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A Delphi Study on Technical and Socio-Economic Perspectives of Nanotechnology and ICT Industries Relations

Vinodh Rida Arumugam [1], Boon-Kwee Ng [1,*] and Kavintheran Thambiratnam [2,3]

1 Department of Science and Technology Studies, Faculty of Science, Universiti Malaya, Kuala Lumpur 50603, Malaysia
2 IIUM Photonics and Quantum Research Centre (iPQC), Kulliyyah of Science, International Islamic University of Malaysia, Bandar Indera Mahkota, Kuantan 25200, Pahang, Malaysia
3 Department of Physics, Kulliyyah of Science, International Islamic University of Malaysia, Bandar Indera Mahkota, Kuantan 25200, Pahang, Malaysia
* Correspondence: bkng@um.edu.my

Abstract: By using the Delphi technique and a case study on Malaysia's nanotechnology research and Information and Communication Technology (ICT) industries, this paper aims to determine the development and convergence of nanotechnology and ICT innovation systems from the perspective of science-industry relations. A total of 25 experts have provided their opinions and consensus on the present stage and possible future scenarios of nanotech-ICT development from four dimensions: technology landscape, economic viability, governance, and social acceptance. Results from two survey rounds indicate that the Malaysian ICT innovation system is presently economically viable and easily accepted by the market. The best-case scenario can be achieved with the help of nanotechnology. This would also require the implementation of policies and regulations from government. Although industrial and social adoption and the acceptance of nanotechnology are already strong, government is responsible for creating various programs to ensure greater awareness and development of knowledge.

Keywords: technology foresight; ICT innovation systems; nanotechnology; science-industry interaction; Malaysia

Citation: Arumugam, V.R.; Ng, B.-K.; Thambiratnam, K. A Delphi Study on Technical and Socio-Economic Perspectives of Nanotechnology and ICT Industries Relations. *Systems* **2023**, *11*, 190. https://doi.org/10.3390/systems11040190

Academic Editors: Wendong Yang, Jinpei Liu and Jianzhou Wang

Received: 3 March 2023
Revised: 27 March 2023
Accepted: 6 April 2023
Published: 8 April 2023

1. Introduction

Nanotechnology is a paradigm-leading technology primed to radically change and transform the economy and society [1,2]. As for industrial development, nanotechnology brings industry to a threshold of a revolution regarding how materials and products are created [3]. Indeed, nanotechnology's rapid advancement and development have opened new avenues for real-world applications due to its colossal potential. The key reason for this is its multidisciplinary nature and the unique property of being an enabler for numerous other branches of emerging technologies, including Information and Communication Technology (ICT). However, as with any emerging technology, proper planning, assistance and cautious strategic management and administration of nanotechnology are required both at national and sectoral levels to ensure the development of its technological capabilities and market and social acceptance, which are key elements of determining the success of a technology [4]. In the realm of industrial technology development and policy, a systemic approach is extensively used for understanding the technological capabilities of nanotechnology (and nanoscience) and ICT-related industries (including semiconductors). The interaction between nanotechnology and ICT industries resulted in increased social connectivity and a transformation of ICT industries, particularly in the application of artificial and virtual reality, quantum computing, smart sensing, communications, data storage, and display and graphene. Overall, nanotechnology enables ICT industries to venture into the next generation of integrated circuits [5,6]. The spill-over effects of nanotechnology in ICT convergence are evidenced in the increasing degree of digitisation [3].

Based on this background, this study examines the convergence of nanotechnology and ICT innovation systems through the lens of science-industry relations. Based on the concept of socio-technical systems and insights derived from a case study on Malaysia's nanotechnology in ICT-related industries, this study is guided by these main research questions: (a) what is the extent of the current technology landscape, which encompasses the economic viability, adaptation and market acceptance of nanotechnology products and services?; (b) what are the possible future scenarios for applications of nanotechnology in ICT industries in developing nations? It is timely for a foresight study to explore these research questions particularly in the context of nanotechnology as it has the potential to revolutionise sectoral and industrial development and developing countries such as Malaysia can seize opportunities to utilise nanotechnology as a main driver for technological and economic development. Moreover, policymakers can anticipate and prepare for these challenges.

In an academic context, this study extends the discourses on the convergence of the nanotechnology-ICT paradigm in four dimensions: technological landscape, economic viability, governance, and societal acceptance; and advances our understanding regarding the concept of total societal enterprise of emerging technologies—a holistic and interconnected system that is deeply embedded in society. In a practical context, the findings from this Delphi study as well as the possible scenarios developed that bring together different actors from different disciplines (industry, academia, government) will provide policy insights for policymakers and industrialists. Overall, this study responds to calls from the preceding literature on the critical need to provide empirical evidence for understanding the progress of emerging technologies that are ambiguous in nature and which are extremely difficult to manage [7], as well as the critical requirement to position the discourses on emerging technologies from the perspective of socio-technical systems and technology foresight [8].

2. Conceptual Basis

2.1. Sectoral Innovation: Systemic and Socio-Technical Context

Science-based sectors such as chemical and electronic/electrical are mainly driven by rapid research and development (R&D) of the underlying science in universities and research institutions [9]. In this respect, the concept of Sectoral Innovation Systems postulates that the process of technological learning, development and catching up is specific and differs across sectoral boundaries. The sectoral dynamics and transformation are determined by three building blocks: actors, knowledge base and institutions [10,11]. Progress in a sectoral system is a collective result of the synergy exchanges and co-evolution of these various elements [8], which are widely mapped and explored by scholars in understanding the evolution of industrial technology change [12,13]. In science and technology (S&T) based programmes, R&D actors (e.g., universities and public research agencies) undertake basic and applied research, as well as capacity-building in human capital. Start-ups from universities and public laboratories are the major source of new technological opportunities. Similarly, active government policies facilitate direct interventions, including R&D programmes, public research organisations and support for research, and training and public procurement [10].

Innovation scholars highlight sectoral innovation as the interaction among a wide variety of actors for the creation and dissemination of knowledge that takes place in the realm of industry structure and catch-up capabilities [10,14]. In this respect, S&T dissemination and adaptation of industry should also consider human values and public perception. Consequently, sectoral innovation should consider the socio-technical elements that stress the mutual interrelationship between humans and machines. This led to the concept of a socio-technical system that integrates an industry's technological and social elements [15], and emphasises the co-operative optimisation of socio-technical systems [16]. At the production level, the socio-technical regime has consistently demonstrated cultural concerns and societal disputes, labour organisation and supervision, and government laws [17,18]. Nonetheless, as most studies on the socio-technical regime of sectoral development are conceptual in basis, insights from empirical evidence on the policy and other practical elements of socio-technical systems, particularly in the context of future studies, are limited. This remains as a research gap to be bridged by current research on emerging science-based technological applications following the systemic approach in a socio-technical context.

2.2. Nanotechnology and ICT Innovation Systems Relations

As a radical generic technology, the commercial potential and benefits of nanotechnology to society are comparable to the electronics and computing revolutions [19,20]. In fact, investment in emerging technologies is considered an art but not a science. New approaches and mechanisms emerge to identify and evaluate emerging technologies [21]; thus, nanotechnology cannot be readily accommodated by past and present regulatory structures, educational systems or societal choices. The two challenges in governing emerging technologies, such as nanotechnology, include the lack of flexibility in decision-making and the swift changes in technology as the result of socio-political constraints [22].

With specific reference to the responsible R&D of nanotechnology, rational management of R&D and technological progress should engage multiple stakeholders in making decisions that balance the likely benefits and technological risks. It is argued that dealing with unanticipated repercussions requires an anticipatory approach, as well as collaboration with local, national and worldwide partners. The public should have faith that the government has taken the necessary precautions to protect the environment and human health during the dissemination and commercialisation of nanotechnology while allowing for the growth of new industries and technologies [5].

The ICT innovation system was introduced to reflect the smart media industry suggesting collaboration activities as key sources of innovation, apart from other tangible and intangible factors such as financial support, R&D, human resources and policy environment [23]. ICT advances have had detrimental impacts beyond industries, economies, traditional value chains and business models due to their distributive character, pervasiveness in society, rapid change, potential to boost productivity and ability to give workable solutions for social problems. ICT innovation systems must, therefore, be expanded to the societal level [24]. Various agents are involved in creating an efficient innovation system for ICT. Concerning industrial economic growth through ICT, the main agents engaged are the ICT industry (i.e., firms and associations), R&D performing institutions, incentive structures, availability of ICT human resources and supporting institutions. The ICT users in the domestic market evolved around local applications, local content, awareness, affordability and accessibility to ICT [25]. As the basis of science and business systems differ in terms of interpretation, decision-making processes, goals and means of communication, a variety of knowledge sources are required [26].

The main impact of interaction concerns the scientific performance of ICT industries as an emerging sector [24]. Compared to other disciplines, nanotechnology-related research is more likely due to the availability of new research instruments, and these researches are more applied-oriented as to where commercialisation is feasible. The availability of public funding, including large public investments, has had an impact on nanotechnology research [27]. Thus, a specific technology and sectoral foresight study on the potential of nanotechnology to capture the future is timely to complement the current literature on the responses to forthcoming trends in new technological paradigms from both a technological capabilities and a social acceptance perspective.

2.3. Nanotechnology and ICT-Related Industries in Malaysia

In Malaysia, molecular manipulation in the creation of nanomaterials, nanoelectronics and living systems are key fields of nanotechnology R&D [28]. Malaysia's nanotechnology R&D and its development agenda began in 2000 with the formation of a nanotechnology research group in the country followed by Malaysia joining Asia Nano Forum officially in

2004. The first comprehensive framework for nanotechnology in Malaysia was the National Nanotechnology Initiative (NNI), aimed at promoting nanotechnology as a key driver for the high-technology economy. Malaysia has since increased its participation in, and support for, nanotechnology. Among the key steps taken towards achieving this goal was the formation of NanoMalaysia Berhad, the primary objective of which is to commercialise nanotechnology activities throughout Malaysia through the Nanovation programme, the National Graphene Action Plan 2020, and the Advanced Materials Industrialization and NanoVerify programme. In general, NanoMalaysia Berhad serves a dual function, as a government agency to coordinate and guide nanotechnology R&D in the country, and as a business entity to commercialise nanotechnology outputs and activities. In terms of the focus areas of nanotechnology, four strategic sectors were identified: electronics devices and systems; food and agriculture; energy and environment; and wellness, medicine and healthcare.

Figure 1 illustrates the chronology and milestones of nanotechnology development in Malaysia and highlights several main achievements in the sector of nanotechnology ICT-related industries (mainly the electronics devices and systems sector). Since 2010, extensive investments in the form of R&D grants have been made available by the Malaysian government to support both public and private sectors of nanotechnology R&D and commercialisation. In 2015–2020, SilTerra Malaysia, a Malaysian semiconductor wafer fabrication factory owned by Khazanah Nasional Berhad, which is the investment arm of the Malaysian government, received MYR 40 million from the Domestic Investment Strategic Fund from the Malaysian Investment Development Authority (MIDA) for the commercialisation of nanotech products. These investments contributed to an approximate 6% increase in SilTerra's annual revenue, i.e., from MYR 24 million to MYR 36 million per year. Meanwhile, Malaysian Institute of Microelectronic Systems (MIMOS) has been awarded four commercialisation programmes amounting to MYR 143.86 million. The collaboration between MIMOS and NanoMalaysia Berhad (NMB) focuses on the commercialisation of the nanoelectronics market, especially those based on graphene, which will improve the electrical and electronics (E&E) industry in terms of high-complexity products and the creation of high-value jobs through the National Graphene Action Plan 2020 [29].

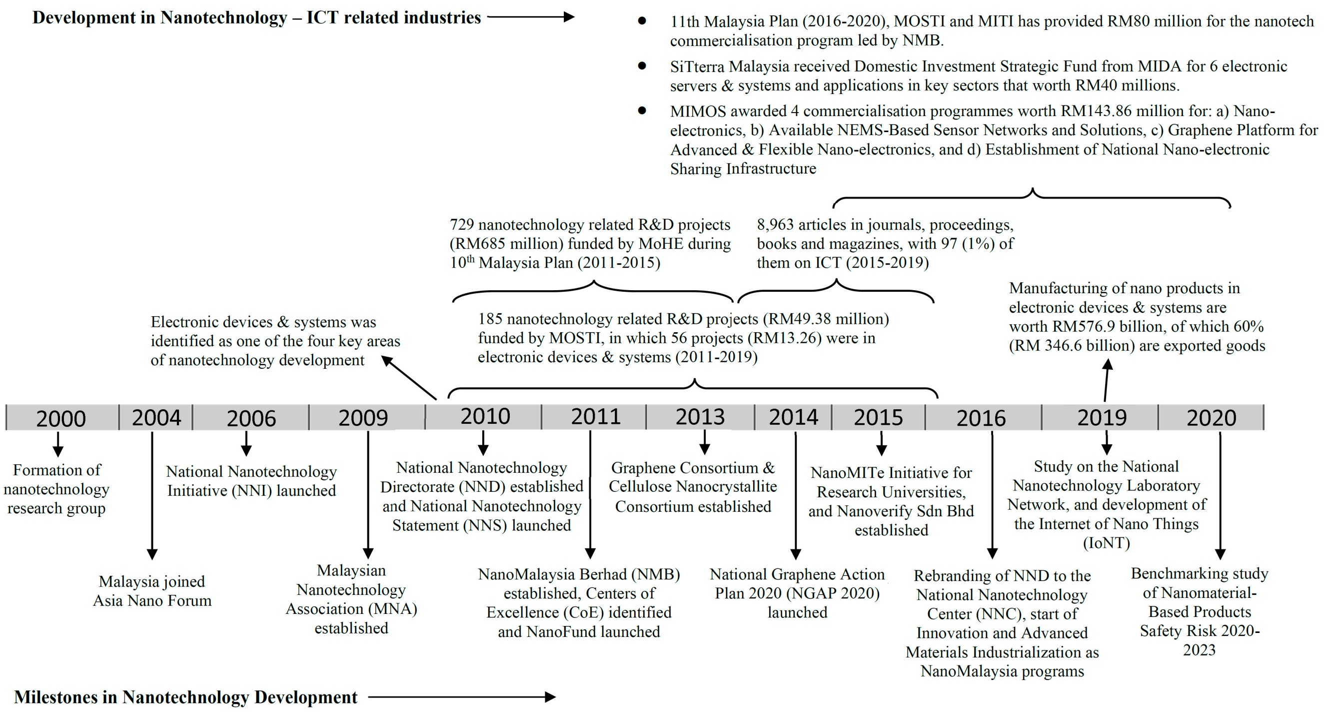

Figure 1. Development of Nanotechnology Research—ICT Related Industries in Malaysia. Source: Data extracted from National Graphene Action Plan 2020; NanoMalaysia Strategic Report 2019.

The ICT industry of Malaysia is a part of Malaysia's electronics and electrical (E&E) industry. The E&E sector has been growing steadily since the 1970s. After initially focusing on simple products and components, the sector grew steadily and moved up the value chain, from the assembly of full consumer electronics to design and R&D, integrated circuit (IC) design, wafer fabrication, ingot growing and digital consumer goods. This essentially marked a shift from high-volume, low-complexity products to low-volume, high-complexity products. By 2019, Malaysia accounted for 8% of global back-end semiconductor output and contributed RM 372.67 to the total exports of Malaysia, amounting to 44.7% of all manufactured goods exported. It also accounted for a remarkable 6.3% of Malaysia's GDP in 2019, and the industry has created nearly 560,000 jobs nationwide [30]. Nanotechnology plays an important role in the E&E sector, not just as a part of the finalised product, but also as an enabler for many of the processes that take place in the E&E industry.

Based on a study conducted in 2017 on the Klang Valley in Malaysia, the Malay ethnic group, which has a distinct protected status under the Federal Constitution, enjoys greater security when it comes to the advancement of emerging technologies such as nanotechnology. Individuals with greater education levels tend to have more trust in the capacity of both researchers and the government to protect the public from the potential risks linked to nanotechnology. Consequently, they perceive more potential benefits from investing in this area. Despite this, it appears that Malaysians have a limited understanding of nanotechnology and are not informed about the fact that different government organisations are working together to regulate the risks associated with nanotechnology [31]. Interestingly, a separate study that looked at nanotechnology among engineering students indicated that students were not aware of the significance of their societal and environmental responsibilities due to the absence of socio-ethical aspects in their engineering syllabus [32].

In the telecommunications sector, Malaysia has achieved a certain degree of success in establishing virtuous cycle diffusion pathways, wherein the government aids in the distribution of profitable returns to entrepreneurs and sets up competitive frameworks for them to progress in their endeavours [33]. However, in a case study on pure-play ICT foundries, as slow path-followers Malaysia's latecomer fabs have not been able to catch up effectively. For instance, Malaysia's Silterra has not managed to deploy the linkage, leveraging and learning approach in its catch-up process. Even MIMOS has contributed to developing industrial structures, shifting value systems, and catch-up strategies across many aspects of the industry [34]. Additionally, although Malaysia has benefited from a structure that encourages technology market push to pull dynamics in the development of Internet of Things (IoT) technical capabilities, there are still gaps that must be addressed, notably those related to data security [35].

However, studies on nanotechnology and ICT-related industries in Malaysia are mostly from the perspective of economics such as technological catch-up, market penetrations and R&D investments which are not able to capture the overall sectoral and socio-technical systems of industrial development. In this context, the PEST framework adapted in this study provides a socio-economic-technical hybrid model for understanding nanotechnology development which is indeed a novelty, and which is able to contribute to a holistic account of the socio-economic perspectives of nanotechnology and ICT industries relations. This study offers expert insights on how ICT spearheaded Malaysia's development with assistance and advancements in nanotechnology, in contrast to the majority of studies' attempts to link ICT (as innovation-knowledge) to National Innovation Systems in specific national economies [25].

2.4. Research Framework

The research framework of this paper utilised the systemic approach on environmental scanning inspired by the four building blocks of PEST (Political-Economic-Social-Technological) [36]. As shown in Figure 2, these four building blocks are correlated with each building block. The feasibility of nanotechnology in ICT from a technology point of view would undoubtedly be the crucial consideration. Meanwhile, its economic, regulatory, and social feasibility would be important in seeing the realisation of nanotechnology in ICT industries. These factors range from the cost of manufacturing, regulations governing its usage and impact, and overall social acceptance of the product. The following notes provide a brief account of each of these building blocks:

- Technology landscape–Available and assessable to the types and forms of new technologies. It busts the myth of what an imaginary technology would look like and sets proper expectations. Technology trajectory in one field could lead to benefits in another field, i.e., in a multi-disciplinary setting.
- Economic viability—The emerging technology should be affordable to manufacture and cheap enough for the public to obtain. This includes a sustainable manufacturing process. The main beneficiaries include all levels of stakeholders, from the government to the manufacturers and consumers.
- Social and ethical—Safety and ethical issues of technology should be the main concern in the use and dissemination of technological know-how in society. The stakeholders refrain from involving the manufacturers and consumers but focus on non-governmental organisations (NGOs) who champion various ethical causes and the government. Educators are also brought in as stakeholders, in preparation to disseminate information and awareness to the public.
- Appropriate governance—The current and draft policies in place are re-examined and new appropriate ones are recommended, as well as the implementation of policies for wide-sweeping changes in the associated technology. This will be a very diverse decision-making effort and will have different levels of impacts from regional to national, and possibly even down to the state and council levels.

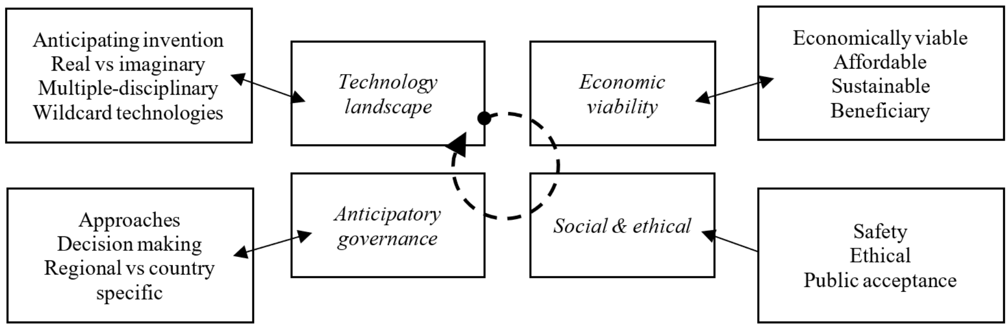

Figure 2. Research framework.

3. Methods

Figure 3 illustrates the Delphi survey process employed in this study. Detailed explanations on each step are provided in the following subsections.

3.1. Research Design

Foresight is widely used in shaping the future through the rigorous actions of self-sustaining networks of stakeholders. Future studies are a method for predicting the likely and foreseeable future, which enables preparations to be made [37]. It is a qualitative approach to organising a group iterative communication process among people (often specialists) to solve a challenging issue [38] that incorporates anonymity of participation, survey and statistical analysis in the framing of possible future scenarios [39]. Foresight activities conducted at a comprehensive level are implemented to encompass the complete array of science and technology. These efforts can take various forms at macro-, meso- and micro-level foresight [40]. As for this study, we adopt the meso-level analysis on the prospect of nanotechnology adaptation in the ICT industry. The Delphi method used here is an iterative process used to form a group consensus or opinion (or group response) by surveying a panel of experts, which is the unit of analysis to establish a holistic account of the study subject. In other words, it makes use of individuals (or experts) who possess knowledge of the topic being investigated [41].

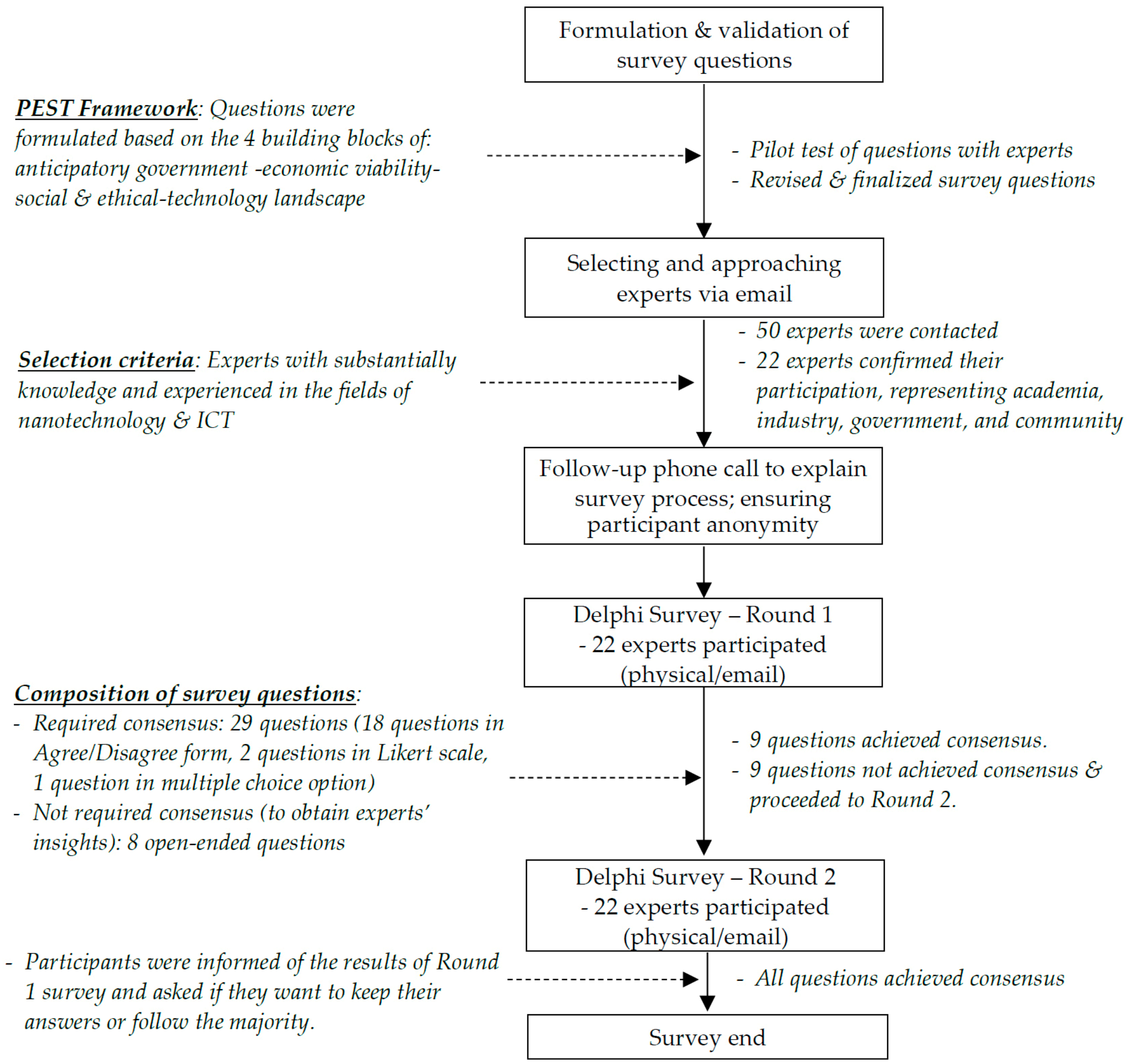

Figure 3. Delphi process.

3.2. Identification and Selection of Experts

Although Delphi surveys with panels of experts have been widely utilised in foresight, there is still a lack of agreement concerning the expert panel's sample size to ensure the stability of results, and the number of panellists can range from 10–100 based on situation-specific requirements [42,43]. Most Delphi studies incorporate between eight and sixteen experts, subject to the study's characteristics, such as available experts, geographic representation and resources of the research team [44]. An important guiding principle in the Delphi method is that the expert panel does not need to be a statistically representative sample, but rather, the quality of the experts is the concern [45–47]. In fact, the Delphi method offers the flexibility of using a small or large sample to generate reliable conclusions [47,48]. Experts are selected to apply their knowledge, and thus the sample of experts is selected with nonprobability sampling techniques [41].

In this study, once the participants had agreed to participate in the survey, a follow-up phone call was arranged. During this process, a detailed overview of the survey was provided in terms of how the survey outcomes would be used as policy recommendations for the study. A total of 50 potential experts were approached in the process of the recruitment of survey participants. They were briefed on the survey process and the potential need for more rounds of surveys to establish a consensus of views. They were selected based on qualifications to apply their knowledge and experience [41,42,45]. The participants selected for this study were experts and defined as individuals who were substantially knowledgeable and experienced in the fields of nanotechnology and ICT. It must be noted that individually, expertise and knowledge in nanotechnology and ICT are significantly easy to acquire; i.e., there are many experts of each in field. However, identifying knowledgeable and experienced experts in ICT and nanotechnology was difficult since they had to possess a deep understanding and knowledge of ICT and nanotechnology and its cross-applications and linkages.

Furthermore, the experts were chosen from various areas that would be impacted by using nanotechnology in ICT. Therefore, they had to represent one or more aspects of the impacted groups, i.e., academia, industry, government, and communities. The academic group represents the technology block and encompasses the researchers and developers of nanotechnology in ICT applications. However, while this group is labelled as academic, it encompasses all technology developers, including researchers from the industry. As the bulk of developments hail from academia, this group is named as such. The industry group represents the economic building block, as their inputs determine the feasibility of the actual manufacturing and production of the nanotechnology-enabled ICT products and services. The government group represents the regulatory building block, and the inputs obtained from this group provide insight into regulations and policies that go into the development of nanotechnology-enhanced ICT goods and services, as well as any missing gaps that need to be addressed. Finally, the communities represent the social building block, and investigate the acceptance and awareness of nanotechnology-enabled ICT products and services among the general population and end users.

A total of 22 participants agreed to contribute to this study. Table 1 provides the list of participants, a brief background for each and the area they represent. Each participant can represent more than one area, as indicated in the table.

Table 1. Profiles of participants.

ID	Profile and Background	Representing/Knowledgeable in:			
		Academic	**Industry**	**Government**	**Community**
1	Researcher in nanophotonic with a physics background	√	√	√	
2	Researcher in telecommunications with an engineering background	√	√		√
3	Background in ICT and nanotechnology, currently retired.		√		√
4	Researcher in telecommunications with knowledge in nanotechnology	√	√		
5	Researcher in nanotechnology	√	√	√	
6	Researcher in telecommunications with knowledge in nanotechnology	√	√		
7	Researcher in telecommunications with knowledge in nanotechnology	√	√		
8	Employed in telecommunications with nanotechnology background		√		√
9	Policy maker and consultant with physics background		√	√	√
10	Employed in education, specialising in ICT with nanotech experience	√		√	√
11	Employed in aviation, specialising in ICT with nanotech experience		√	√	√
12	Researcher in economics with nanotech and ICT background	√	√	√	√
13	Expert in waste-management in a nanotech firm		√	√	√
14	Researcher in economics with nanotech and ICT background	√	√	√	√
15	Researcher in waste-management with nanotech and ICT background	√	√	√	√
16	Advisor on clean and sustainable energy with nanotech background	√	√	√	√
17	Advisor on telecommunications with nanotech background	√	√	√	√
18	Researcher in technology management with nanotech specialisation	√	√	√	
19	Researcher in technology management with nanotech specialisation	√	√	√	
20	Marketing expert, focusing on nanotech and ICT		√		√
21	Marketing expert, focusing on nanotech and ICT		√		√
22	Marketing expert, focusing on nanotech and ICT		√		√

3.3. Survey Instruments

Twenty-nine questions have been developed and used to gain the experts' views on the present and future development of nanotechnology. Twenty-one questions were designed such that agreement must be reached throughout the Delphi survey, whereas eight were intended to gather specific insights from the participants and were not aimed to form consensus. These survey questions were validated and revised after consulting two experts in the ICT and nanotechnology industry to ensure these questions are easy to understand

and capture the specific information which they attempt to capture. Table 2 provides the survey questions. Eighteen questions were in the dichotomy format that required the participants to indicate agree/disagree (or Yes/No) on a given statement. There was one multiple choice question. Two questions were in Likert-scale format to indicate their level of agreement on a scale. Additionally, there were eight open-ended questions that were used to obtain participants' insights such as providing specific examples, factors and issues. Unlike the other questions, these open-ended questions were not aimed to establish consensus and they were only asked in the first round of the survey. As the Delphi survey focuses on eliciting experts' opinions over a short period of time [43], the survey questions used in this survey required the experts to provide their views based on their foresight on the forthcoming 5 years. This is also aligned with the rapid development of nanotechnology and ICT industries.

Table 2. Delphi survey questions.

Building Block & Elements	**Questions**
	1. Technology landscape
1.1 Anticipating new technology	Would you agree that new nanotechnologies and their applications are constantly being discovered? Would nanotechnology be useful in the development of faster and more powerful technologies and systems in ICT? Could you give examples of nanotechnology in ICT? *
1.2 Real vs Imaginary	Do you think that the image of nanotechnology has been accurately portrayed in current movies and media? Do you believe that the enhancements depicted in movies for ICT (e.g., holography and quantum computing) could be made possible by nanotechnology?
1.3 Multiple/inter-discipline	Are you aware that nanotechnologies and their applications are cross-disciplinary? Specific examples of nanotechnology that enable the cross-discipline applications in ICT? *
1.4 Wildcard technologies	What do you think are the chances of wildcard nanotechnology or application? Specific examples of wildcard nanotechnology in ICT? *
	2. Economic
2.1 Economically viable	Would nanotechnology and its applications be an economically viable tool? Would the applications of nanotechnology increase output and productivity?
2.2 Affordability	Would nanotechnology applications produce a cheaper and affordable product in the market? If yes, how cheaper can we expect?
2.3 Sustainability	Would the use of nanotechnology be sustainable? As nanotechnology can increase production significantly, would this mean that natural resources are being drained faster? If yes, what would be the rate of consumption?
2.4 Benefits to stakeholders	Rank from highest to lowest, the economic beneficiaries of nanotechnology, with the beneficiaries being the Government, Consumers, Industry, and Research/Universities in ICT. *
	3. Social and ethical
3.1 Safety	Would you agree that nanotechnology is safe? Would the use of nanotechnology pose a potential safety problem in the future? Specific examples of potential safety problems in ICT? * Would you agree that nanotechnology is not harmful to the human body? Would you agree that nanotechnology could not have a negative effect on the environment?
3.2 Ethic	Would you agree that the use of nanotechnology presents a potential ethical issue? Specific ethical issues you foresee with the use of nanotechnology in ICT? *
3.3 Assessment of Stakeholders	Rank from highest to lowest who would be responsible for ensuring the safety and ethical use of nanotechnologies and their applications in ICT, these being NGOs, the Government, Educators, Industry, Media, and Public. *
	4. Anticipatory governance
4.1 General	Are you aware of the current policies and regulations for the use of nanotechnology? Should these policies encompass just the country or have a regional/international reach as well? How do you rate the efficiency of the implementation of the above-mentioned policies? How do you rate the efficiency of the government in making various parties aware of these policies? What are the factors that promote or hinder the implementation of these policies? *

Note: Asterisk (*) indicates that the question is not intended to obtain consensus and is only asked in the first round of the Delphi survey.

3.4. Data Collection and Analysis

The survey was emailed to each expert. All information was confidential, and each participant was provided with an ID number to prevent the disclosure of personal information from preventing a biased response to the survey. During the first round of the Delphi survey in May 2019, questionnaires were distributed to the experts to obtain their views on the issues. For the twenty-one questions that required the establishment of consensus among the 22 participants, the percentage of participants who agreed/disagreed on a survey statement was calculated manually based on the returned questionnaire. In this study, the level of consensus value was fixed at 75%. In other words, the survey reached a consensus on all questions with a consensus value of 75%. It is important to note that Delphi studies do not have a fixed percentage for consensus. Nonetheless, most studies have indicated that a high enough score falls between 70% and 80% [49–52].

A total of nine questions did not successfully achieve consensus during the first round of the survey. These questions were repeated during the second round of the survey in January 2020. In the second round of the survey, the experts were informed of the overall results and their answers in the first round. The experts were also asked if they would like to join the majority or keep their initial answers. In the first round of the survey, a total of 22 experts participated, all of whom also participated in the second round. After collecting response data and based on the key indicators, the various possible scenarios were framed. As for the eight open-ended questions which were not required for the forming of consensus, the answers and insights provided by the experts were used to support the framing of the scenario.

4. Results

4.1. Technology Landscape

From the Delphi survey, we seek to determine how well participants understand nanotechnology in terms of its uses and how it can be related to other technologies and applications. A total of 96% of the experts agreed that new nanotechnologies and their applications are continually being developed and this signifies an emerging trend that features rapid R&D and shorter product life-cycles. As evidence, these experts quoted specific examples of nanotechnology applications in ICT, namely computer chips and sensors, wireless sensors, fibre optic nanowires, batteries, molecular computers, etc.

Nanotechnology is vital for creating new technologies, systems and services that would increase the capabilities of ICT and this view was supported by 91% of the experts. Interestingly, there was widespread disagreement (95% consensus) among the experts over the portrayal of nanotechnology in current media. However, there was a high degree of agreement (95% consensus) that advanced features of holography and quantum computing which are portrayed in the movies could be made possible by nanotechnology. Moreover, the experts also overwhelmingly agreed that nanotechnology eases cross-disciplinary applications and that there is a good chance for the creation of unconventional wildcard nanotechnology or applications. According to the experts, such cross-disciplinary applications of nanotechnology in ICT can be witnessed in, for instance: resonant tunnel elements in logical circuits, quantum computing; power systems, chip sets, solar technology, fibre laser and fibre sensor. On the other hand, examples of wildcard technologies are machine intelligence, fragrance and mobile electronic devices.

4.2. Economic Viability

The output of this pillar of the survey determines how well the participants are informed on the economic benefits and costs of nanotechnology. Out of the six survey questions, two questions were unable to achieve a consensus in the first round of the survey and had to proceed to the second round of the survey. In terms of increasing output and productivity, 91% of the experts believe that nanotechnology and its applications are beneficial for promoting and increasing output and productivity. Meanwhile, 96% of them stated that nanotechnology applications result in products that are more affordable and cheaper in the market, with price reductions from 5% to 15%. All experts concurred that the use of nanotechnology is appropriate and does not result in a faster depletion of natural resources. Moreover, the experts were asked to rank the economic beneficiaries of nanotechnology. It was found that the majority of the respondents believed that industry, including research centres and universities, as well as consumers, would receive the greatest benefits. Interestingly, government was ranked as the lowest beneficiary compared to other groups.

4.3. Social and Ethical

In relation to other pillars, consensus for questions on social and ethical issues was more difficult to reach amongst the experts. Out of the five questions, four of them required the second round of the survey to form a majority agreement. The experts agreed that nanotechnology is considered safe (87% consensus). Nonetheless, it may also potentially contribute to safety threats such as bio-application, privacy, labour, health, radiation, etc.

Nanotechnology is still considered to be safe for the human body at the moment (91% consensus). There was general agreement among the experts (82% consensus) that the advancement of nanotechnology may have a detrimental effect on the environment. Furthermore, the experts (77% consensus) stated that nanotechnology may present potential ethical issues such as privacy rights, risk aversion, workers' medical, etc. A rating of the applications of nanotechnology in terms of its safety and ethical use was also requested from the experts. Generally, the experts believed that all stakeholders would be crucial in ensuring the ethical and safe use of nanotechnology. Though, some experts thought that some stakeholders such as NGOs, media, the general public, and research institutions play a smaller contribution in this specific issue.

4.4. Anticipatory Governance

A total of 86% of the experts were alert to the current nanotechnology-related policies and regulations. They thought that these policies and regulations should be framed and coordinated in a more global setting. Overall, the experts concurred that it is the government's responsibility to inform all stakeholders of nanotechnology policies and regulations. The experts also proposed that factors to encourage or impede the execution of policies are popular understanding, awareness and education. The insights from the two-round Delphi survey are shown in Table 3. Based on data and information captured from the Delphi survey, the trends and problems related to the growth of nanotechnology in Malaysia's ICT industries in accordance with the four pillars of the study are shown in Figure 4.

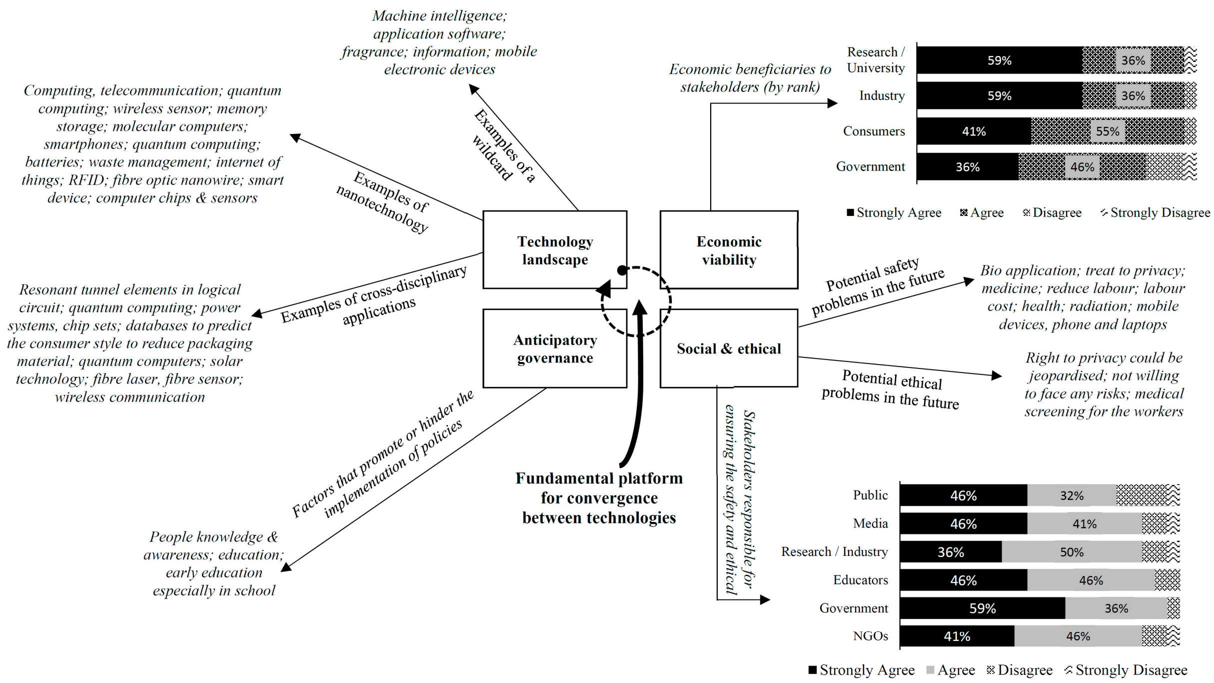

Figure 4. Trends and concerns on nanotechnology—ICT industries relations.

Table 3. Results of Delphi survey.

Building Block	Statements	% of Consensus
	1. Technology landscape	
1.1 Anticipating new technology	New nanotechnologies are constantly being discovered.	Agree (96%)
	Nanotechnology is useful in producing faster and more powerful ICT.	Agree (91%)
1.2 Real vs imaginary	The image of nanotechnology is accurately portrayed in current movies/media.	Disagree (95%) *
	Enhancements depicted in movies could be made possible by nanotechnology.	Agree (96%)
1.3 Multi-disciplinary	Nanotechnology enables cross-discipline applications.	Agree (91%)
1.4 Wildcard	There are chances of wildcard nanotechnology or application.	Agree (91%) *
	2. Economic viability	
2.1 Economically viable	Nanotechnology and its applications are economically viable.	Agree (91%)
	Nanotechnology helps increase output and productivity.	Agree (96%)
2.2 Affordability	Nanotechnology produces cheaper and affordable products in the market.	Agree (96%) *
	If yes, the range of price reduces.	5—15% (77%)
2.3 Sustainability	Nanotechnology is sustainable.	Agree (100%) *
	If yes, the rate of consumption.	5—10% (82%)
	3. Social and ethical	
3.1 Safety	Nanotechnology is safe.	Agree (87%)
	Nanotechnology poses a potential problem in the future.	Agree (87%) *
	Nanotechnology is not harmful to the human body.	Agree (91%) *
	Nanotechnology could not have a negative effect on the environment.	Disagree (82%) *
3.2 Ethics	Nanotechnology presents a potential ethical issue.	Agree (77%) *
	4. Anticipatory governance	
4.1 General	I am aware of the current policies and regulations for nanotechnology.	Agree (86%) *
	The level of coverage of the policies (national, regional, or international).	International (81%)
	I am strongly disagreeing that the implementation of the policies is inefficient.	Disagree (91%)
	I am strongly disagreeing that the government is inefficient in making various parties aware of these policies.	Disagree (91%)

Asterisk (*) indicates the consensus established in the second round of the survey. Otherwise, the consensus was established in the first round of the survey.

5. Discussion

5.1. Insights from Delphi Survey

Similar to other technological drivers, nanotechnology serves as a foundational platform that spans across numerous existing scientific and technoscientific domains [3]. The experts' opinions gained from this study provide an in-depth understanding of such a fundamental platform resulting from the convergence of nanotechnology-ICT industries.

Since the experts in this study are informed about nanotechnology, it may be assumed that most of these experts possess this same understanding. School education and informal exposures (such as books and the media) would surely be the source of this awareness and understanding. However, it was fairly unexpected that over half of the participants did not distinguish between nanotechnology that can be realised and fictitious or even pseudo-technologies. It is exciting to see that most experts thought that some fictional features (e.g., holography and quantum computing) might eventually come to exist. This suggests that they have a thorough understanding of nanotechnology and are mindful of potential upcoming nanotechnology applications. However, it may be assumed that this information would derive from unofficial sources because it would be too sophisticated to be covered in the school or university curriculum at this time. This shows that the public is interested in nanotechnology and supports its usage as a potential tool to enhance current technologies. They likely understand nanotechnology better as a tool for facilitating cross-disciplinary utilisation than as a multidisciplinary technology in and of itself. This would raise awareness of nanotechnology and the need for a deeper understanding of its uses among the general population. This is consistent with the notion of science-industry knowledge transfer, frequently characterised as unidirectional and interactive relations that necessitates the use of co-creation platforms in the dissemination of information [53]. Furthermore, both formal and informal channels of education, training and information should be made available to educate the public on the true potential of nanotechnology (or any emerging technologies).

According to the literature, the interaction between science and industry involves a minimum of three socio-technical systems: business, science, and policy; each with its own modes of objectives, interpretation, decision-making rules, and communication standards [26]. This phenomenon is observable through empirical evidence in this case study. We noticed that all experts concurred that an increase in output and productivity would be nanotechnology's primary contribution to economic viability. It utilises the advantages of nanotechnology in which nanotechnology has several distinctive qualities that can accelerate production and increase its effectiveness. One of the main applications of nanotechnology, for instance, is to catalyse the production of diverse materials. This demonstrates how the economic viability of many sectors, such as the electronics and ICT industries, may be considerably increased by nanotechnology. Unexpectedly, during the first round of the study, not every respondent thought that nanotechnology would lead to cheaper and more economical items. Further conversations with the experts revealed that although the most recent technologies, notably electronics, promise to include certain aspects of nanotechnology into its conception or manufacture, this rarely leads to lower costs. Most of the time, adding nanotechnology to gadgets adds value to them rather than lowering their costs; therefore, the prices of these products stay the same. Overall, this supports a previous hypothesis of the ICT paradigm in which various critical resources such as information, knowledge, skills and finance will become increasingly important in new technology development [54], and not only on the cost factor per se.

Most of the participants acknowledged that the government would reap benefits from the emergence of nanotechnologies. It is important to note that the government may not be the direct beneficiary. Nonetheless, the government is perceived to accumulate the outcomes from the increased economic productivity and quality resulting from nanotechnology investments. Additionally, as customers utilise the majority of the items created employing nanotechnology, as indicated by respondents, they would be the direct benefactors of this technology. On the other hand, industry appears to be the main beneficiary in two ways—nanotechnology as a production technology as well as a final product for market. Moreover, universities and research institutions have been identified as significant beneficiaries of nanotechnology. In general, it is reasonable to assert that the feedback to this survey recognises the advantages of nanotechnology and the individuals or groups it is aimed at benefiting.

Although most of the participants expressed agreement that nanotechnology is safe, a few disagreed. This difference in opinion was attributed mainly to the portrayal of nanotechnology in the media and a lack of expertise or knowledge to challenge this perspective. Consequently, it can be assumed that most participants hold a positive view of nanotechnology, but there is a need for significant effort to correct misconceptions. Meanwhile, more respondents expressed concern about potential issues that could arise with nanotechnology in the future, such as threats to privacy and radiation emission. This supports the concern that nanotechnology will fall under wild attack from consumers (including the industries) concerning its safety and credibility during its market diffusion phase [55]. Cost reduction was also raised. While it would benefit businesses and customers, it would not benefit workers who would experience staff cutbacks.

The experts reached a consensus that nanotechnology may raise ethical concerns. A more pertinent concern would be the adoption of nanotechnology in opposition to an individual's personal preferences, who would be required to utilise a product or service enhanced by nanotechnology even if they prefer not to. This presents a noteworthy ethical predicament that can only be resolved through policy intervention. Most of the participants strongly believed that the government should take responsibility for this, since all of the entities mentioned acknowledged that government entities have the legal and regulatory autonomy and mechanisms to safeguard the applications of nanotechnology. At the same time, members of the public and NGOs would play a part in disseminating this information and knowledge, while educators and the media would have a critical role in promoting awareness of the safe and ethical use of nanotechnology. Ultimately, researchers and industries would fulfil their responsibilities by establishing appropriate protocols and technologies to ensure its secure application.

The government is responsible for ensuring that all interested parties are informed about these policies and regulations. Most experts agreed that developing and implementing rules would require a global perspective because nanotechnology goods and services would be imported into or exported to numerous nations all over the world. As a result, a standardised approach would be required for its execution, and this can be accomplished by globally accepted procedures.

5.2. Possible Scenarios

In this study, three possible situations were framed, which are hypothetical and relate to the utilisation of nanotechnology in the industrial sector, particularly in the ICT industry in Malaysia. These scenarios include an ideal situation, a scenario that is expected to continue without significant change and a scenario with the worst outcome. The technological preparedness, economic viability and social acceptability of each scenario were further discussed. These three potential outcomes are represented in Figure 5.

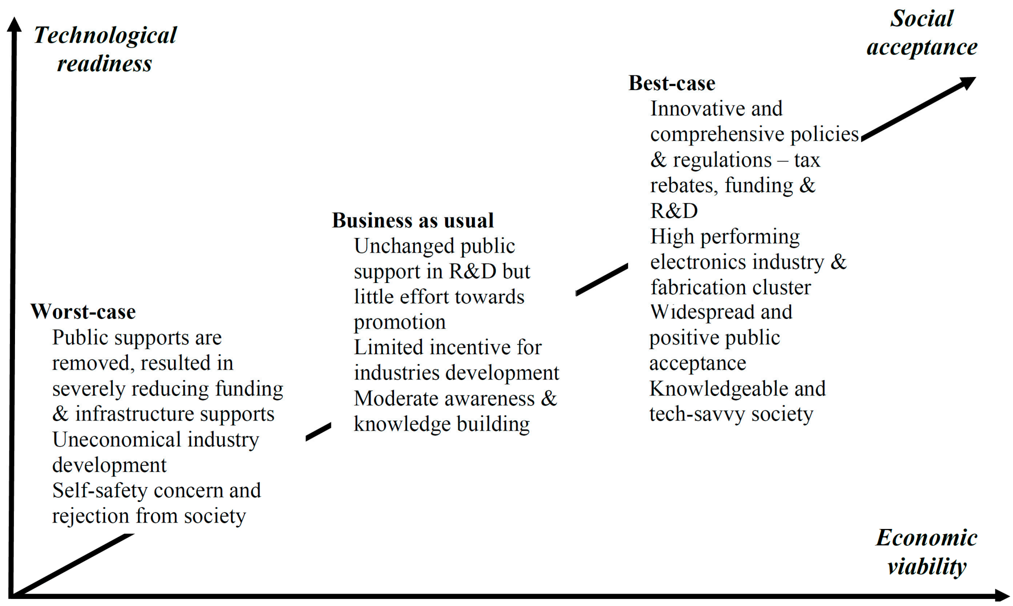

Figure 5. Hypothetical scenarios of nanotechnology in Malaysia ICT industries.

If the best-case scenario comes to realisation, Malaysia will be heavily involved in implementing nanotechnology in various industries related to ICT. Furthermore, it will have the necessary technological infrastructure to support these endeavours. In addition to offering incentives to the sector (i.e., tax incentives and grants), the government strongly encourages the use of nanotechnology and ICT through the formulation and implementation of comprehensive policies and regulations. The government also supports R&D centres in order to establish a substantial body of knowledge and increase the talent pool in nanotechnology. In terms of economy, Malaysia has regained its position as a market leader in the electronics industry, specifically in the specialised field of nanotechnology for ICT. The country is currently constructing manufacturing and fabrication businesses to strengthen its position in this area. To establish Malaysia as a regional manufacturing hub that attracts substantial international involvement, manufacturing and fabrication enterprises are being set up. Other supporting activities and platforms, such as design firms, material processing and maintenance services, are also being introduced to reinforce the manufacturing and fabrication cluster. Complementary sectors such as education and logistics sectors are also playing a vital role to enable Malaysia to gain regional dominance.

The general public acceptance of both nanotechnology and ICT is widespread and positive. They possess knowledge regarding the use of nanotechnology in ICT, and actively encourage its application. As a result of this widespread awareness, they possess an understanding of its safety and are less susceptible to outside biases or influences that could influence their opinion. This is the most desirable state in terms of technological progress, financial feasibility and social acceptability of nanotechnology in ICT.

In the second possible scenario—business-as-usual, we are expected to witness no improvement in public support. Current R&D agendas in nanotechnology and ICT are continuing but there is no high commitment shown to promote them. This is potentially leading to stagnation or even the reduce of R&D and researchers shift their focus to other country and research domains. Such an occurrence would hinder Malaysia's preparation for the utilisation of nanotechnology and ICT, as well as the development of local talents and skilled workers. Despite being able to establish a robust industry that incorporates both nanotechnology and ICT, the country would forfeit its potential to emerge as a leader within the region. These might be hampering factors that constraint Malaysia as part of regional supply chains to other regional hubs. As a result, there will be less of an incentive for the growth of numerous sectors involved directly or indirectly in the production and manufacture of ICT applications based on nanotechnology, thus decreasing Malaysia's economic viability. Eventually, this would result in a negative impact on R&D activities, perhaps affecting technical preparedness even further. Although the public acceptance of nanotechnology-based ICT products would continue relatively unchanged, there are minimal attempts made to raise awareness and expand knowledge. As a result, the public would be less informed about the safe and ethical application of nanotechnology. This would have an impact on future market acceptability of nanotechnology-based ICT goods, exacerbating the drop in industrial progress and economic viability. Due to the unrestricted usage of nanotechnology-based ICT goods, there could potentially be an increase in social issues such as ecological damage or privacy infringement. As a result, the business-as-usual scenario would see modest technological growth of nanotechnology in ICT, with low economic feasibility and modest public acceptance.

The worst-case scenario is featured with significant deficiencies in technological readiness, economic feasibility and social acceptance. This is the consequence of multiple shortfalls to the progress of nanotechnology in the country. In this context, public support would be restricted, and we witness a significant decrease of funding and infrastructure supports for nanotechnology R&D. This will lead to a major drop in technological preparedness, and thus hinder Malaysia from playing a critical function in R&D. This would make it impossible for Malaysia to establish a financially sustainable nanotechnology sector, particularly one that focuses on ICT. Therefore, Malaysia would lose its significant position in the region, and there would be no further advancements in this field in the country. Society would be deliberately misled about the use of nanotechnology in ICT, leading them to either accept nanotechnology-based ICT with little consideration for their safety or reject them entirely without taking their safety into account. Moreover, informal information sources, including the media, would significantly influence public acceptance of nanotechnology-enabled ICT thus leading to a biased perception and decision-making process. The ethical issues surrounding these products would also present a similar dilemma, with minimal attention paid to concerns such as ecological impacts and privacy or overreactions to ethical anxieties due to low awareness. In summary, the worst-case scenario involves a reversal of the technological progress of nanotechnology in ICT development.

6. Conclusions, Implications and Limitations

In this study, it is evident that Malaysia's present nanotechnology development is extensive and sturdy, with significant backing from the government in terms of infrastructure and policy supports. Malaysia's research base in nanotechnology and ICT is also strong, with universities and industries actively involved in nanotechnology research, particularly in nanomaterials. For instance, there is currently a strong research push for nanotechnology and ICT applications using 1-dimensional (1D) and 2-dimensional (2D) materials to enhance the performance of batteries and photonics applications. A key finding of this study shows that not only is the awareness of nanotechnology in ICT high in Malaysia, but so too is its level of acceptance by the public, including the industry. This provides contrasting evidence to the perception that it is too early for nano-oriented research to be applied in the private sector [27].

We found evidence to support the premise that the impact of nanotechnology occurs via its convergence with other emerging technologies including ICT [5]. We discovered that the market still shows high acceptance of nanotechnology-enhanced ICT products, despite there being no significant decrease in their prices for consumers and end-users. This is due to its perceived increase in performance at the same price. This indicates the present technological landscape of nanotechnology in Malaysia's ICT industries is both economically feasible and well-received by the market. While there would be significant acceptance and uptake of ICT products enhanced by nanotechnology, there would be little requirement for nanotechnology at the end user's level. In context, an end user would accept a graphene-enhanced battery but have little to no interest in purchasing graphene itself. As such, the industry would see significant economic benefits by including nanotechnology in its production process.

Beyond contributing to advancing the body of knowledge in the field of future socio-technical paradigms of emerging technologies in developing countries, the findings from this study have significant implications in policy and this can be observed through the specific case of Malaysia:

- Framing of new policy direction—The Government of Malaysia has long understood the importance and role of nanotechnology in the nation's development. Since the year 2000, the government has been actively promoting nanotechnology as a part of the manufacturing and development of Malaysia in the Eighth, Ninth and Eleventh Malaysia Plans as well as the Third Industrial Master Plan (IMP3). Nanotechnology served merely as a component of the overall development and was not the focus of any study in these plans. However, from 2014 onwards, that changed, beginning with the NGAP where nanotechnology began to play a more important role in the ICT sector. This has continued into other national-level policies, roadmaps and frameworks. However, most of these policies are set to end in 2030, which means that the development of new policies to guide development after this period must begin to take place soon. The findings of this work will therefore serve as a guide to the situation on the ground regarding nanotechnology and ICT, and which steps must be taken to achieve the desired best-case scenario as shown in Figure 3.
- Believe in possible best-case scenario—The industrial adoption of nanotechnology in the Malaysian ICT sector is also substantially strong and would be able to achieve the best-case scenario with proper support. This is because Malaysia already has a strong electronics manufacturing sector, including the supporting industry and services clusters; thus, the use of nanomaterials in ICT systems can be easily achieved. As mentioned in an earlier part of this report, in 2015 the Malaysian electronics and IT sector accounted for a market value of USD 256.3 billion and is expected to exceed USD 2 trillion by 2025. As such, there is no indication that the electronics industry, and ICT as a subset of this industry, would slow down at any time in the future. Furthermore, most of the existing industries in Malaysia involved in the manufacture of electronics products and devices have already utilised nanotechnology in the fabrication of their devices, and with proper support, they can also be easily encouraged to increase their activities. Support from the government such as tax incentives and the provision of financial support to the industry will promote the industrial adoption of nanomaterial technologies and applications in ICT systems. As discussed earlier in this section, the acceptance of nanotechnology in ICT in Malaysia is also high from a social standpoint; thus, at the current rate, the desired best-case scenario can be achieved. However, increased awareness and knowledge must be implemented. This task falls to the government's hands to increase such awareness

and knowledge of nanotechnology among the public, be it through formal education programs or informal education avenues.

- Sectoral strategic thrusts—The best-case scenario should be the destination. With regard to technical readiness, the government must exert significant pressure, putting laws and regulations into place before funding and infrastructure. A two-pronged strategy for policy development is vital to improve Malaysia's technological preparedness for nanotechnology advancement in the ICT industry. To create a solid knowledge basis and talent basis, the government must seek to boost financing and infrastructure for nanotechnology research. The development of Malaysia's ICT and nanotechnology industries should be supported by the implementation of policies that have been tailored to the sector. Nanotechnology-based ICT applications might be regarded as mature technology. The electronics industry has already embraced nanotechnology to a large extent, particularly in applications involving energy storage devices such as batteries and capacitors. However, the true benefit of nanotechnology is in the improvements in manufacturing processes for the parts and components used in a variety of improved ICT gadgets. From a technological perspective, nanotechnology is ready to apply in the ICT industry with government backing to increase its participation. This can be done by fostering the transition from lab research to prototype, testing and manufacture in the ICT industries, as well as increasing awareness of, and support for, pathways to cross the valley of death in nanotechnology research. In order to create equal access to these prototypes and testing platforms, the essence of co-creation between public research agencies and business entities can be fostered. Additionally, focused campaigns must be launched to educate and involve the public in matters relating to science plus nanotechnology's applications and their implications. To persuade society that nano-ICT devices can be used safely, standards and certification for these goods must be established. Simply put, public policies should support the creation of holistic value that combines economic, environmental, social and technological factors.

The potential of nanotechnology is nearly limitless, spanning a wide range of industries and technologies and serving as a catalyst for countless others. The ideal outcome for Malaysia's nanotechnology and ICT development would be achieved by staying on the current path, but with an increase in government support and public education. However, if there is a lack of effort, the nation may return to a business-as-usual scenario thus losing the progress made so far. The results of this study clearly demonstrate the level of readiness and acceptance from the viewpoint of the foundational elements of technology, economy, policy and social acceptance. Although Malaysia performs well in each of these areas, it cannot allow complacency to set in and cause it to lose its advantage. It is also an objective of this study that the data obtained here can be used as the starting point for other studies. This could range from more detailed studies into each of the building blocks that formed the basis of this study, to policy and market reviews that review and suggest revisions to policies so as to bring them up to speed with current technological and market progress. Finally, the findings from this study can also be used by researchers and the industry to gauge the requirements and expectations of the end user, and as such tailor research and production to meet these new demands.

This study is not without limitations. This study will confine its focus to nanotechnology and its applications in ICT due to its significant potential for advancing the ICT industry, notably in the realm of the Internet of Nano Things (IoNT). Future research should consider ways to explore other emerging technologies such as biotechnology and advanced robotics to make comparisons with progress and trends in socio-technical perspectives. As this Delphi is qualitative in nature, the results of a Delphi survey can be difficult to interpret. Thus, the interpretation of the results may be subjective and influenced by the biases of the researcher. It is suggested that future research should try to collect relevant socio-technical data to support the scenario-building process.

Author Contributions: Conceptualization, V.R.A., B.-K.N. and K.T.; Data curation, V.R.A. and K.T.; Formal analysis, V.R.A.; Methodology, V.R.A., B.-K.N. and K.T.; Project administration, V.R.A.; Supervision, B.-K.N. and K.T.; Validation, B.-K.N.; Visualization, B.-K.N.; Writing—original draft, V.R.A.; Writing—review and editing, B.-K.N. and K.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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