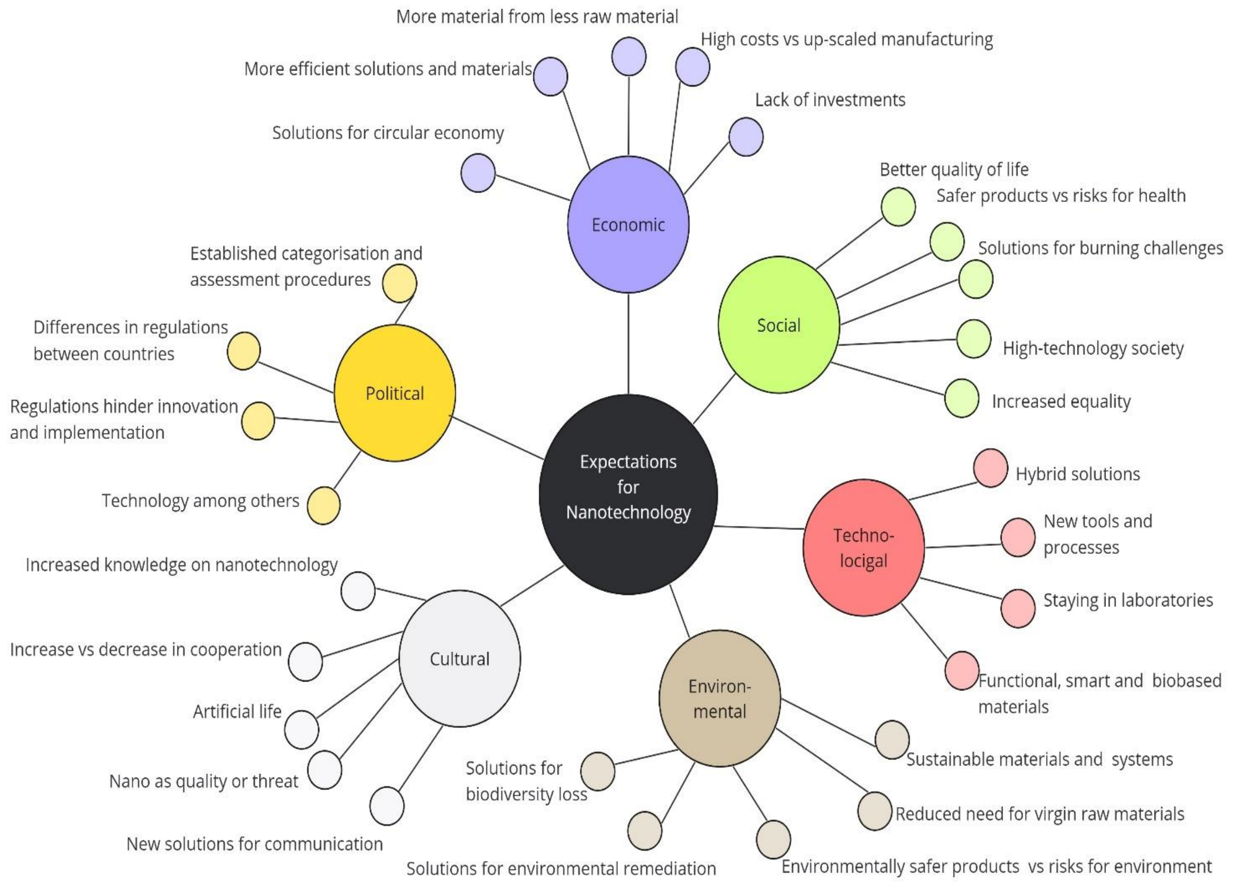


Figure 7 Summary of the results
(Created by the author)

The results from this study confirm many earlier findings. Nanotechnology is still seen as one of the most promising technologies, which will be discussed more in the conclusions. At the same time, the hype around it is moderate even though some breakthroughs are anticipated. The fears of nanorobots invading the world were missing. The focus is rather on safety for the health and environment. Nanotechnology is in a divergent state. Some fields are more mature and already in the mainstream while other branches are still emerging. There is increased interest in nanotechnology as it is expected to offer solutions for green transition and a more sustainable world. However, nanotechnology is considered among other emerging technologies and the potential of hybrid solutions is high.

Most of the participants found it hard to anticipate future developments and indicate their expectations. The experts' comments were at some point more explaining the current state whereas the goal was to find how these factors' impact will evolve in the future. It was an acknowledged choice to ask directly about expectations. However, the experts recognised well the power of expectations in building momentum for technological and scientific innovations (Borup et al. 2006; Hielscher & Kivimaa 2019). Also constructing the nanojourney at the beginning of the study showed how expectations affect the potential of technologies as they shape activities, investments and regulations (Borup et al. 2006). Expectations among the experts were quite similar even though some contradictions were found, which is typical for expectations for emerging technologies as they are collective (Konrad 2006; Selin 2007).

# 5 Discussion and conclusions

This section gives an overview of the study discussing the findings and evaluating the process and the outcomes. It begins with insights on findings and continues with observations of the reliability, validity, and ethicality. After that, the impact of the study and ideas for further research are discussed.

## 5.1 Discussion on findings

The Real-time Delphi survey with nanotechnology experts elaborated with interviews demonstrated that nanotechnology is expected to change all fields in the next ten years. The impact was evaluated to be highest in the fields of energy, medical applications, information technology, and materials sciences. Expected changes were described to be for example more advanced materials, more efficient solutions, and reduced need for raw materials. New technological solutions and significant development in existing innovations are expected. Developments in these fields may bring remarkable economic benefits as more material can be created from less material and energy efficiency improves and social gains through medical applications. Many solutions serve multiple fields, for example sensing, energy production, energy storage, and smart materials. However, niche solutions may not function on a large scale and ten years might not be enough for changing manufacturing processes. Nano alone cannot solve current challenges, but other technologies are needed along it.

The commercialisation of the findings in nanotechnology continues to be slow. The experts estimated that laws and regulations as well as the health risks will have the biggest impact on commercialisation in the next ten years. Expenses and environmental risks were also evaluated to have a high impact. The biggest variety in the answers was about the impact of public opinion as it was seen varying a lot between the fields. Laws and regulations are not keeping up with the phase of development. Differences between countries and regions will create uncertainty and disturb cooperation. Until clear classification models for nanomaterials have been developed, the commercial introduction will be slow. The lack of information especially on the long-term effects of nanotechnology on the safety of humans and the environment will continue to be one of the biggest obstacles. The high expenses of nanotechnology were seen as relevant only for some applications, especially those in the early phase of development and not yet reached the mainstream. The lack of workforce was estimated moderate as the need for experts is high but there are lots of academic education options in nanotechnology to ensure future needs. Information is not transparent and it's difficult to understand as the technology is complex and multidisciplinary which complicates the cooperation between academia and business and decreases the trust of the public.

A variety of trends push the development of nanotechnology. The expert panel evaluated the impact of the green transition clearly as the highest. Digitalisation was also expected to have a high positive impact. The impact of the circular economy was estimated moderate, and the uncertain political environment was evaluated to have a negative impact. Green transition and moving to a circular economy create the need for applications promoting sustainability. However, competition is high, and some other technology might replace nano. Nanotechnology is highly needed to support digitalisation and quantum computing introduces promising solutions. An uncertain political environment may hinder the development as focus and investments are steered elsewhere. Increasing tension between countries may impair cooperation. Aim for independence may be a driving force for the development.

Nanotechnology has diverged into specialised branches and the development have multiple phases. Overall steady development continues as moving from laboratories to manufacturing takes time to adapt and the processes are still slow. Some of the experts believed that the breakthrough has not yet come, and the promises are not yet fulfilled. Research methods have evolved, and new discoveries will appear as understanding the nano level gets better. Nano will stay as a key enabling technology even though it is not constantly in the spotlight.

From the beginning of the discovery of nanotechnology, its potential has remained magnificent. It is a completely new level of understanding of the world. As nanotechnology manipulates atoms and molecules, making changes at the nanoscale enables improved materials and devices. At some point, the wild visions for nanotechnology relied more on fiction than facts. Even though it is not the case anymore nano has the characteristics to spark imagination. The complexity, abstraction, and multidisciplinary make it hard to understand and even mystify the technology.

Many of the nanotechnology applications have not yet reached the mainstream and it still holds the reputation of promising technology. Exciting findings in the laboratories have the potential for scaling. Even though some fields have not remedied the expectations, the variety of applications is so broad that individual failures have not changed the overall expectations. One reason behind still high expectations is the pervasiveness of nanotechnology. As a general-purpose technology offering solutions to all aspects of society, it holds potential solutions for many global challenges as currently for the twin transition towards a green and digital society. On the other hand, recent developments in hybrid solutions combining nanotechnology with other emerging technologies, create even new visions and again increase the expectations.

## 5.2 Evaluating the study

Some aspects of validity and reliability have already been discussed in the previous sections when describing the literature review, research process, methods, and results. This chapter gives an overview of the quality of the study.

### 5.2.1 Validity and reliability

Validity of the research means the accuracy of the results and reliability refers to how the chosen methods can produce consistent results (Saunders & Lewis 2018, 134). These are dependent on the research strategy, methods used for data gathering and analysis, quality of the data, relation to theory, and the generalisation of the results.

Transparency increases both validity and reliability and a detailed description of the study process is essential. The role of the researcher is highlighted in qualitative research since the researcher has freedom in many steps of the study which makes describing the research process the most important measure. (Eskola & Suoranta 2008, 210, 219–221.) This report has explained each step of the research process as well as the choices and reasons behind them. The description of the process is detailed and honest. It involves the description of the context to allow the reader to evaluate the validity, the description of the theories behind the research and the reasoning for choosing them, the description of the methods to gather and analyse the data not only on a general level but also how they are utilised in this study. To support the analysis, some examples from the data are revealed.

Another aspect of validity is the objectivity. In the qualitative study, one part of it is acknowledging the subjectivity of the researcher (Eskola & Suoranta 2008, 210-212). My freshness in the subject may have caused biases in gathering and analysing the data but also made me more objective about the topic and free from strong presumptions. According to interpretivism, we interpret the social world through our values (Sanders & Lewis 2018,109). Values are often so deep in our thinking that we do not always be aware of them and my values may have caused some biases.

Reliability includes also consistency throughout the research. The characters of the phenomena should define the research questions and research questions should define the methods. (Saunders & Lewis 2018, 135.) The research questions were defined based on the literature review. The study methods were not traditional for studying expectations. The Delphi method was chosen to observe current expectations while most of the studies on expectations use articles and other material from the past. The strength of the study is the use of triangulation. Triangulation in research refers to combining different theories, data-gathering techniques, or analysis methods. It often enables a wider and richer perspective. (Eskola & Suoranta 2008, 68-74.) This study benefits triangulation by gathering empirical material by utilising Delphi and interviews and even before supplementing the literature review with scanning the nanotechnology strategies and initiatives.

External validity means how well the research results can be generalised (Eskola & Suoranta 2008, 210-212; Saunders & Lewis 2018, 134). The objective was to gather an overview of the expectations for nanotechnology. However, the sample of participants remained low. Not all fields of nanotechnology or stakeholder groups were represented, and the geological coverage remained narrow. The study fails to give the basis to do a comparison between different variables but remains rather a case example. Since the study perceived nanotechnology in general, it does not capture the specific circumstances of each branch. It can also be criticised if the experts were capable of sharing expectations beyond their specific fields. Nanotechnology is used here as one case example of emerging technologies. This and previous studies reinforce that nano follows the principles of other emerging technologies if compared to other interdisciplinary and pervasive technologies which makes the results generable.

### 5.2.2 Ethicality of the study

Research can be considered ethical if it follows good scientific practices. The researcher should be honest and careful in conducting the research, recording the results, and reporting the study. The researcher must use ethical data acquisition-, research- and evaluation methods and be transparent when reporting on the results. The work of other researchers must be respected. The research should be designed, conducted, and reported as required by scientific knowledge. (TENK 2012.) This study follows good scientific practices in every step from planning to reporting the results. All the steps are transparently described in this report and validated through the scientific principles also explained in this report.

Ethical principles of research with human participants insist on respecting the dignity and autonomy of participants, not causing significant risk or harm to participants, guaranteeing that participation is voluntary and participants have the right to discontinue or withdraw their participation, giving information about the research to participants and appropriate handling of data and privacy (TENK 2019, 50-52). The empirical data for this study was collected from human participants, in this case, nanotechnology experts. Participation was voluntary. The experts were invited to participate by email explaining the aim and focus of the study. The experts were invited to answer the Delphi and the interview from their own personal perspective regardless of the organisation they worked in. In every step, the participants received information about the phase of the study, and they had the opportunity to ask for more information or withdraw their participation. After the Delphi, all participants were asked to indicate whether they wanted to volunteer also to the second part of the data gathering. There was no need for ethical review since the topic of the study was not considered to be particularly sensitive, no delicate personal information was collected, and none of the participants were minors or with limited capacity (TENK 2019).

Planning the study involved a data collection and handling plan following the scientific practices of the University of Turku. Participants received privacy and data protection notice (See Appendix 4 Privacy and data protection notice) explaining the practices. The interviews were recorded, and participants were asked to give their consent before starting the recording. The study ensured the anonymity of the participants according to the scientific principles (TENK 2019). The data was anonymised already at the transcription phase. All the identifiers were erased from the examples presented in the report and participants were referred by acronyms. The background information about the participants was also presented in a way that protect anonymity.

One aspect of ethicality is to acknowledge and explain the representativeness of the results. In futures studies this is also linked to democratising futures, which refers to giving a voice to also those who are not often heard when envisioning the futures. Societal research on nanotechnology is a typical example of a discussion, where the views of ordinary people have been ignored in the debate (Sand 2019). It was a conscious choice to gather experts' opinions and not include laymen. However, the aim was to give voice to different stakeholder groups inside the expert scope; academia, industry, governments, and associations. The goal was to include experts globally and from different sectors on nanotechnology. Since the scope was limited for the thesis work the variety of stakeholders was narrow but acknowledged.

### 5.3 Impact of the study and further research

The absurdism in futures studies is that besides being scientific the aim is not finding out the truth since there is no knowledge about the future (Bell 2009, 46-47). One of the main principles of futures studies is that the future is unknown. A sociologist's role is to create images of the future scientifically using speculation and creative imagination and presenting both critical and optimistic anticipations (Bell & Mau (1971, 37-40). This study observed expectations and provided a glimpse into the futures enabled by nanotechnology.

Nanotechnology is developing in many sectors and may have a crucial role in mitigating the current challenges, especially for green transition. Expectations on emerging technologies steer the development, funding, and focus of technologies that are not yet real but imaginable. The results of the study reveal some of the expectations and reflect the assumptions, hopes, and fears experts have for nanotechnology. The broadness of the subject was a challenge and an opportunity. The general perspective prevented the deep dives into particular applications and kept results at a rather abstractive level. The benefit of the broad view was on revealing expectations from a holistic perspective.

The study aimed to bring a human perspective to technology development. Technological development is assumed to be even more rapid in the future but at the same time, the importance of human touch is emphasised. Expectations were selected as study objects as they bring together different actor groups in technology development and link together technological and societal aspects (Borup et al. 2006). Study showed how expectations guide the development in a practical way but also at a more abstract level determining areas of interest and objectives. Expectations can create a trap for solutions that never come but lull in a sense of security. Under current crises, it is tempting but dangerous to hope that technology is going to solve the problems and we can continue the business as usual. Emerging technologies may bring many solutions but also create new challenges. Above all, the study has been a learning path for a humanist about the importance of technology in society.

The results highlighted the need for cooperation at all levels and between all stakeholders. The development of multidisciplinary nanotechnology demands a reflexive system of innovation. The complexity of the field creates different islands of discussions that often lack consensus (Munshi, Kurian, Bartlett & Lakhtakia 2007). International and multistakeholder commitment is needed for anticipative governance as it is crucial in controlling the societal impacts of emerging technologies. The role of anticipative governance is more obvious for emerging sustainable technologies as they demand long development time, large investments, involvement of many actors, and many regulations and policies (Alkamade & Suurs 2012). While the path forward may be fraught with uncertainties, sustained commitment to collaboration can pave the way for transformative breakthroughs in nanotechnology and beyond.

Further research is still needed on the expectations for nanotechnology especially as it is identified as a general-purpose technology an emerging sustainable technology. General-purpose technologies are even more tight to expectations since the promises are so widespread. In addition, the government’s role in creating expectations is specifically important for emerging sustainable technologies and should be more studied. On the other hand, to gain more tangible results, expectations could be studied separately in the different fields of nanotechnology. Finally, more emphasis is needed to perceive laymen's expectations for complex technologies to build better communication.

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# Appendices

## Appendix 1 Delphi questionnaire

**Introduction and instructions**

Dear participant, welcome to the journey 10 years ahead of our time. Future is always unknown, but we can still anticipate it. Your task is to imagine how the field of nanotechnology will change in the upcoming years.

Nanotechnology in this study is understood in its wider sense, meaning the technology in the nanoscale (one billionth of a meter) of molecules and atoms, which provides unique opportunities for developing materials and devices. It draws on the scientific knowledge of biology, physics, chemistry, and materials science. Nanotechnology will be used here as a collective term, encompassing its various branches. Even if your expertise in nanotechnology lies in a specific field, try to answer this panel from a wider perspective. You are asked to express your personal thoughts, not presenting the organisation or the role you work in.

The method of this study is a realtime Delphi. Delphi is a research method often used in Futures Studies to identify the views of experts. Characteristics of this method are anonymity and the possibility to revise your answers. In a way, Delphi is a controlled conversation. First, answer the questions by yourself. Give as much reasoning as you like to clarify your thought process. After most of the participants have given input the answers and comments are revealed anonymously to the others. It is highly recommended that you come back then and see the other participant´s answers. You also have an opportunity to change and specify your answers based on other experts’ points. You may receive new questions during the panel based on the findings. The panel is scheduled to be open 6.2.-19.2.2023 and during it you will receive announcements of the state of the panel.

The panel includes three sections

1) Impact on different fields

2) Obstacles for commercialisation

3) Trends

In the last part, you will submit some background information.You will find more instructions before every statement.

Have a great journey!

**Impact in different fields**

Nanotechnology has been said to be the defining technology of our time. The development over the decades has been full of stable development, astonishing findings, hype, and disappointments. Now you get to imagine, what changes might be ahead over the next ten years.

Categorisation of nanotechnology into different branches can be done in multiple ways. This study uses the categorisation adapted from European Commission and United States National Nanotechnology Initiative documents as well as used in other Futures Research studies (1,2,3). The approach is based on different applications of nanotechnology.

Nano is said to be the general-purpose technology changing almost all fields of industry. Impact of the nanotechnology varies in different fields. It has changed some fields dramatically and some use it among other technologies.

Please, estimate how much nanotechnology will impact the different fields during the next ten years. There are altogether eight fields. You may be more expert in some fields than others, but please try to evaluate the impact in all the branches in some depth. After each field, you can explain your ideas of the impact and give your reasoning.

<u>Energy</u>

Please, estimate the impact of nanotechnology on the field of energy over the next ten years. Energy refers here to efficient energy production and storage. In the comment box please explain your ideas on the impact and give your reasoning.

<u>Environment remediation</u>

Please, estimate the impact of nanotechnology on the field of environment remediation over the next ten years. Environment remediation refers here to repairing and cleaning the environment. In the comment box please explain your ideas on the impact and give your reasoning.

Information technology

Please, estimate the impact of nanotechnology on the field of information technology over the next ten years. Information technology refers here to information elaboration processes: electronics and computing. In the comment box please explain your ideas on the impact and give your reasoning.

Manufacturing

Please, estimate the impact of nanotechnology on the field of manufacturing over the next ten years. Manufacturing refers here to creating nanoscale devices, assembling them into functional systems, and creating architectures suitable for various environments. In the comment box please explain your ideas on the impact and give your reasoning.

Material science

Please, estimate the impact of nanotechnology on the field of material science over the next ten years. Material science refers here to improving characteristics of materials, developing new materials, and finding new ways to utilise materials. In the comment box please explain your ideas on the impact and give your reasoning.

Medical applications

Please, estimate the impact of nanotechnology on the field of medical applications over the next ten years. Medical applications refers here to precise solutions for prevention, diagnosis, and treatment of diseases. In the comment box please explain your ideas on the impact and give your reasoning.

Metrology

Please, estimate the impact of nanotechnology on the field of metrology over the next ten years. Metrology refers here to studying the properties of matter on the nanoscale. In the comment box please explain your ideas on the impact and give your reasoning.

Security

Please, estimate the impact of nanotechnology on the field of security over the next ten years. Security refers here to using nanotechnologies in the defence industry, for example, to enable the detection of hazardous materials and entering dangerous environments. In the comment box please explain your ideas on the impact and give your reasoning.

Missing fields

You now have the opportunity to name new fields if you feel that all branches of nanotechnology weren't covered. You can also leave other comments on the categorisation.

**Obstacles on the commercialisation**

Please estimate the impact of the obstacles on the commercialisation of nanotechnology over the next ten years. The commercialisation of the findings in nanotechnology has been slow at least in some fields. Studies on nanotechnology have recognised some obstacles typical for emerging technologies and some peculiar to nanotechnology. You are now asked to evaluate the significance of the typical obstacles in the near future. In the comment box, please explain your ideas on the impacts and give your reasoning. You can also add more obstacles if some important aspects seem to be missing.

**Trends**

Please estimate the impact of the megatrends on the development of nanotechnology over the next ten years. The globalised world is driven by trends shaping societies. Trends are the trajectories of longterm development. Megatrends are the most obvious trends observed in almost every field of society (5,6). Next, you will evaluate how the current megatrends will shape the nanotechnology in the near future. Megatrends selected here are assumed to have the most impact on the development of nanotechnology. In the comment box, please explain your ideas on the impacts and give your reasoning. You can also add more trends if some important aspects seem to be missing.

**Future visions**

You have now evaluated the impact of nanotechnology on its different branches, the relevance of obstacles, and the effect of the megatrends. I hope these questions have made you visualise the future of nanotechnology. Please describe any other future visions for nanotechnology that were not asked in the previous questions.

**Background information**

How long you have been working in nanotechnology?

What kind of organisation you work in?

What field of nanotechnology you work in?

What country you work in?

**Thank you!**

Thank you for your answers. You will receive an email if new statements are created for you to answer. Please come back before the panel closes to see other participants' answers. You still have the opportunity to modify and specify your answers

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**Appendix 2 Summary of Delphi**

# Summary of the Delphi results: Expectations for Nanotechnology

## Introduction

Altogether 14 participants from various fields of nanotechnology and from six different countries participated the Delphi expert panel on expectations for nanotechnology. Realtime Delphi was organized in the eDelphi platform 9.2.-24.2.2023. This summary presents the results for the participants and will be used as discussion material for experts' interviews.

## Impact on different fields

Nanotechnology is said to be the general-purpose technology changing almost all fields of industry. Impact of the nanotechnology still varies in different fields. It has changed some fields dramatically and some use it among other technologies. Participants were asked to estimate how much nanotechnology will impact the different fields during the next ten years. The categorization of nanotechnology into eight fields is based on different applications of nanotechnology.

**The question: Please, estimate how much nanotechnology will impact the different fields during the next ten years.**

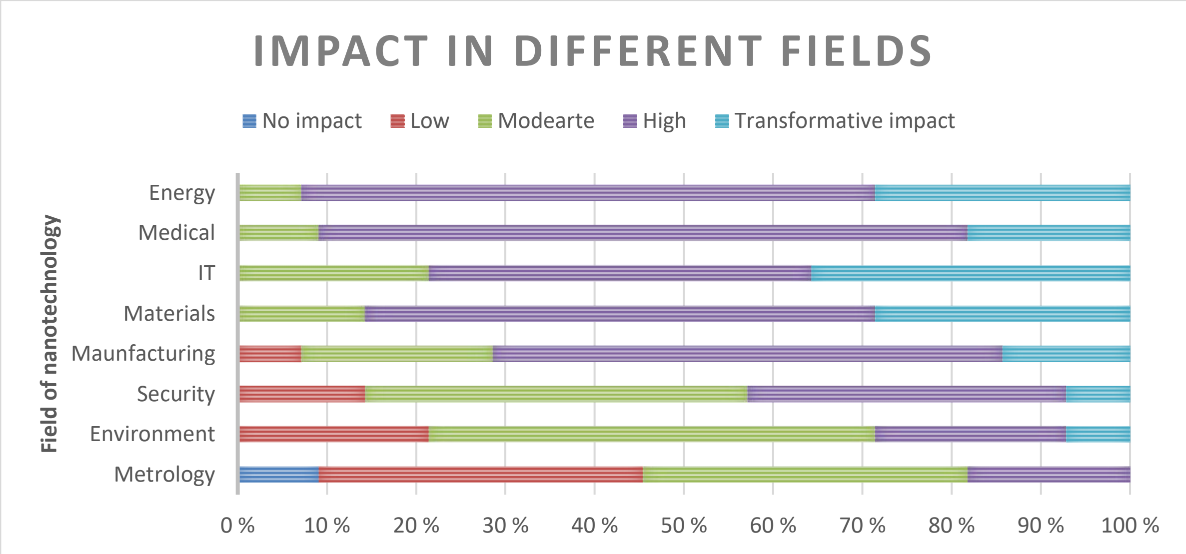


Table 1: Impact of nanotechnology in the different fields in the next 10 years

Among the fields, the impact of nanotechnology in the next ten years' time was evaluated to be high in the fields of energy, medical applications, information technology, materials science and manufacturing and moderate in the fields of security, environmental remediation and metrology. The impact was evaluated to be highest in the energy field and also very high for medical applications, information technology, and materials sciences. Next, you will find a short summary of the experts' reasoning behind the expected impacts on the different fields dived to drivers of change, specific technologies and doubts.

**Energy** - Consensus on high impact

*Drivers:* Nanotechnology has the potential to remove toward a renewable energy-based economy and low-carbon society. It can make solutions smaller, more effective, and more efficient.

*Technologies:* Especially the role of new energy storage technologies and the development of batteries were highlighted. Also, solar energy solutions, hydrogen production and fuel cells were mentioned in multiple comments.

*Doubts:* It was questioned if ten years is enough for remarkable changes in industrial implementation and manufacturing processes as well as lowering the costs.  It is valid to notice that also other promising technologies compete in this sector.

**Environmental Remediation** - Moderate impact with variation in estimates

*Drivers:* Achievements to consider environmental issues and biodiversity loss increase the interest in utilizing nanotechnology in remediation. Seeking for more efficient solutions and reducing the need for raw materials achieved by nanotechnology help indirectly environmental remediation.

*Technologies:* The most mentioned potential future solutions were related to water purification. Also catalysts and reactive nanomaterials were mentioned as well as advanced sensing technologies for detection.

*Doubts:* Nanotechnology offer solutions for this sector but at the same time poses risks. Safety regulations slow the implementation of solutions and there is scepticism about large-scale solutions. Other technologies are needed alongside nano to find solutions.

**Information Technology** - Consensus on high impact

*Drivers:* The constant need for fast, reliable, sustainable and low-energy devices and systems accelerates the development.

*Technologies:* Quantum computing was seen as the most promising in the field, but also spintronics, and printable and wearable electronics were mentioned.

*Doubts:* There were some doubts if quantum computing can meet all the expectations. It was also mentioned that high energy consumption may hamper development

**Manufacturing** - High impact with variation in estimates

*Drivers:* Nanotechnology has the potential to solve current problems in manufacturing. It can increase efficiency and produce new nano-based materials and components.

*Technology:* Impacts both on the process and material design. Processes such as distributed sensing and manufacturing metamaterials were mentioned.

*Doubts:* Participants expressed that the field was difficult to evaluate since the concept of manufacturing is so broad and the impacts on different fields vary a lot. The transition from nanotechnology innovations to full-scale production has been slow and remarkable changes may not occur in the next ten years.

**Materials Science** - Consensus on high impact

*Drivers:* Materials science is one of the key areas for nanotechnology. There is potential to increase knowledge on the characteristics of materials, improve material functionality, find tailor-made solutions and create completely novel materials.

*Technologies:* New materials will be strong, flexible, smart or biobased and will have for example self-cleaning and healing properties and optical characteristics.

*Doubts:* Nanotechnology alone is no longer enough but the future lies more on developing advanced materials together with other technologies. The high costs and difficulties with scalability hinder the development.

**Medical applications** - Consensus on high impact

*Drivers:* Nanotechnology will have a remarkable contribution to health and have major economic and social gains by improving diagnosis, gaining better impacts with less amount of chemicals, and better targeting with treatments and medicines.

*Technologies:* Promising development in various sectors from prevention to testing and diagnosis to new kinds of medicines and drug delivery solutions. Also medical equipment, genetic surgery and vaccinations were mentioned.

*Doubts:* The safety of nanotechnology was highlighted in this field. The slow approval processes will delay the implementation of new innovations.

**Metrology** - Moderate impact with variation in estimates

*Drivers:* There is a continuing need to improve accuracy, reliability and efficiency when creating new applications.

*Technologies:* Metrology is especially valid in the medical field, material science, and quantum technology.

*Doubts:* Nanotechnology is one tool among others to study the properties of materials and metrology for nano is already well developed.

**Security** - Moderate impact with variation in estimates

*Drivers:* The defence sector is constantly utilising and looking for new technologies. The goal is to increase sensitivity, reduce power consumption and obtain energy autonomy.

Technologies: Most mentioned nanotechnology areas were sensors, nanomaterials, robotics, and cyber safety solutions.

Doubts: Some participants expressed the need to define more precisely and separate safety and security. The defence industry might already be ahead of commercial applications.

The experts suggested the agriculture and food sectors as well as transportation and space technology when asked about the missing fields. Also sensors and 3D were mentioned.

## Obstacles to commercialization

The commercialization of the findings in nanotechnology has been slow at least in some fields. Studies on nanotechnology have recognized some obstacles typical for emerging technologies and some peculiar to nanotechnology. Participants were asked to evaluate the significance of the typical obstacles in the near future.

The question: Please estimate the impact of the obstacles on the commercialization of nanotechnology over the next ten years.

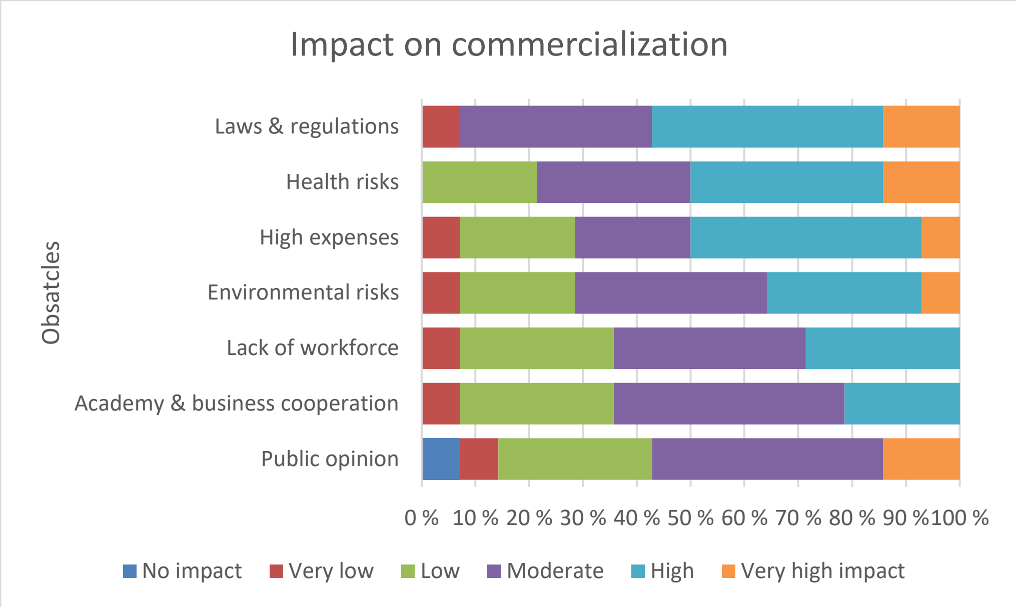


Table 2: Impact of the obstacles on the commercialization of nanotechnology in the next 10 years

The experts estimated that laws and regulations as well as health risks will have the biggest impact on the commercialization of nanotechnology in the next ten years. Expenses and environmental risks were also evaluated to have a high impact. The biggest variety in the answers was about the impact of public opinion. Next, you will find a short summary of the experts' reasoning.

It was highlighted that legislation is not up-to-date and does not cover all aspects of nanotechnology. Differences in laws and regulations between countries and regions create uncertainty and hinder cooperation. The lack of information on safety for humans and the environment was evaluated as a high factor. The expenses on the other hand were seen as relevant only for some applications. Even though the lack of workforce was estimated moderate it was not considered typical only to nanotechnology. Lack of information and transparency can lead to a negative public perception and the term nanotechnology is often misunderstood. Development of nanotechnology requires a deep understanding of various sciences and it can be difficult to reason the benefits of new applications to the representatives of the manufacturing industry. Obstacles to the commercialization intertwine but the key factor seems to be the lack of communication between fields of nanotechnology, countries, academy and business, and experts and public.

## Megatrends

The globalised world is driven by trends shaping societies. Trends are the trajectories of longterm development and megatrends are the most obvious trends observed in almost every field of society. The participants were asked to evaluate how the current megatrends will shape nanotechnology in the near future. Megatrends selected here are assumed to have the most impact on the development of nanotechnology.

**The question: Please estimate the impact of the megatrends on the development of nanotechnology over the next ten years.**

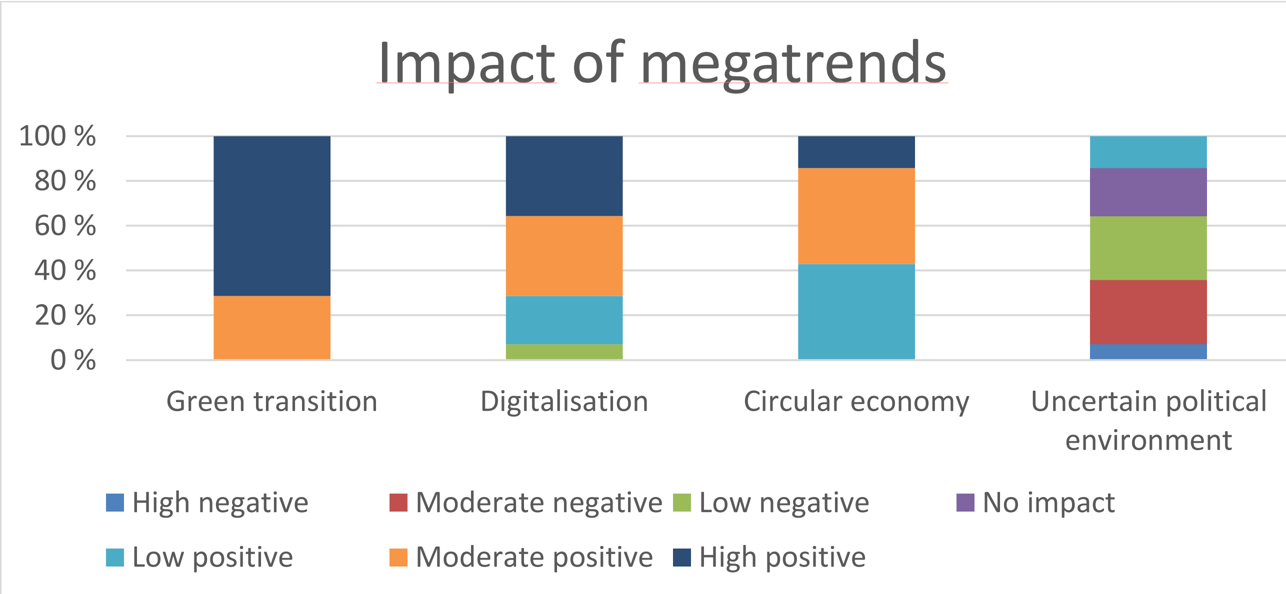


Table 3: Impact of the megatrends on the development of nanotechnology in the next 10 years

The expert pane evaluated the impact of the green transition clearly as the highest. Digitalisation is also expected to have a high positive impact. The impact of the circular economy was estimated moderate and the uncertain political environment was evaluated to have a negative impact but the estimates had a lot of variation.

According to the panellists, nanotechnology is highly needed to support the green transition and digitalisation. Nanotechnology can offer new materials and systems. For the circular economy nanotechnology is needed to reduce the need for rear materials and energy consumption. The uncertain political environment may hinder the development as focus and investments are steered elsewhere. Also global cooperation, much needed in nanotechnology, encounter challenges.

Besides megatrends mentioned in the questionnaire, finding solutions for energy generation to solve the energy crisis and health needs of the growing aged population were mentioned as factors which accelerate the development of nanotechnology.

### Other future visions

Finally, the participants were asked to describe any other future visions for nanotechnology. They stated that nano will stay key- enabling technology and keep developing even though it is not in the spotlight. The focus will be on advanced materials in general and nanotechnology will have an important role combined with other technologies. To ensure further development education in the field is essential. Basic science is expected to still do new remarkable findings which will lead to groundbreaking discoveries. Even some wild visions of multiversum and simulation theory were mentioned.

## Appendix 3 Interview structure

**Introduction**

consent to record and transcribe the interview, introductions, structure of the interview and the timeframe

**Comments on the Delphi results (15 min)**

Intro: We are not going to go through the whole questionnaire, only briefly the key findings, interesting points, contradictions, and insights.

1) Impact in different fields of nanotechnology

Do you agree with the evaluated impact in your field/in general? What will be to biggest changes nanotechnology might bring to the field in the next 10 and why? What are the alternative futures? Do you see any other possible development trajectories for the field? Would you like to comment on anything else?

2) Obstacles to commercialisation

Do you agree with the evaluated impacts? What is in your viewpoint the most relevant obstacle (in your field)? Why? How can it be tackled? Public opinion received the most controversial answers. What is the impact in your opinion/field? Is there something else you would like to comment on this chart?

3) Megatrends

Do you agree with the evaluated impacts? What is in your viewpoint the most relevant trend (in your field)? Why? How it affects? Are there other significant trends impact the field that were not mentioned here? Would you like to comment on anything else on this subject?

**Development cycles (5 min)**

Intro: There are lots of theories describing the development of emerging technologies. One of them, Gartners hype cycle, explains expectations at different phases of the development of the technology from hope to hype to disappointment to differentiation and steady development. Since nanotechnology has been around for many decades and includes various technologies there is a lot of oscillation and multiple hype cycles occurring simultaneously and even new curves emerging. Based on my literature review nanotechnology is now at the state of differentiation since there are multiple domains of nano and nano has also merged with other technologies. Development seems to be steady but nano has not yet gained its full potential. There is some increase in interest because of the demands green transition puts on technologies.

1) In what development phase nanotechnology is now in your opinion? In your field or in general? Why?

2) What are the peculiarities in the development curve of nanotechnology compared to other emerging technologies?

**Societal impacts (5 min)**

Intro: Society adapts to the development of technologies. Societal impacts here mean how nanotechnology affects the political, economic, social, environmental and cultural aspects of our everyday life.

1) What societal impacts nanotechnology will have to society in the next 10 years? Your field or in general?

2) What transformations society is ready for?

3) What does responsible nanotechnology resemble to you/in your field? How it can be achieved?

4) Ethical concerns?

**Future images (5 min)**

Intro: Try to forge the current realities and imagine life far away in the future.

What are we going to see in the next twenty years in the field of nanotechnology?

What are the biggest possibilities, threats and uncertainties?

What can be the alternatives for the most likely future?

Any other comments

Thank you!

## Appendix 4 Privacy and data protection notice

1. Name of the register:

Expectations for nanotechnology

2. Data Controller:

Master's degree student Maija Knutti maija.t.knutti@utu.fi, +358407625065

3. Purpose and legal basis for the processing of personal data:

The research collects experts' views on the development of nanotechnology with interviews. Email addresses are used when sending out invitations to interviews. The legal basis for processing personal data in the Article 6 of the EU General Data Protection Regulation is:

Processing is necessary for scientific research (public interest, Point 1a of the Article 6)

Data subject has given their consent to processing personal data (consent, Point 1e of the Article 6)

4. Processed personal data:

The following information of the data subjects is stored in the register:

Name, email address, occupation, name of the workplace

5. Recipients and recipient groups of personal data:

The data will not be transferred or disclosed to parties outside the research group.

6. Information on transferring data to third countries:

Personal data will not be disclosed to parties outside the EU or the European Economic Area.

7. Retention period of personal data or criteria for its determination:

The recorded interviews will be transcribed into text files and the recordings will be destroyed. Simultaneously, the research data will be anonymised by erasing identifiable personal data. Personal data is stored until 1 April 2028, after which the data is disposed of securely.

8. Rights of the data subject:

The data subject has the right to access their personal data retained by the the Data Controller, the right to rectification or erasure of data, and the right to restrict or object the processing of data. The right to erasure is not applied in scientific or historic research purposes in so far as the right to erasure is likely to render impossible or seriously impair the achievement of the objectives of that processing.  The realisation of the right to erasure is assessed on a case-by-case basis.The data subject has the right to lodge a complaint with the supervisory authority.

9. Information on the existence of automatic decision-making, including profiling:

The data will not be used for automatic decision-making or profiling.