Developing a UK Standards Strategy for Graphene

2018

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Executive Summary

Overview

Graphene is a two-dimensional carbon based material with a molecular structure that results in a combination of unique properties such as high strength, thermal and electrical conductivity, flexibility and high surface area. Its superior performance against other existing advanced materials makes it attractive for a wide range of applications ranging from lightweight composites, functional coatings to energy harvesting and storage.

Innovation Landscape

- The diversity of graphene formulations and associated range of properties support a wide range of applications and current and future market opportunities, e.g. energy storage and conversion, composites, biomedical, environment and sensors.
- The UK is amongst the top 10 countries with the largest number of graphene-related scientific publications and patents in the world. China, US and South Korea are the top 3, with the UK ranking in 8th position.
- In Europe, the UK is ranked second in publishing graphene-related scientific work - behind Germany - but has submitted the highest number of collaborative projects involving graphene and funded by the European Commission.
- Within the UK, 300 graphene-related projects have received public funding, mainly from the Engineering and Physical Sciences Research Council (EPSRC) and Innovate UK, which have involved some 80 UK businesses.
- Graphene standards have been found to be in their early stages of development, with only one formally/internationally recognised graphene standard published so far - ISO/TS 80004-13:2017 Nanotechnologies -- Vocabulary -- Part 13: Graphene and related two-dimensional (2D) materials.
- The need for standards in the graphene industry is attracting a lot of interest as indicated by the number of standards work programmes currently under development.

Market and Industry

- The graphene market is expected to reach $1.6bn by 2025 at a high growth rate of 72.8%, driven by applications mainly targeted at the aerospace sector but with cascaded benefits in other sectors.
- The market is currently challenged by a number of factors, which include high cost and variable quality of graphene, a fragmented market, availability of substitute materials, unestablished supply chain and a lack of demonstrated applications.
- Today’s market offers mainly graphene formulations for research and development activities. However, companies are starting to focus on the development and commercialisation of graphene applications, albeit only a few graphene-based consumer products can be found in the market.
- The graphene supply chain includes graphene suppliers, advanced material developers,

component and device manufacturers. The UK market is dominated by graphene suppliers, which are established SMEs and start-ups.

- Lack of standards for graphene manufacturing, transportation, application and end of life is seen as a barrier to market acceptance of graphene and graphene-based products.

Research and findings

To explore the potential for standards in the commercialisation of graphene, the British Standards Institution (BSI) commissioned the Knowledge Transfer Network (KTN) to carry out a research project to determine the opportunities and challenges for graphene commercialisation and to identify how standards can play a key role in accelerating supply of graphene and graphene-based products into the market. The research was aimed at reviewing and determining gaps in current standards, identifying key areas where standards are needed and developing a standards roadmap.

The research has involved primary research, including extensive outreach through a community survey, and detailed fact finding secondary research. The community consultations were conducted with the help of a questionnaire specifically designed for the project. Overall, 129 detailed responses were received through online survey, interactive survey at workshops (69 respondents in 2 workshops) and one-to-one detailed interviews with senior business executives from 17 different companies. In total, around 60% of the survey respondents were UK businesses, 29% from universities and research organisations, and 11% from other organisations.

From the responses received, it is clear that the graphene industry is ready to embrace standards, as it seeks to create an environment of trust and to provide assurances and confidence to potential Original Equipment Manufacturers (OEMs) and end-users. The following key requirements have been identified:

- Standards are required in areas such as: definition, manufacturing, characterisation and application-specific properties of graphene.
- Health and safety standards are needed for graphene manufacturing and waste management.
- The development and application of standards is needed to increase user and investor confidence in the use of graphene in terms of benefits and safety, to promote openness of supply chains and to reduce cost through economies of scale.
- New standards should be highly promoted to speed up adoption by business to ensure high impact on the commercialisation of graphene.
- For greater impact to be realised, graphene standards should be implemented internationally in a timely manner.
- There is a need to increase the awareness of the existing standards applicable to graphene, such as the terminology standard (ISO/TS 80004-13).

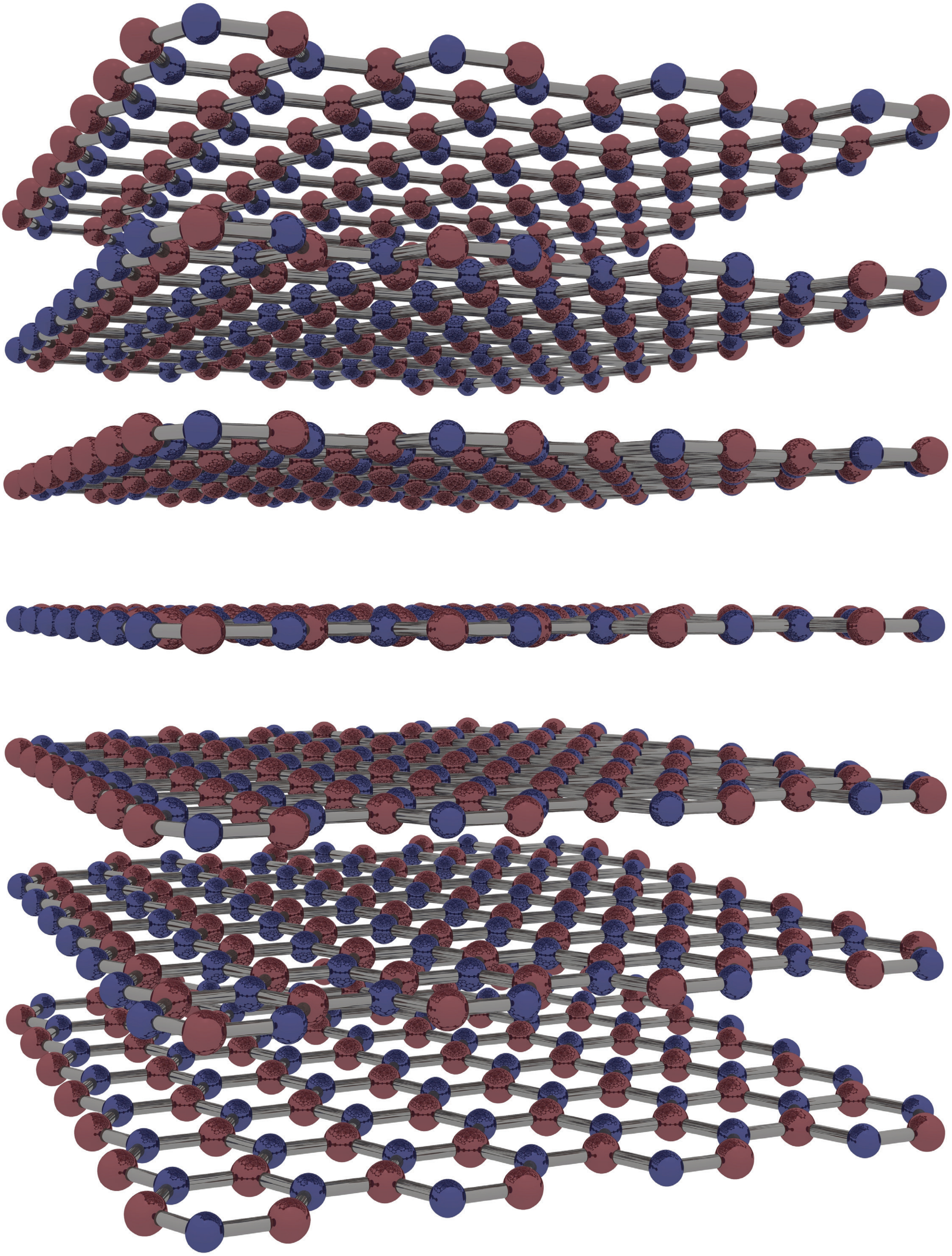
It is recommended that:

1. Existing standards applicable to graphene must be widely promoted across the industry by engaging networks and technology/sector organisations.
2. Development of new standards for graphene should focus on priority areas, such as:

- graphene production and manufacturing;
- definition of types, forms and properties of graphene;
- available information about graphene properties & production method by suppliers;
- graphene material characterisation;
- property data to benchmark against other materials;
- health and safety of graphene in production and recycling.

3. The UK's work with international standard bodies to develop and disseminate graphene standards should be extended to ensure timely collaboration with all relevant countries.

4. The use of common graphene standards must be encouraged in all relevant countries.



1. Introduction

The research described in this report was undertaken by the Knowledge Transfer Network (KTN) by commission from the British Standards Institution (BSI). The research was carried out to determine the opportunities and challenges for graphene commercialisation and to identify how standards can play a key role in accelerating the supply of graphene and graphene-based products into the market. The main aims of the research were to determine gaps in current standards, identify key areas where standards are needed and develop a standards roadmap for graphene.

In its role as the UK National Standards Body, BSI represents UK economic and social interests across the international standards organisations ISO, IEC, CEN, CENELEC and ETSI, providing the infrastructure for over 11,000 experts to work on international, European, national and Publicly Available Specification (PAS) standards development in their chosen fields. Renowned as the originator of many of the world's best known business standards, BSI's activity spans multiple sectors including aerospace, automotive, built environment, energy, food, healthcare and ICT.

The purpose of this report is to outline the priorities, gaps and recommendations for a standards programme supporting the commercial application of graphene through the following objectives:

- Description of the graphene innovation landscape;
- Review of commercial opportunities for graphene;
- Review of graphene market and industry dynamics;
- Industry survey to identify the role of standards in the commercialisation of graphene.

The report details findings from primary research including an online survey, interviews and workshop consultations with the UK's industrial and academic graphene community, and secondary research consisting of a review of publicly available data from bibliometric sources, patent records, industry reports and company information.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2. Graphene Innovation Landscape

2.1 History

For over 20 years the research community has invested efforts into the search for few-layer graphite, motivated by the findings from carbon nanotubes research (Dresselhaus, 2002; Novoselov, 2004). However, it was not until 2004 that graphene material was successfully isolated by Professor Andre Geim and Professor Kostantin Novoselov from Manchester University (Novoselov, 2004). Throughout this time, a consensus had not been reached on the definition of "graphene"; that was used (and in some cases mis-used) to describe a two-dimensional and honeycomb structure of carbon atoms. In this report we will refer to the recently published terminology standard which defines graphene as "single layer of carbon atoms with each atom bound to three neighbours in a honeycomb structure" (ISO/TS 80004-13:2017).

The isolation of graphene material brought about a new physical phenomena in materials. Much of the interest lies in the unique combination of properties which are superior than that of other materials, for example, high strength but thin layered, better electrical conductivity than other metals (e.g. silver) and high thermal conductivity compared to copper. Moreover, graphene can potentially be more cost effective than other substitute materials as it can be sourced from inexpensive carbon sources such as coal and sugar.

The demonstrated unique properties of graphene have attracted much interest from the scientific community which has led to a growing number of research projects and infrastructure developments, many of which are backed by government funding (e.g. Innovate UK, EPSRC in the UK).

Industry, on the other hand, have for many years been following the development of such a promising and potentially inexpensive material. More recently new start-ups have been created to commercialise graphene and graphene-based products and established businesses have also started to invest in new graphene-based products. In spite of this, several challenges have limited the commercialisation of graphene and graphene-based products.

2.2 Graphene Opportunities: Formulations, Properties and Applications

Graphene can be isolated by different methods such as mechanical exfoliation, chemical exfoliation and chemical vapor deposition (CVD). The type of manufacturing method and processes used will determine the form of the graphene material produced, such as in powder form, nanoplatelets, inks, foams, films and as graphene oxide (see Table 1). These formulations may contain single layer graphene and/or few-layer graphene which often cause confusion to the consumer or buyer as graphene is by definition a single layer material (ISO/TS 80004-13:2017). Depending on the application and required properties, graphene can be incorporated into different substrates or matrix. For instance, graphene powder can be embedded into polymers, elastomers or ceramic matrix to enhance strength to the composite or provide functionality to a composite whilst conferring lightweight properties.

The benefits of the use of different graphene forms are wide and these include high specific strength, surface area, thermal and electrical conductivity as well as photovoltaic and photocatalytic properties. Table 1 shows a list of different properties observed in graphene material.

Table 1: Graphene properties and formulations
(ISO/TS 80004-13:2017 ; Sharon, 2015; Ferrari, 2015)

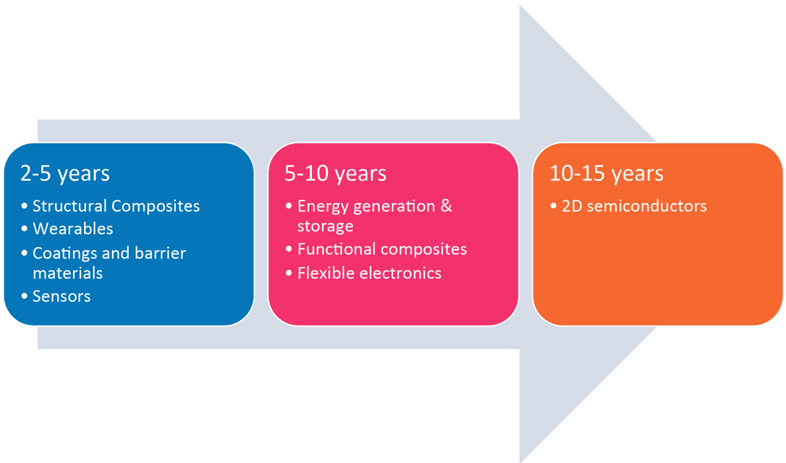
Properties	Formulations
High specific strength	Powders
High surface area	Nanoplatelets
High thermal conductivity	Dispersions and Inks
High electrical conductivity	Foams
High flexibility	Nanosheets
Lightweight	Aggregate
Film impermeability	Nanoribbon
Atomic thickness	(nano) Films
High carrier mobility	Quantum dots
Optical properties (optical absorption, photo-thermoelectric)	Graphene oxide (GO)
Photovoltaic	Reduced Graphene Oxide (RGO)
Photocatalytic	
Transparent	

A number of graphene applications have been proposed and demonstrated, covering several fields including energy conversion and storage, sensors, electronics, photonics and photoelectronics, composites, biomedical and environment (Figure 1).

Figure 1: Examples of proposed applications for graphene.
(Sharon, 2015; Ferrari, 2015)

Although some of these applications have been explored by industry and research organisations, the expected timeline for commercialisation may be rather different. A previous KTN study reported a timeline for some of these applications, as shown in Figure 2 *(KTN report, 2017)*.

Figure 2: Timeline for commercialisation of graphene applications.



2.3 Research to Commercialisation: R&D and Patent landscape

Since the discovery of graphene material, a chain of research and development work has followed in the quest to gain a better knowledge of the wonder material's physical mechanisms, its properties and how to manufacture it. Figure 3a shows the trend of graphene-related scientific publications, with a significant increase from the year 2010. China, US and South Korea are the top countries with the most scientific publications on graphene whereas the United Kingdom ranks 8th (Figure 3b).

Many of these research projects have focused on the development of applications for graphene and the scale up of manufacturing processes and methods. But although this research is still largely led by research organisations, there is a growing number of businesses now investing in graphene application-focused developments.

Figure 3a: Number of scientific publications with keyword "graphene" in the abstract
Source: Web of Science, 14/03/2018

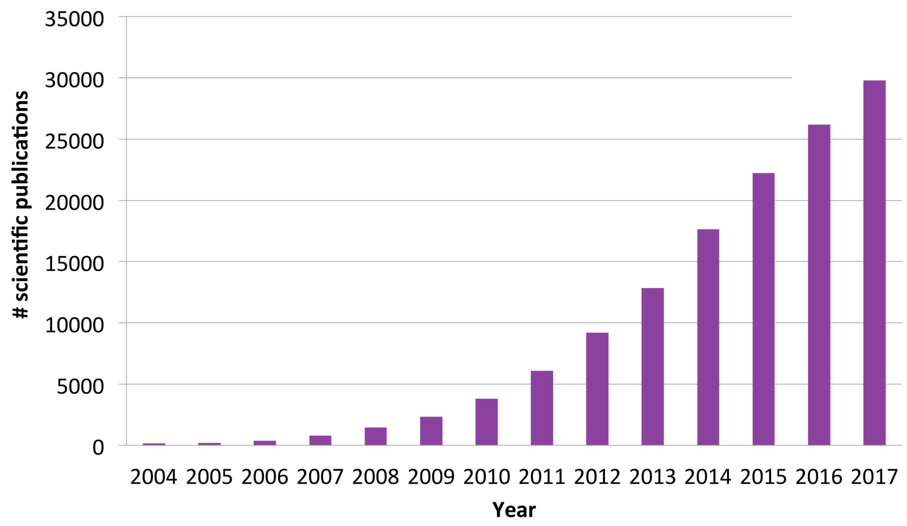
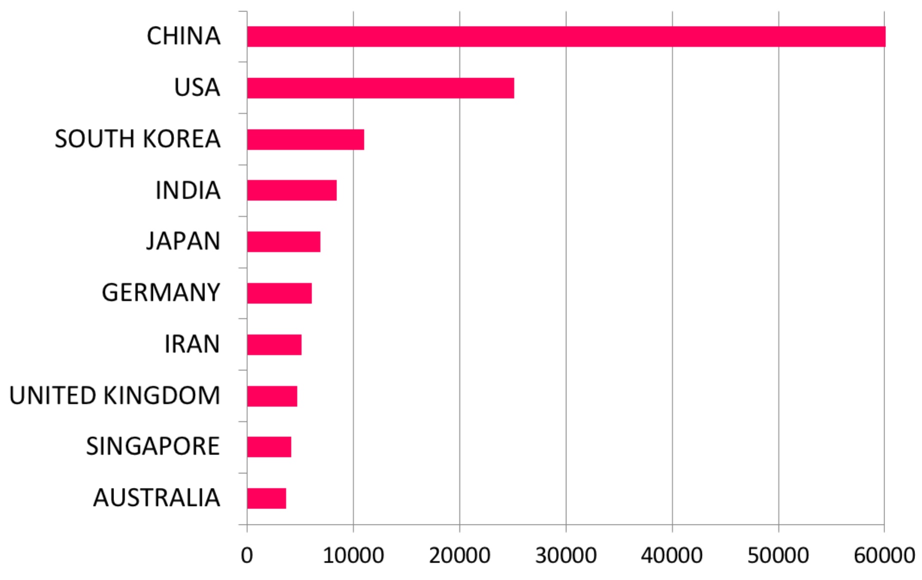


Figure 3b: Top 5 countries publishing scientific work on graphene
Source: Web of Science, 14/03/2018



Another key dimension in describing the innovation landscape for graphene, is patents which have been submitted and granted on graphene. Although not by itself an indication of innovation, patent analysis can provide a view on efforts in translating graphene research into potential commercial products. Figure 4a, shows that from over 150,000 published patents (including pending and granted), 55.1% have been classified either as applications/ measurements/ manufacturing or semiconductor/electric solid state devices. Within the applications, measurements or manufacturing classification, patents are mostly related to nanocomposites, manufacturing and information processing, storage or transmission (Figure 4b).

Figure 4a: Patents submitted against different Cooperative Patent Classifications.
Source: Google Patent search, 19/10/2017

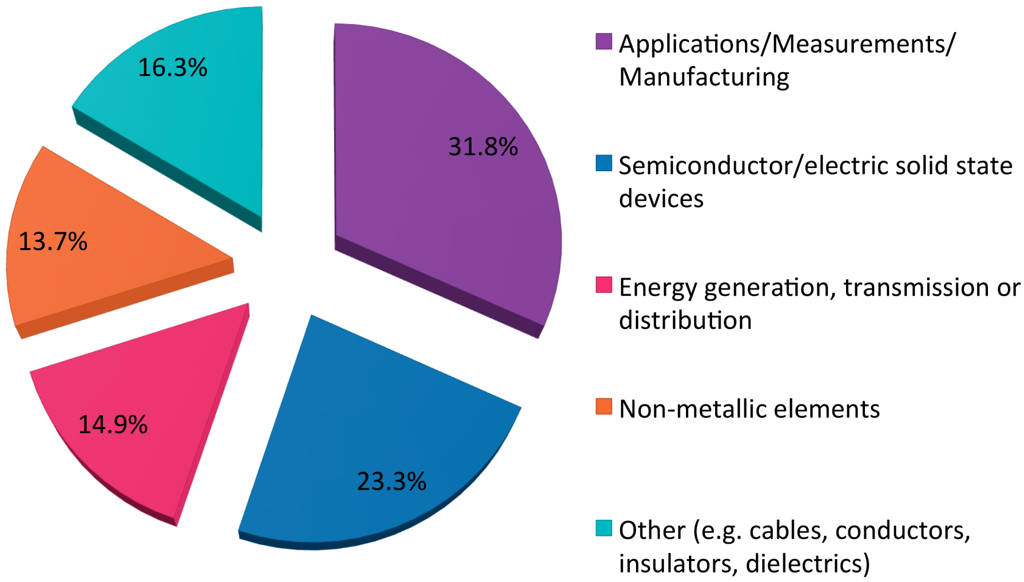
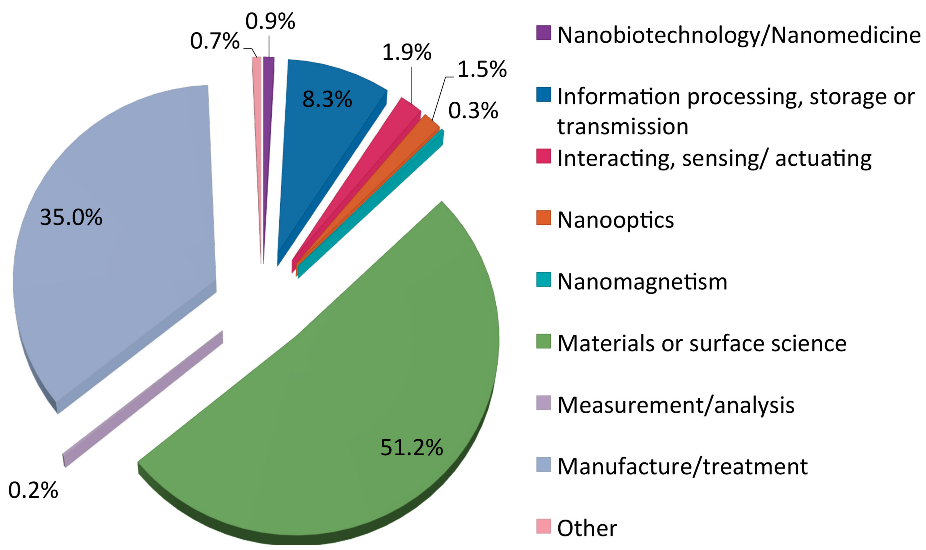


Figure 4b: Detailed breakdown of patents submitted for specific uses or applications of nanostructures; measurements of nanostructures; manufacture or treatment of nanostructures.
Source: Google Patent search, 19/10/2017

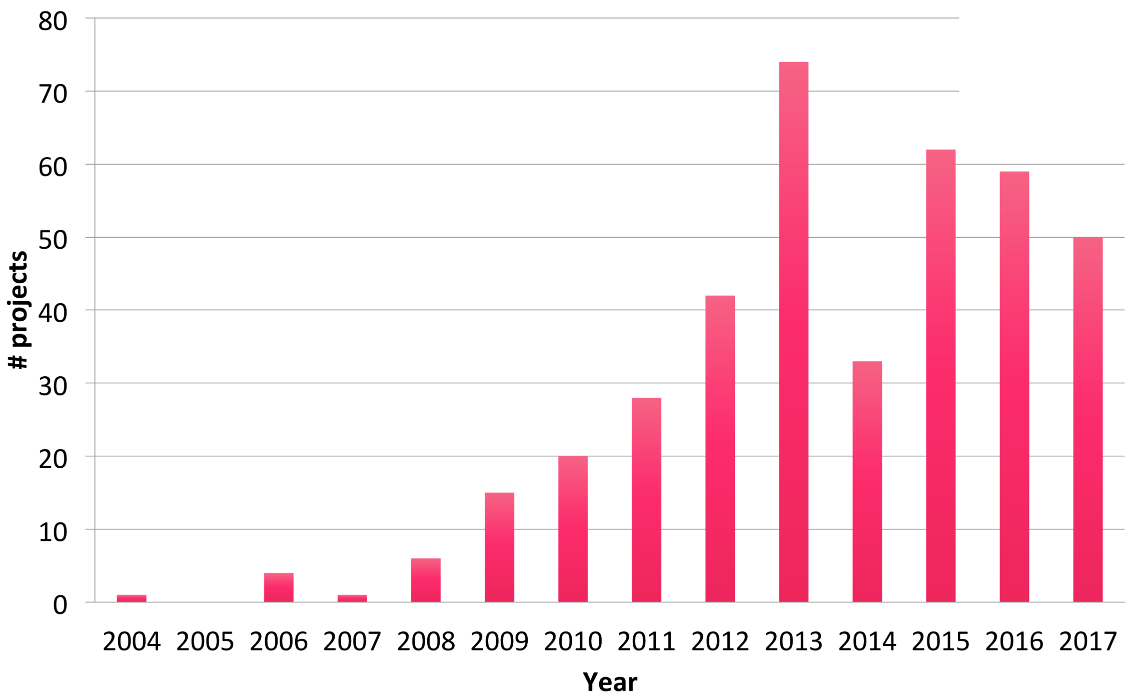


Although the recipients of public funding for R&D and graphene commercialisation are mostly SMEs, large corporations lead on patent applications. Over 20% of patent applications globally have 5 current assignees, namely:

1. Samsung Electronics 4.9%
2. Aruna Zhamu 4.5 % (Nanotek Instruments or Angstron Materials)
3. IBM Corporation 4.1%
4. Jang Bor Z 3.8% (Nanotek Instruments or Angstron Materials)
5. Zhejiang University 3.3 %

In Europe, graphene innovation has benefited from increased funding by governments and institutions. Figure 5 illustrates the number of projects funded by the European Commission across different programmes since 2004. There was a significant ramp up in the number of graphene projects funded from 2008, within the FP7 programme, reaching a maximum in 2013. Here, the UK is found to be the country that has contributed the most to European collaborative projects with 146 submissions, followed by Germany (120), Spain (113), France (103) and Italy (84). See Appendix I for details.

Figure 5: Number of graphene-related funded projects by European Commission since 2004
Source: https://cordis.europa.eu/projects/home_en.html, 30/03/2018



As shown by the graph in Figure 6a, the UK itself has provided national funding for graphene R&D projects with over a total of 300 projects funded since 2006. Figure 6b shows that funding for these projects have mainly been by EPSRC (214 projects) and Innovate UK (79 projects). The detailed breakdown of funding amount, winning applicants and the regional locations for the awards are shown in Appendix 3. The North West and South East of England are the regions that have received the most funding which may be related to the proximity of world-renowned graphene research institutions such as the National Graphene Institute, Manchester University and Oxford University. Eighty (80) companies are shown to be involved in the 79 Innovate UK funded projects, which are a mixture of single company and business–led collaboration projects (Appendix 3).

Figure 6a: Graphene funded projects by Innovate UK and UK Research Councils
*Source: http://gtr.rcuk.ac.uk, 11/03/2018. * 2018 data reports up to March 2018 only.*

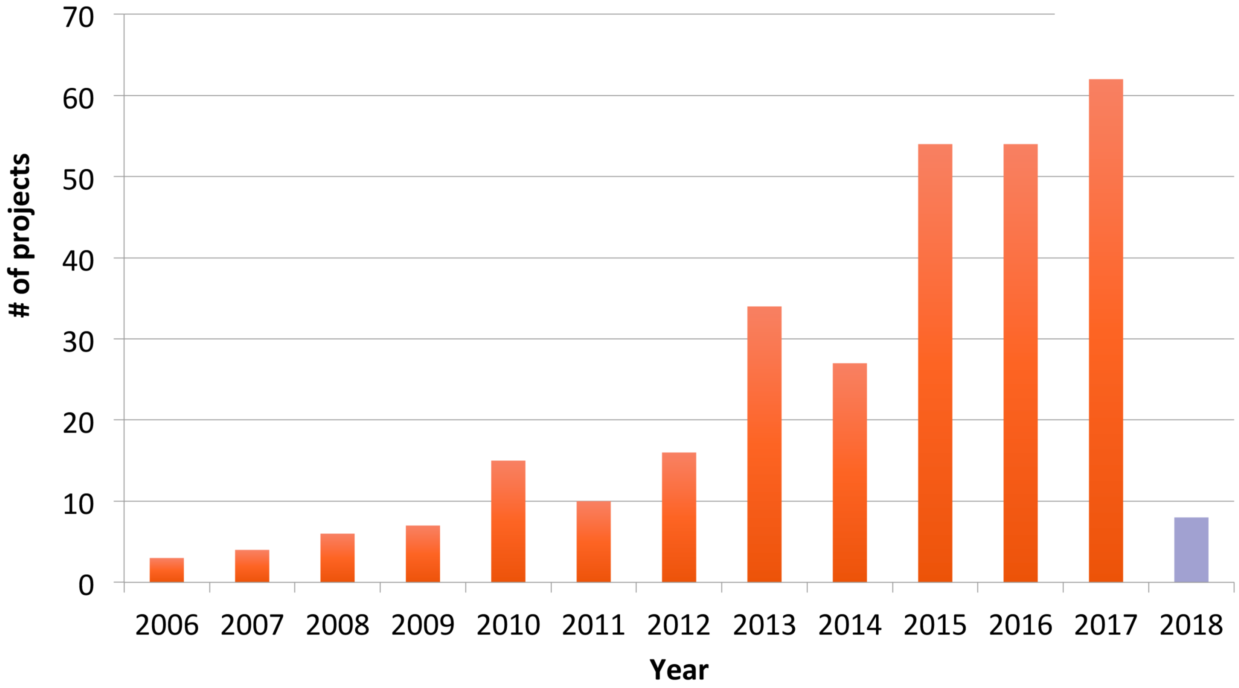
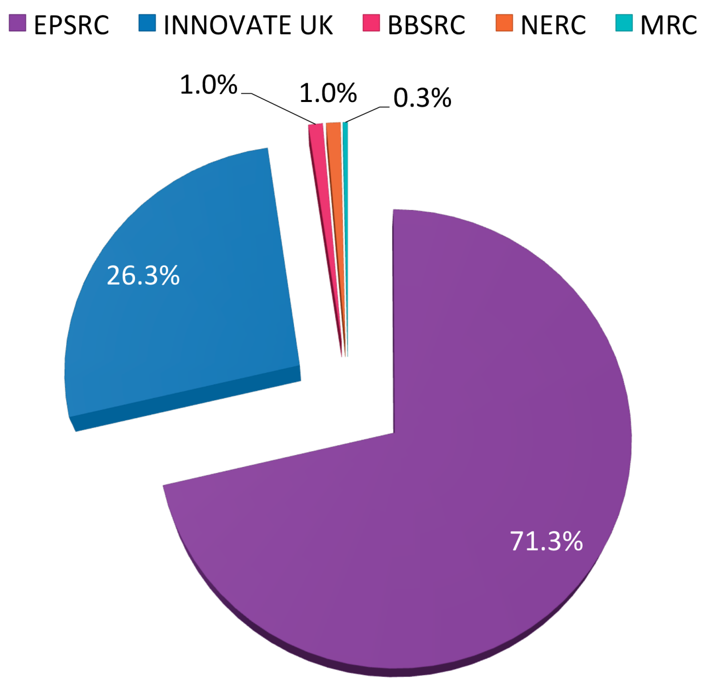


Figure 6b: Percentage of graphene funded projects by UK funding bodies
Source: http://gtr.rcuk.ac.uk, 11/03/2018



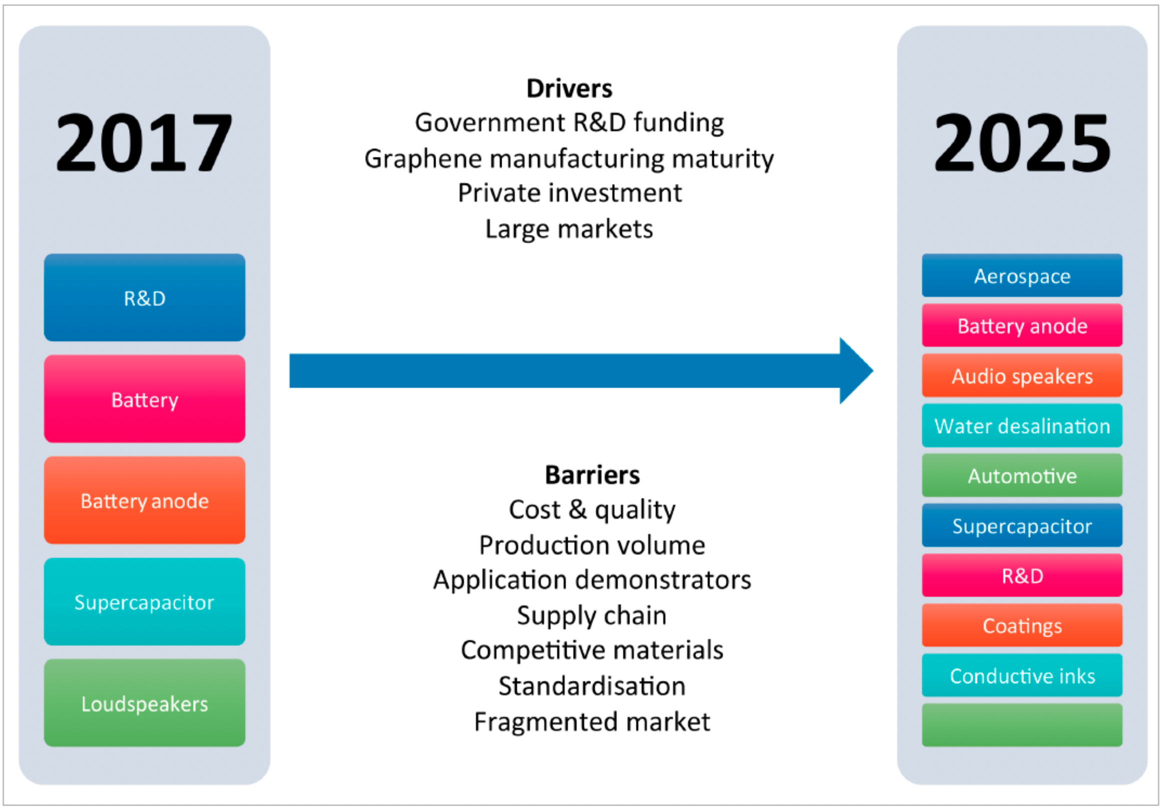
3. Graphene Market and Industry

3.1 Graphene Market: Growth and Challenges

The market for graphene and graphene-based products is still in its infancy, but a rapid growth has been observed, compared to other "wonder" materials such as carbon nanotubes. The graphene market is expected to reach $1.6bn by 2025 at a growth rate of 72.8% *(Frost & Sullivan, 2017).*

Today this market is dominated by graphene formulation suppliers to the R&D market. As illustrated in Figure 7, other markets are also currently sourcing graphene material for applications in battery anode, supercapacitor and loud speakers. However, by 2025, the graphene market is expected to undergo a transformation whereby the aerospace market is expected to be the largest segment for graphene, and new markets starting to appear such as water desalination and automotive *(Frost & Sullivan, 2017).*

Figure 7: Top market segments commercialising graphene-based products
(Frost and Sullivan 2017; Thompson, 2015, KTN Report 2017)



As described earlier in Figure 1, graphene material can be used in a wide range of applications. These developments are bound to have a transformative role in several markets *(Frost and Sullivan 2017; Thompson, 2015)*, including:

- *Energy storage, $62bn market* - graphene applications in battery anodes ($300 million, CAGR[1] 24%) and supercapacitors ($140 million, CAGR of 24%).

1 CAGR compound annual growth rate

- *Composites, $20bn market* - graphene has the potential to capture a significant market share for lightweighting composites in particular in the aerospace ($3bn) and automotive ($14bn) composites market.
- *Water desalination, $12bn market* - graphene is expected to capture a share of this market, as used as high throughput and low cost water membrane.

In the short term (2 year timescale), wearables and barrier materials are also expected to capture a significant market for graphene, resulting in growing demand for graphene-based coatings and inks (KTN report, 2017):

- *Paints and Coatings, $53bn market* - graphene is expected to enter this market as additives for instance for photocatalytic paints, barrier materials and functional coatings.

- *Conductive inks, $3bn market* - the growing demand for conductive inks for wearables and electronics makes graphene inks an attractive and cost-effective solution.

The graphene market, on one hand, is driven by the growing R&D and innovation in graphene manufacturing and applications and, on the other, by the increasing demand from emerging applications e.g. flexible electronics and energy storage. Yet, there are a number of recognisable barriers which are currently constraining the growth of this market (*Frost & Sullivan; Ren, 2014; Zurutuza, 2014; KTN Report 2017)*. These include:

- *Cost & Quality:* High cost of high quality graphene due to limited supply, complex production and expensive processing, all of which require further development. To benefit from the unique properties of graphene, single-layer and defect-free graphene should be used.

- *Production volume:* Production volume and scalability for high quality graphene can be limited using some processing methods like CVD.

- *Demonstrated applications:* Graphene applications have been proposed due to properties demonstrated at laboratory or small scale. The translation of such properties into real applications is challenging due to processing and property reproducibility.

- *Supply chain:* The supply chain for graphene is not yet well established. Although several companies supply graphene material to the market, currently there is limited offer of graphene-based components, devices and systems. Linking the supply chain in early stages of development can drive the graphene market growth.

- *Competitive materials:* Carbon nanotubes and graphite are examples of materials currently being used in some applications, which also provide both lightweight and conductive properties. Although the properties of these materials are inferior to those of graphene, these substitute materials are cheaper and supported by an established supply chain and route to market.

- *Standardisation:* The lack of a common language and standards for graphene manufacturing, transportation, application and end of life, is a recognised barrier to market acceptance and confidence.

- *Fragmented market:* The graphene market is highly fragmented such that research and development is not focused on key applications or industries.

3.2 The Graphene Industry

As with other advanced materials, graphene industry is characterised by three main groups:

1. *Primary suppliers:* producers of different forms of graphene, suppliers of production equipment, graphite producers.

2. *Manufacturers of advanced materials:* integrators of graphene into composites, coatings, inks, etc.

3. *Component/system integrators:* developers of devices and final products, e.g. batteries, electronics, sensors, etc.

In the UK, the industry is fragmented and led by SMEs and start-ups, with a strong focus on the supply of different graphene formulations. More recently, a number of start-ups have been founded to develop and commercialise graphene-based applications, such as photonics, batteries and sensors. Figure 8 illustrates the identified companies in the UK graphene supply chain. A number of the UK graphene producers operate globally and these are listed in Table 2, which also presents other identified global companies currently commercialising different formulations of graphene. Today these companies serve mostly the R&D market, however, there are encouraging activities globally to develop different applications for graphene. Table 3 shows the companies that are developing and commercialising graphene-based applications globally. It is interesting to observe that the SMEs are leading the development of commercial applications for graphene, with energy storage, electronics and composites being the top applications addressed by these companies. A few graphene-enhanced consumer products have made it to the market and examples of companies producing these have been listed in Table 4.

Figure 8: Example of companies in the UK graphene supply chain

Primary Suppliers	Advanced Material Manufacture	Component/System Integrator
• Cambridge Nanosystems	• Haydale Composites	• Emberion
• Graphitene	• Haydale	• Zapgocharger
• Applied Graphene	• Versarien	• Prognomics (sensors)
• William Blythe		• Eksagon (energy storage)
• Cambridge Graphene		• Graphene Lighting
• Versarien		• Graphene Security
• Graphene Enabled Systems		• Graphenex
• 2D Tech (part of Versarien)		• Paragraf
• BGT Materials		
• DGS - Durham Graphene Research		
• Graphene industries		
• Gwent Electronic Materials		
• Perpetuus Carbon Technologies		
• RD Graphene		
• Thomas Swan		

Table 2: Examples of global companies commercialising graphene formulations

Company	Product	Country
Graphene Supermarket	Films, powder, foam, solutions, aerogel, CVD, Graphene oxide	US
Graphene Square	Quantum dots, CVD films, solution Graphene, Graphene oxide	US
Angstron Materials	Dispersions, powders Graphene, graphene oxide	US
XG Sciences	Nanoplatelets, films, inks	US
Graphenea	CVD films, dispersion, Monolayer, multilayer, Graphene oxide, reduced graphene oxide	Spain
Applied Graphene Materials	Nanoplatelets, dispersions	UK
Cambridge Nanosystems	Powder, dispersion, inks	UK
Thomas Swan	Powder, dispersion	UK
William Blythe	Powder, flake, dispersion Graphene oxide	UK
Graphitene	Powder, nanoplatelets, film Graphene oxide, Reduced Graphene oxide	UK
Versarien (Cambridge Graphene, 2D Tech)	Nano-platelet powder Graphene-enhanced polymer filaments for 3D printing	UK
Haydale	Graphene-enhanced polylactic acid (PLA) filaments for 3D printing	UK
Graphenemex	Flakes, graphene oxide, reduced graphene oxide and CVD graphene	Mexico
Dotz Nano	Quantum dots	Israel

Table 3: Global companies developing and commercialising graphene-based applications

Company	**Application**	**Country**
Graphene ESD	Energy storage	US
CalBattery	Energy storage	US
Vorbeck	Electronics; Energy storage	US
Graphenano	Energy storage; Biomedical; Composites; Sensors; Energy conversion	Spain
Graphenstone	Composites	Spain
Eskagon	Energy storage; Energy conversion	UK
Flexenable	Flexible electronics	UK
Graphene Lighting	Composites; Electronics	UK
Graphene security	Electronics	UK
Graphenex	Energy storage	UK
Haydale	Composites	UK
Graphenemex	Composites	Mexico
GMCC	Energy storage	China

Table 4: Examples of consumer products enhanced by graphene.

Company	Consumer product	Country
HEAD	Tennis rackets, Women skis	US
Biolin Scientific	Q-Sense Graphene Oxide sensor	US
Nanomedical Diagnostics	Graphene-based sensor	US
Catlike	Cycling helmets (Mixino); Cycling shoes	Spain
Vittoria	Bicycle race wheels (Qurano)	Italy
Dassi Bikes	Graphene-enhanced bikes	UK
Team Group	Graphene copper foil cooling on the SSD module	Taiwan
Tata Steel	Graphene-coated stirrups	India

4. Standards for Graphene Commercialisation

4.1 Graphene Standards: Current State

National and international standards are known to enhance productivity and efficiency of businesses. For example, standards help to reduce production costs, improve risk management and enable access to new markets and international trade. Standards can contribute to businesses' competitive edge by demonstrating to the market that their products and services are of a high quality (CEBR (2015)).

Standards are also a key part of the innovation process as they establish technical specification and requirements for any technical system, such as processes, methods and products. A new innovative advanced material, such as graphene, may benefit from standards to enhance market and supply chain acceptance which ultimately will drive the commercial viability of such material.

Although graphene standards are still in their early stages of development, some progress has been made. One example of progress is the graphene and related two-dimensional materials terminology standard which has been published (ISO/TS 80004-13:2017) and discusses definitions for graphene and other 2D materials and terms for naming production methods, properties and characterization. This standard aims to harmonise the communication across the value chain. A graphene-related work programme of NTI/1[2] is currently in progress with a number of standards (ISO and IEC) under development (see Table 6) such as ISO/TC 229 and IEC/TC113. ISO/TC229 aims at developing standards to support control, processes and properties of nanoscale materials and ultimately lead to materials, devices and systems with better performance, whereas IEC/TC113 technical committee develops standards on nanotechnology-based electrotechnical products and systems. A Publicly Available Specification (PAS 1201), titled "Properties of graphene flakes - Guide" is under development. Sponsored by Innovate UK, this document aims to facilitate the confident use of graphene in commercial applications.

Pre-standard research project on structural and chemical composition of graphene has been carried out within the scope of the Versailles Project on Advanced Materials and Standards (VAMAS). The VAMAS programme aims to develop best practices and standards in measurement methods of advanced materials, through collaboration on pre-standards measurement research, laboratory intercomparison and agreement on standards priorities. This programme has an ongoing technical working area on graphene and related 2D materials, which aims at validating measurement, sample preparation and data analysis methodologies (VAMAS, n.d.).

UK-China Joint Working Group on graphene standardisation has recently been established as a partnership between BSI and SAC (Standardisation Administration of China). This working group aims to promote cooperation between the two countries on graphene standardisation, through pre-standardisation work and standards proposals related to graphene information, handling, transportation, storage and testing.

Recognising the need for industry players to work on graphene in an environment of trust, reliability and consistency, the Graphene Council has created a Standards Task Force to develop peer reviewed graphene standards. These are focused in areas such as physical characteristics, nomenclature, measurement methodologies, equipment and tolerances, electrical properties, chemical properties, batch numbers and traceability, standardised symbols/labelling and quality assays. As of yet, there are no known outcomes published by the task force. Participation in the task force is open to Graphene Council members only. Similarly, the IEE Nanotechnology Council

2 NTI/1 is the BSI technical committee responsible for formal standards development in nanotechnologies, also the UK mirror committee for ISO/TC 229 and IEC/TC 113

has created a Graphene Standards working group, although limited information on outcomes and progress is available (IEE Standards Association, n.d.).

Table 6: Current graphene-related work programme

BSI **PAS 1201 [Under development] Properties of Graphene Flake – Guide** **ISO/TC 229 Nanotechnology** • **ISO/TS 80004-13:2017** [Published] Title: Nanotechnologies - Vocabulary Part 13: Graphene and related two-dimensional (2D) Materials • **ISO/NP TR 19733** [Under development] Matrix of characterization and measurement methods for graphene and related two-dimensional (2D) materials' • **ISO/PWI 21356-1** [Under development] Nanotechnologies — Structural characterisation of graphene from powders and dispersions

IEC/TC 113 Nanotechnology

- **IEC/TS 62607-6-2 ED.1.0 [Under development]** Nanomanufacturing – Key control characteristics – Part 6-2: Graphene – Evaluation of the number of layers of graphene
- **IEC/TS 62607-6-1 ED.1.0 [Under development]** Nanomanufacturing - Key control characteristics - Part 6-1: Graphene - Electrical characterization of powder-type graphene, Volume resistivity of its pellet
- **IEC/TS 62607-6-3 ED.1.0 [Under development]** Nanomanufacturing - Key control characteristics - Part 6-3: Graphene-Characterisation of CVD graphene domains
- **IEC/TS 62876-3-1 ED.1.0 [Under development]** IEC 62876-3-1 Nanomanufacturing - Reliability assessment - Part 3.1: Graphene - Stability test: Temperature and humidity
- **IEC/TS 62607-6-5 Ed.1.0 [Under development]** Nanomanufacturing - Key control characteristics Part 6-5: Graphene - Sheet resistance and contact resistance of two-dimensional materials including graphene
- **IEC TS 62607-6-13 [Under development]** Nanomanufacturing - Key control Characteristics - Part 6-11: Graphene - Defect level of graphene analysed by Raman spectroscopy
- **IEC TS 62607-6-13 [Under development]** Nanomanufacturing – Key control characteristics – Part 6-13: Determination of Oxygen Functional Groups Content of Graphene Materials with Boehm titration method
- **IEC 62607-6-14 [Under development]** Nanomanufacturing – Key control characteristics – Part 6-14- Graphene – Defect level analysis in graphene powder using Raman spectroscopy
- **IEC TS 62607-6-6 [Under development**: Nanomanufacturing - Key control characteristics - Part 6-6: Graphene - Uniformity of strain in graphene analysed by Raman spectroscopy
- **IEC/TS 62607-6-9 [Under development]** Nanomanufacturing - Key control Characteristics - Part 6-9: Graphene - Measurement of sheet resistance by the non-contact Eddy current method
- **IEC 62565-3-1 ED1 [Under development]** Nanomanufacturing - Material specifications - Part 3-1: Graphene - Blank detail specification
- **IEC/TS 62565-3-2 [Under development]** Nanomanufacturing - Material specifications - Part 3-2: Graphene - Sectional blank detail specification for nano-ink

4.2 UK Graphene Community Consultations

KTN, on behalf of BSI, consulted with the UK graphene community to capture views on the challenges that the industry is currently facing and the potential role standards can play to address any barriers preventing the large-scale commercialisation of graphene.

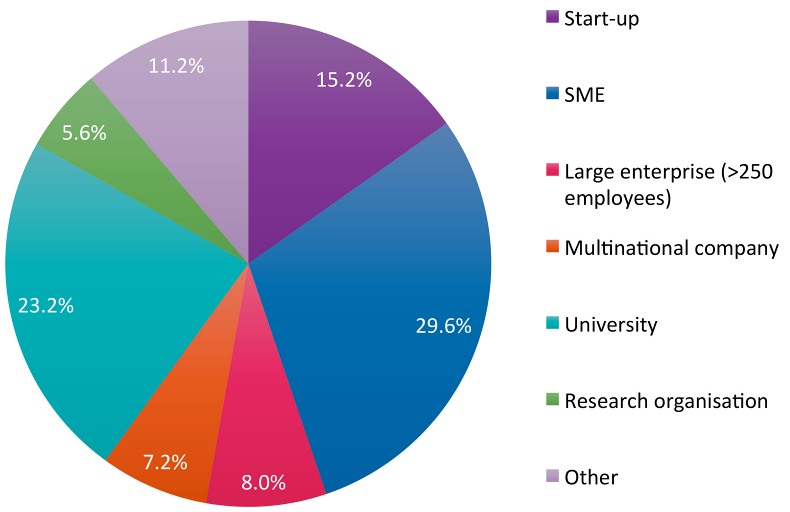
The consultations were conducted with the help of a questionnaire that was posted online and promoted widely to the UK graphene innovation community, including potential end users. In addition to outreach through email, newsletters and various social media, surveys were conducted using an interactive web tool (Mentimeter) at two Special Interest Group (SIG) workshops [3]. A sample of the survey questionnaire, which was constructed and agreed with BSI beforehand, is shown in Appendix 4.

One-to-one detailed interviews in person or by telephone were also conducted with selected senior business executives from 17 different companies. In this case, the questionnaire was used as a guide allowing the respondents to answer the headline questions in their own words rather than select options.

4.2.1 Analysis of Participating Organisations

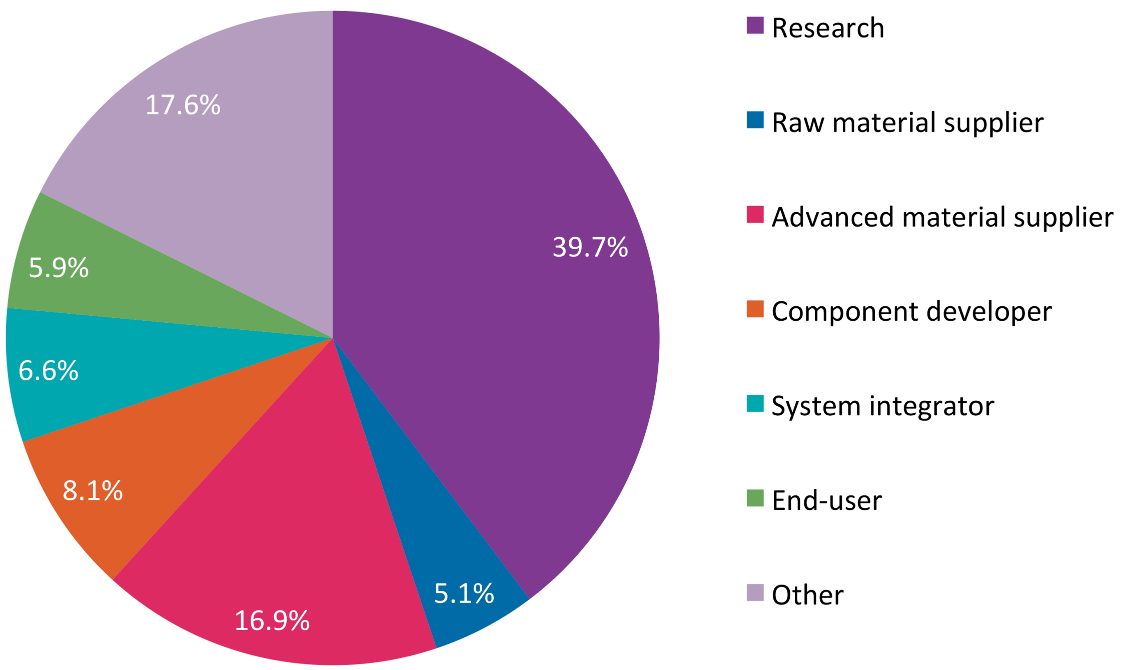
Overall, 129 organisations responded to the consultation. Responses to Question 1 were analysed to determine the size and type of organisations the respondents belong to. As shown in Figure 9, 60% of the survey respondents were UK businesses compared to 29% from UK universities or other research organisations. Similarly, the responses to Question 2 was analysed to determine the organisational profile of respondents in relation to their position in the graphene value chain. Among the organisations surveyed, 40% are currently engaged in graphene R&D and are well-positioned across the value chain (Figure 10).

Figure 9: Size and type of organisation of respondents



3 "Leading Graphene and other 2D Materials into the Future: A stakeholder workshop", 14th December 2017; HiPerNano2018, 12th March 2018.

Figure 10: Organisational profile of respondents in relation to the graphene value chain



4.2.2 Survey Results and Discussion

For the online survey, the number of respondents per question asked is shown in Appendix 5. The responses to each of the questions were reviewed to determine which of the respective options had received the largest number of votes. Figures 11 and 12 show the results for Questions 3 and 4 respectively.

The design of the questionnaire was based on a number of challenges identified in graphene-focused workshops conducted by BSI (BSI, 2016; BSI, 2017) and from work by Prior et al. (2015) and KTN (2017). These reports listed challenges currently threatening the commercialisation of graphene. These challenges were collated and put forward to the graphene community to determine which challenges and needs most crucially required addressing in order to advance commercialisation of graphene.

Challenges limiting the advancement of graphene commercialisation

Result 1: Challenges limiting the advancement of graphene commercialisation are largely linked to the provision of graphene information and ensuring the consistent quality of the graphene material.

Figure 11 shows the results for the question on the challenges limiting the advancement of graphene commercialisation. The top 5 challenges were identified as:

1. Delivery of consistent graphene properties between batches;
2. Standard definitions of different types, forms and properties of graphene;
3. Standard provision of information on graphene properties & production method by suppliers;

4. Consistent evidence/data on the value of using graphene against competitive advanced materials (e.g.carbon nanotubes);
5. Advanced knowledge of graphene toxicology.

A common thread running through these top challenges is linked to the provision of graphene information and the quality of the graphene material. The requirement for information includes details on graphene toxicology.

Appendix 5 shows the breakdown of challenges by respondents from different organisation type and sizes. Consistency of graphene properties has been ranked as first priority by respondents from universities and research oragnisations, start-ups, SMEs and large companies. Nonetheless, the ranking differs among organisation types and sizes. For instance, start-ups prioritise the lack of evidence of the value in using graphene in applications as their second most important challenge, whereas SMEs valued product validation. In contrast, large companies identified lack of definitions of different types, forms and properties of graphene as the second major challenge in commercialising graphene.

Respondents were also asked to provide comments and from these it was possible to capture other challenges seen as important. Appendix 5 provides a comprehensive list of the responses (Question 5). Three common themes emerge and these are:

- Standardisation of graphene production;
- Demonstration of the use of graphene in different applications;
- Improving the confidence of graphene users in the material properties, benefits, applicability in different sectors and safety in using graphene.

Figure 11: Challenges limiting the advancement of graphene commercialisation

Impact of standards on the commercialisation of graphene innovations

Result 2: Graphene standards will create a successful commercial environment by strongly promoting consumer confidence, fostering collaboration within the supply chain and opening up access to international markets.

Figure 12 shows how respondents perceive the impact of graphene-related standards on the commercialisation of graphene and graphene-related products. According to the results, graphene standards will strongly:

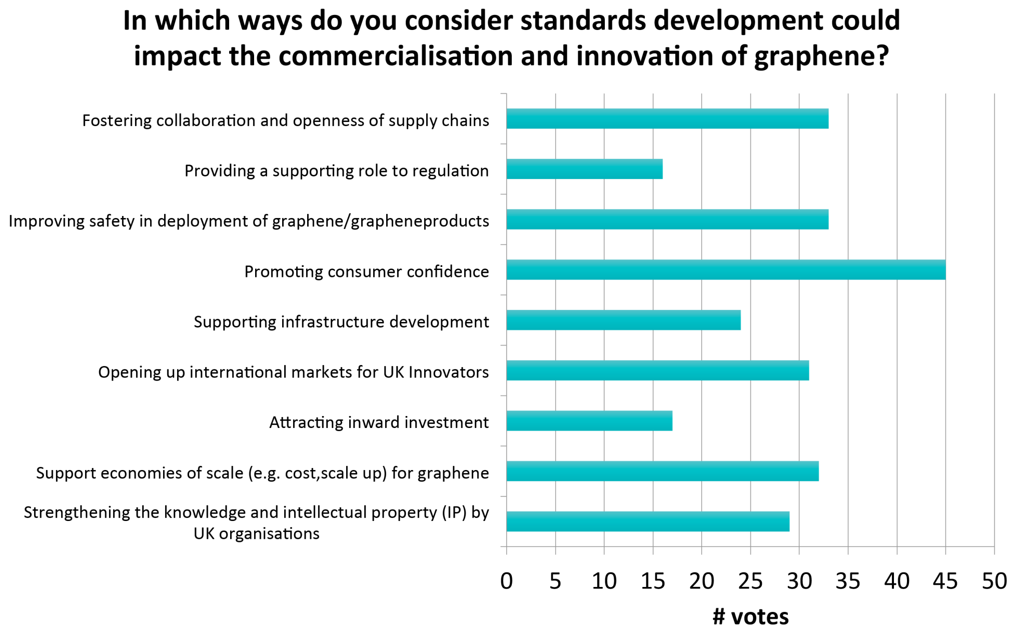
- Promote consumer confidence;
- Foster collaboration and openness of supply chains;
- Open up international markets for UK Innovators;

Result 3: Graphene standards will help manufacturers achieve economy of scale and improved safety.

As shown also in Figure 12, the response to Question 4 further identifies that standards will strongly:

- Improve safety in deployment of graphene/graphene products;
- Support economies of scale (e.g. cost, scale up) for graphene.

Figure 12: Standards impact on the commercialisation of graphene innovations



How the impact of standards in the commercialisation of graphene is viewed depends on the size and type of organisation. Large businesses and universities see the major impact as promoting consumer confidence in using graphene, whereas start-ups value the opportunities to collaborate across the supply chain and established SMEs are interested in supporting economies of scale.

4.2.3 Interview Results and Discussion

As mentioned earlier, the one-to-one interviews were based on the headline questions in the survey questionnaire without asking the respondents to select options. Instead, they were allowed to provide their own detailed answers. These were captured and analysed for key responses. The interview questions are presented in Appendix 6. From the discussions, it was possible to capture their views on needs for standards, the impact anticipated in graphene commercialisation and also concerns regarding the development and implementation of these standards.

Need for standards

Result 4: Graphene manufacturing to be carried out under 'Good Practices' with quality information and characterisation methods.

The following points were made with regards to the need for graphene standards:

- Graphene manufacturing under Good Manufacturing Practices';
- Feedstock materials and type of graphene definitions and terminology to reduce feedstock variability;
- Analytical characterisation techniques and methods for graphene and graphene-based products;
- Standards to cover other non-carbon 2D materials;
- Reference to measurable properties and quality characteristics for specific applications of graphene;
- Standard materials for different property characterisation;
- Health and safety to address manufacturing and recycling of graphene.

Impact of standards

Result 5: Graphene standards will reduce risks, increase both end-user and investor confidence and promote a high and consistent quality offer across the supply chain.

Responses in the one-to-one interviews about the impact of graphene standards were consistent with those expressed by the majority of the respondents to the online questionnaire. The views expressed by the business leaders interviewed were that the impact of standards will:

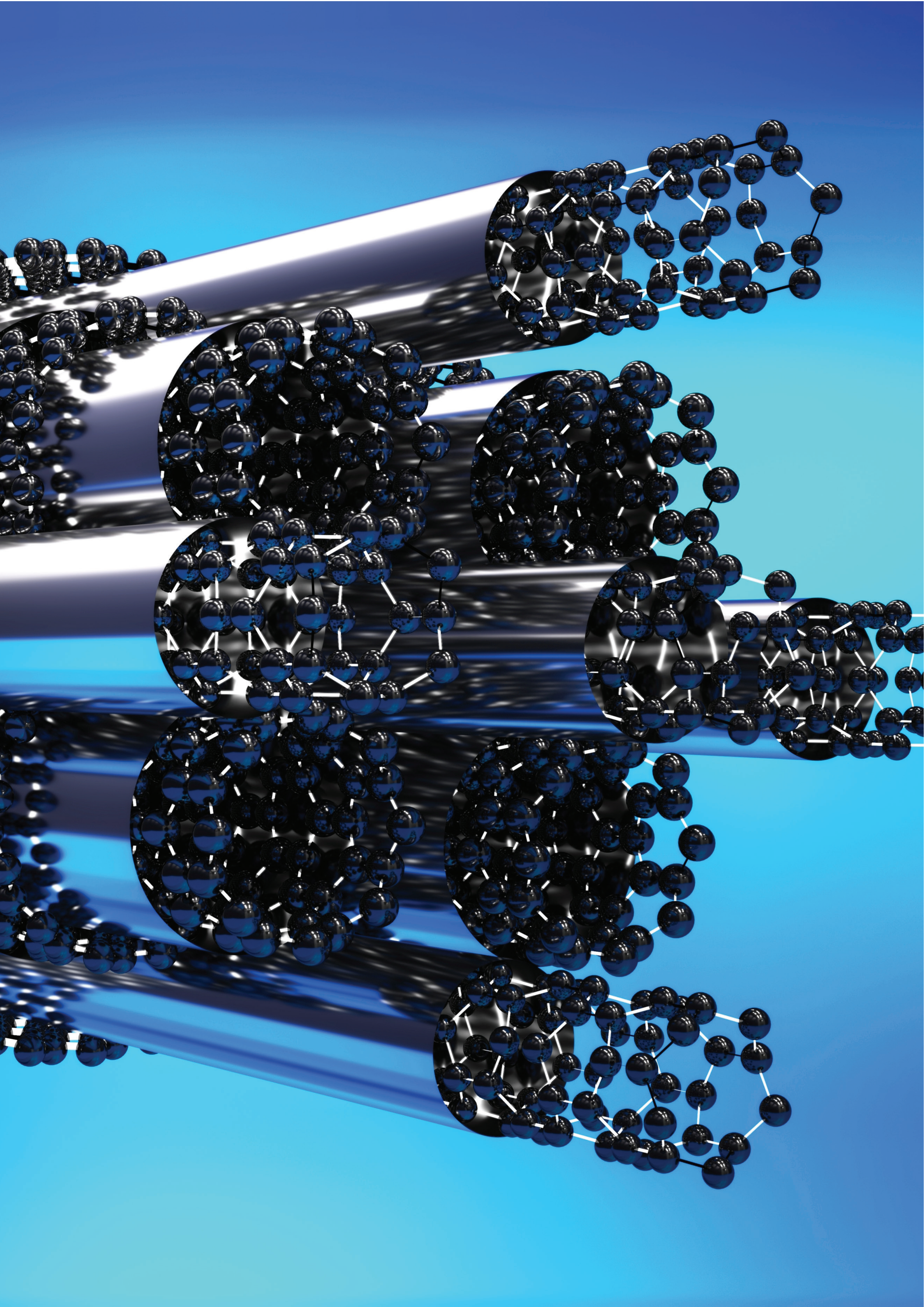
- Help the identification of quality suppliers;
- Speed up the process of specifying the material;
- Give end users the confidence that graphene based products are properly made, fit for specific application;
- Reduce risk venture to increase investor confidence;
- Create a clear supply chain with product comparability and benchmarking;
- Speed up the growth in the use of functionalised graphene and other 2D materials.

Concerns about graphene standards

Result 6: Cost of compliance, scope and timing of international acceptance of standards may constrain the commercialisation of graphene.

The following concerns were expressed by those interviewed:

- Cost of standards testing should not be prohibitive;
- Standards can make it difficult for a functionalised form which does not fit into any definition / standard test methods;
- Definitions which are too broad will leave confusion in the marketplace;
- Poor adoption of standards could mean that standardisation has limited impact on graphene commercialisation;
- Acceptance of standards by other countries.



5. Conclusions and Recommendations

A review of the graphene innovation landscape and market showed that increasingly R&D activities are focused on the production, scale-up, manufacturing and applications of graphene. This should help provide the evidence that users and device manufacturers need to engage with the development and commercialisation of graphene. Globally, public funding has played a pivotal role in driving innovation and helping to de-risk the early research undertakings and adoption of graphene. The UK ranks among the top 10 countries in the world that have published the most research papers and patents and are helping to stir-up business interests in graphene. Currently the market for graphene is fuelled by the increase in both public and business funding for R&D. However, there are signs of application developments being driven by the potential to capture market share in large markets such as automotive, energy storage, applications for composites and water desalination.

Despite these positive trends, the market for graphene is currently threatened by several barriers including high cost and low quality, market fragmentation, relatively immature supply chain, property inconsistency, availability of competitive materials and lack of graphene standards.

From the primary research and community consultation, it is clear that the UK graphene industry is ready to embrace standards, as it seeks to work in an environment of trust and to provide assurances and confidence to potential Original Equipment Manufacturers (OEMs) and end-users. The following key requirements have been identified:

- Standards are required in areas such as: definition, manufacturing, characterisation and application-specific properties of graphene.
- There is a need to widen the awareness of the existing standards applicable to graphene, such as the terminology standard (ISO/TS 80004-13).
- Health and safety standards are needed for graphene manufacturing and waste management.
- The development and application of standards is needed to increase user and investor confidence in the use of graphene in terms of the benefits and safety, to promote openness of supply chains and to reduce cost through economies of scale.
- There is a need to build up the uptake of standards through increased awareness and education on key standards.
- For greater impact to be realised, graphene standards should be implemented internationally in a timely manner.

It is recommended that:

1. Existing standards applicable to graphene must be widely promoted across the industry by engaging networks and technology/sector organisations.

2. Development of new standards for graphene should focus on priority areas, such as:

    - graphene production and manufacturing;
    - definition of types, forms and properties of graphene;
    - available information about graphene properties & production method by suppliers;
    - graphene material characterisation;
    - property data to benchmark against other materials;
    - health and safety of graphene in production and waste management.

3. The UK's work with international standard bodies to develop and disseminate graphene standards should be extended to ensure timely collaboration with all relevant countries.

4. The use of common graphene standards must be encouraged by other international standards bodies in all relevant countries.

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Appendices

Appendix 1 - European Commission funded projects by country.

Source: https://cordis.europa.eu/projects/home_en.html

Search date: 30/03/2018

Advanced Search: Projects only, Search term: graphene; Custom dates [01.01.2004 - 31.12.2017]

Country	#Projects	Country	#Projects	Country	#Projects
United Kingdom	**146**	Hungary	12	Norway	3
Germany	**120**	Turkey	11	Slovakia	3
Spain	**113**	Bulgaria	10	Slovenia	3
France	**103**	Czech Republic	10	Georgia	3
Italy	**84**	Cyprus	6	Russia	2
Netherlands	57	United States	6	South Korea	2
Switzerland	47	Argentina	5	Chile	2
Belgium	39	Ukraine	5	China	1
Sweden	33	Belarus	4	Ethiopia	1
Austria	32	Canada	4	India	1
Greece	29	Latvia	4	Japan	1
Ireland	24	Lithuania	4	Kenya	1
Finland	22	Luxembourg	4	Mexico	1
Denmark	21	Romania	4	Niger	1
Poland	15	Armenia	3	Pakistan	1
Israel	14	Estonia	3	Serbia	1
Portugal	14	Iceland		South Africa	1

Appendix 2 - European Commission funded projects by category.

Source: https://cordis.europa.eu/projects/home_en.html

Search date: 30/03/2018

Advanced Search: Projects only, Search term: graphene; Custom dates [01.01.2004 - 31.12.2017]

Category	# Projects
Scientific Research	**97**
Physical sciences and engineering	**57**
Nanotechnology and Nanosciences	**50**
Life Sciences	**40**
Electronics and Microelectronics	**34**
Materials Technology	31
Education and Training	22
Information and communication technology applications	15
Information and Media	13
Innovation and Technology Transfer	12
Industrial Manufacture	11
Information Processing and Information Systems	9
Social sciences and humanities	9
Coordination and Cooperation	8
Network technologies	7
Telecommunications	6
Earth Sciences	5
Employment issues	4
Evaluation	4
Measurement Methods	4
Transport	4
Biotechnology	3
Medicine and Health	3
Regional Development	3
Space and satellite research	3
Aerospace Technology	2
Economic Aspects	2
Environmental Protection	2
Mathematics and Statistics	2
Medical biotechnology	2
Other Technology	2
Policies	2
Construction Technology	1
Energy Saving	1

Energy Storage and Energy Transport	1
Food	1
Healthcare delivery/services	1
Industrial biotech	1
Legislation and Regulations	1
Meteorology	1
Standards	1

Appendix 3 - UK graphene R&D funding landscape

Source: http://gtr.rcuk.ac.uk

Date: 11/03/2018

Keyword: “graphene”

Fields: ORCID iD, Project Abstract, Project Reference, Project Title.

Funding size	#projects
Up to £100K	131
£100K to £1M	130
£1M to £10M	37
Above £10M	2

Public funding above £10M has been focused in the development of graphene R&D infrastructure, such as:

- The National Graphene Institute – creation of NGI at University of Manchester.
  - Funded Value: £38.000.000
  - Funded Period: Feb 12 - Jan 15
  - Funder: EPSRC
- Graphene Innovation Centre – creation of research centre at Centre for Process Innovation
  - Funded Value: £14.000.000
  - Funded Period: Apr 14 - Apr 19
  - Funder: Innovate UK

Region	#projects
North West	**55**
South East	**42**
East Midlands	**32**
South West	**31**
London	**29**
East of England	27
Yorkshire and The Humber	21
North East	16
West Midlands	15
Wales	14
Scotland	11
Unknown	4
Northern Ireland	3
Total	300

Businesses involved in 70 Innovate UK projects

Source: http://gtr.rcuk.ac.uk/

Search date: 11 March 2018

Keyword: Graphene

Dates: 2011- present

1. Advanced Blast & Ballistic Systems Limited
2. Applied Graphene Materials UK Limited
3. SIFCO Applied Surface Concepts (UK) Limited
4. BaSE Materials Limited
5. Made With Glove Limited
6. Dzp Technologies Limited
7. Wilson Benesch Limited
8. Flexenable Limited
9. Moorfield Nanotechnology Limited
10. Delstar International, Limited
11. Nano Products Limited
12. 2-Dtech Limited
13. European Thermodynamics Limited
14. FGV Cambridge Nanosystems Limited
15. Greentech Corporation Ltd
16. Siemens Public Limited Company
17. Coherent Scotland Limited
18. Prognomics Ltd
19. Sharp Laboratories of Europe, Ltd
20. Green Biologics Limited
21. Jason Chehal
22. Haydale Composite Solutions Limited
23. Biovici Limited
24. Gwent Electronic Materials Limited
25. Netcomposites Limited
26. Meggitt Aerospace Limited
27. Polyphotonix Limited
28. Mint Diagnostics Ltd
29. Precision Varionic International Limited

30. Formformform Ltd
31. Oxford Instruments Nanotechnology Tools Limited
32. Zapgocharger Ltd
33. Netcomposites Limited
34. Emyrus Limited
35. Applied Graphene Materials UK Limited
36. Haero
37. Thales Underwater Systems Limited
38. M-Solv Ltd
39. Everon Energy Ltd
40. Haydale Limited
41. Gwent Electronic Materials Limited
42. Eksagon Group Ltd
43. Rapid Powders Limited
44. IS-Instruments Limited
45. Applied Materials Technology Limited
46. Sedgetech
47. Surface Measurement Systems Limited
48. Innovative Technology and Science Limited
49. Tecexec Limited
50. The Falcon Project Limited
51. Thomas Swan
52. Sherwin-Williams Protective & Marine Coatings
53. Esp Technology Limited
54. Evo Dental Centre Limited
55. Nanoregmed Ltd
56. Avon Polymer Products Limited
57. Clwyd Compounders Limited
58. Fraunhofer UK Research Limited
59. Nanoforce Technology Limited
60. B/E Aerospace (UK) Limited
61. Bombardier Aerospace UK Limited
62. Primary Dispersions Limited
63. Cytec Industrial Materials
64. Dycotec Ltd
65. Marshall of Cambridge Aerospace Limited

66. Dupont Teijin Films
67. Printed Electronics Ltd
68. In2tech Ltd
69. L.V.H. Coatings
70. Solaris Photonics Ltd
71. Exergy
72. NeuDrive
73. Novalia Ltd
74. Kw Special Projects Limited
75. Cambridge Nanomaterials Technology
76. Carr's Welding Technologies
77. Cedar Metals Limited
78. TISICS Limited
79. Nquiringminds Limited
80. G2o Water Technologies
81. Centre for Process Innovation
82. National Physics Laboratory
83. Unilever

Examples of funded projects

- Low Cost Printed Graphene-Oxide Membranes for Water Purification (£725,326, Innovate UK)
  Lead participant: G2o Water Technologies Limited
  Other participants: Centre for Process Innovation, William Blythe Limited and Unilever

- Development of Graphene Based Anti-Biofouling Coating, (£100,000, Innovate UK)
  Lead participant: Greentech Corporation
  Other participants: Nanoregmed

- Graphene/Elastomer Nanocomposites for Subsea Applications (£50,721, Innovate UK)
  Lead participant: Siemens
  Other participants: Avon Polymer Products and Clwyd Compounders

- 2D Materials for Next Generation Healthcare Technologies (2D-Health) (£5,327,896, EPSRC)
  Lead participant: University of Manchester
  Other participants: GlaxoSmithKline PLC, 2-DTech Limited, Smith and Nephew, Graphenea S.A., AstraZeneca plc, Janssen Pharmaceutical Companies

Appendix 4 - Survey Questions

Question 1: What is the size of your organisation?

Start-up
Small sized enterprise (<50 employees)
Medium-sized enterprise (<250 employees)
Large enterprise (>250 employees)
Multinational company
University
Research organisation
Other

Question 2: What best describes your organisations core business in relation to graphene?

Research
Raw material supplier
Advanced material supplier
Component developer
System integrator
End-user
Other

Question 3: Of the following areas, how important do you consider the following to address to advance commercialisation of graphene ?

Standard provision of info on graphene properties & production method by suppliers
Standard definitions of different types, forms and properties of graphene
Info on the disposal, handling, transportation & storage of graphene or graphene products
Delivery of consistent graphene properties between batches
Production of large-scale single layer graphene
Traceable and reproducible measurement and characterisation techniques
Cost and accessibility of product testing
Handling, storage & transport of different graphene forms (graphene flakes, CVD, dispersions)
Standard graphene containers and packaging specifications (size, standard material)
Clarification of packaging, storage & transportation environment on graphene product (risks of contamination, effect of moisture, flammability)
Consistent evidence/data on the value of using graphene against competitive advanced materials (e.g.carbon nanotubes)
Integration of graphene into other materials (e.g. Silicon), design or system
Product verification and validation
Advance knowledge of graphene toxicology
Health and safety best practices and guidelines to handle graphene
Standard/specific equipment for handling (e.g. containment units, PPE etc)

Question 4: In which ways do you consider standards development could impact the commercialisation and innovation of graphene?

Strengthening the knowledge and intellectual property (IP) by UK organisations
Support economies of scale (e.g. cost,scale up) for graphene
Attracting inward investment
Opening up international markets for UK Innovators
Supporting infrastructure development
Promoting consumer confidence
Improving safety in deployment of graphene/graphene products
Providing a supporting to regulation
Fostering collaboration and openness of supply chains

Question 5: Other comments - Please state

Appendix 5- Survey responses

Question 1: What is the size of your organisation?

Respondents	109
Choices	**Votes**
Start-up	18
Small sized enterprise (<50 employees)	19
Medium-sized enterprise (<250 employees)	8
Large enterprise (>250 employees)	9
Multinational company	9
University	29
Research organisation	7
Other	10

Other (specify):

- Commercialise Graphene and other 2D materials' applications
- Government
- Consultant (textiles)

Question 2: What best describes your organisations core business in relation to graphene?

Respondents	112
Choices	**Votes**
Research	49
Raw material supplier	2
Advanced material supplier	15
Component developer	9
System integrator	7
End-user	8
Other	22

Other (specify):

- Innovator working with partners
- Quality control systems developer
- Research and Business Development
- Graphene composite innovation
- Interest in applying it to textiles
- We are a producer of Graphene in quantity for our own use. We characterise it for integration into composites that we produce and we also offer bespoke contract R&D.
- Consultant
- Master Planning, Architecture and Bionic Building designers

Question 3: Of the following areas, how important do you consider the following to address to advance commercialisation of graphene ?

Date	TOTAL
Respondents	112
Choices	**Weighted average**
Standard provision of info on graphene properties & production method by suppliers	4.39
Standard definitions of different types, forms and properties of graphene	4.46
Info on the disposal, handling, transportation & storage of graphene or graphene products	4.01
Delivery of consistent graphene properties between batches	4.61
Production of large-scale single layer graphene	3.69
Traceable and reproducible measurement and characterization techniques	4.29
Cost and accessibility of product testing	4.04
Handling, storage & transport of different graphene forms (graphene flakes, CVD, dispersions)	3.81
Standard graphene containers and packaging specifications (size, standard material)	3.25
Clarification of packaging, storage & transportation environment on graphene product (risks of contamination, effect of moisture, flammability)	3.70
Consistent evidence/data on the value of using graphene against competitive advanced materials (e.g.carbon nanotubes)	4.33
Integration of graphene into other materials (e.g. Silicon), design or system	4.15
Product verification and validation	4.27
Advance knowledge of graphene toxicology	4.31
Health and safety best practices and guidelines to handle graphene	4.15
Standard/specific equipment for handling (e.g. containment units, PPE etc)	3.83

Universities and Research Organisations	Average
Manufacturing, process set up and control: Delivery of consistent graphene properties between batches	4.88
Graphene information/material specifications and data sheets: Standard provision of info on graphene properties & production method by suppliers	4.58
Graphene information/material specifications and data sheets: Standard definitions of different types, forms and properties of graphene	4.58
Manufacturing, process set up and control: Traceable and reproducible measurement and characterization techniques	4.50
Product design: Consistent evidence/data on the value of using graphene against competitive advanced materials (e.g.carbon nanotubes)	4.24
Product design: Integration of graphene into other materials (e.g. Silicon), design or system	4.24
Health and safety: Advance knowledge of graphene toxicology	4.16
Product design: Product verification and validation	4.12
Health and safety: Health and safety best practices and guidelines to handle graphene	4.06
Graphene information/material specifications and data sheets: Info on the disposal, handling, transportation & storage of graphene or graphene products	4.03
Manufacturing, process set up and control: Cost and accessibility of product testing	4.03
Handling, storage and transportation: Handling, storage & transport of different graphene forms (graphene flakes, CVD, dispersions)	3.98
Manufacturing, process set up and control: Production of large-scale single layer graphene	3.84
Health and safety: Standard/specific equipment for handling (e.g. containment units, PPE etc)	3.72
Handling, storage and transportation: Clarification of packaging, storage & transportation environment on graphene product (risks of contamination, effect of moisture, flammability)	3.35
Handling, storage and transportation: Standard graphene containers and packaging specifications (size, standard material)	3.23

Start-ups	Average
Manufacturing, process set up and control: Delivery of consistent graphene properties between batches	5.88
Product design: Consistent evidence/data on the value of using graphene against competitive advanced materials (e.g.carbon nanotubes)	5.69
Health and safety: Advance knowledge of graphene toxicology	5.63
Product design: Integration of graphene into other materials (e.g. Silicon), design or system	5.38
Graphene information/material specifications and data sheets: Standard provision of info on graphene properties & production method by suppliers	5.13
Manufacturing, process set up and control: Cost and accessibility of product testing	5.12
Product design: Product verification and validation	5.00
Health and safety: Health and safety best practices and guidelines to handle graphene	5.00
Graphene information/material specifications and data sheets: Standard definitions of different types, forms and properties of graphene	4.88
Manufacturing, process set up and control: Traceable and reproducible measurement and characterization techniques	4.81
Graphene information/material specifications and data sheets: Info on the disposal, handling, transportation & storage of graphene or graphene products	4.69
Manufacturing, process set up and control: Production of large-scale single layer graphene	4.13
Handling, storage and transportation: Standard graphene containers and packaging specifications (size, standard material)	4.00
Handling, storage and transportation: Clarification of packaging, storage & transportation environment on graphene product (risks of contamination, effect of moisture, flammability)	3.88
Health and safety: Standard/specific equipment for handling (e.g. containment units, PPE etc)	3.88
Handling, storage and transportation: Handling, storage & transport of different graphene forms (graphene flakes, CVD, dispersions)	3.47

Small and Medium Enterprises	Average
Manufacturing, process set up and control: Delivery of consistent graphene properties between batches	4.60
Product design: Product verification and validation	4.58
Product design: Consistent evidence/data on the value of using graphene against competitive advanced materials (e.g.carbon nanotubes)	4.54
Health and safety: Advance knowledge of graphene toxicology	4.42
Health and safety: Health and safety best practices and guidelines to handle graphene	4.38
Product design: Integration of graphene into other materials (e.g. Silicon), design or system	4.35
Graphene information/material specifications and data sheets: Standard definitions of different types, forms and properties of graphene	4.33
Graphene information/material specifications and data sheets: Standard provision of info on graphene properties & production method by suppliers	4.30
Graphene information/material specifications and data sheets: Info on the disposal, handling, transportation & storage of graphene or graphene products	4.15
Manufacturing, process set up and control: Cost and accessibility of product testing	4.15
Manufacturing, process set up and control: Traceable and reproducible measurement and characterization techniques	4.11
Handling, storage and transportation: Handling, storage & transport of different graphene forms (graphene flakes, CVD, dispersions)	4.08
Health and safety: Standard/specific equipment for handling (e.g. containment units, PPE etc)	4.08
Handling, storage and transportation: Clarification of packaging, storage & transportation environment on graphene product (risks of contamination, effect of moisture, flammability)	4.08
Manufacturing, process set up and control: Production of large-scale single layer graphene	3.88
Handling, storage and transportation: Standard graphene containers and packaging specifications (size, standard material)	3.59

Large companies	Average
Manufacturing, process set up and control: Delivery of consistent graphene properties between batches	4.72
Graphene information/material specifications and data sheets: Standard definitions of different types, forms and properties of graphene	4.53
Manufacturing, process set up and control: Traceable and reproducible measurement and characterization techniques	4.50
Health and safety: Advance knowledge of graphene toxicology	4.50
Graphene information/material specifications and data sheets: Standard provision of info on graphene properties & production method by suppliers	4.41
Product design: Consistent evidence/data on the value of using graphene against competitive advanced materials (e.g.carbon nanotubes)	4.39
Health and safety: Health and safety best practices and guidelines to handle graphene	4.28
Product design: Product verification and validation	4.22
Graphene information/material specifications and data sheets: Info on the disposal, handling, transportation & storage of graphene or graphene products	4.06
Manufacturing, process set up and control: Cost and accessibility of product testing	4.06
Health and safety: Standard/specific equipment for handling (e.g. containment units, PPE etc)	3.89
Handling, storage and transportation: Handling, storage & transport of different graphene forms (graphene flakes, CVD, dispersions)	3.83
Handling, storage and transportation: Clarification of packaging, storage & transportation environment on graphene product (risks of contamination, effect of moisture, flammability)	3.83
Product design: Integration of graphene into other materials (e.g. Silicon), design or system	3.78
Manufacturing, process set up and control: Production of large-scale single layer graphene	3.67
Handling, storage and transportation: Standard graphene containers and packaging specifications (size, standard material)	2.89

Question 4: In which ways do you consider standards development could impact the commercialisation and innovation of graphene?

Respondents	86
Choices	**Votes**
Strengthening the knowledge and intellectual property (IP) by UK organisations	29
Support economies of scale (e.g. cost,scale up) for graphene	32
Attracting inward investment	17
Opening up international markets for UK Innovators	31
Supporting infrastructure development	24
Promoting consumer confidence	45
Improving safety in deployment of graphene/graphene products	33
Providing a supporting to regulation	16
Fostering collaboration and openness of supply chains	33

Universities and Research Organisations	**Votes**
1. Promoting consumer confidence	13
2. Strengthening the knowledge and intellectual property (IP) by UK organisations	10
3. Fostering collaboration and openness of supply chains	10
4. Supporting infrastructure development	9
5. Improving safety in deployment of graphene/graphene products	9
6. Support economies of scale (e.g. cost,scale up) for graphene	8
7. Opening up international markets for UK Innovators	8
8. Attracting inward investment	6
9. Providing a supporting to regulation	4

Start-ups	**Votes**
1. Fostering collaboration and openness of supply chains	10
2. Promoting consumer confidence	9
3. Support economies of scale (e.g. cost,scale up) for graphene	7
4. Opening up international markets for UK Innovators	7
5. Strengthening the knowledge and intellectual property (IP) by UK organisations	6
6. Improving safety in deployment of graphene/graphene products	6
7. Supporting infrastructure development	5
8. Attracting inward investment	4
9. Providing a supporting to regulation	1

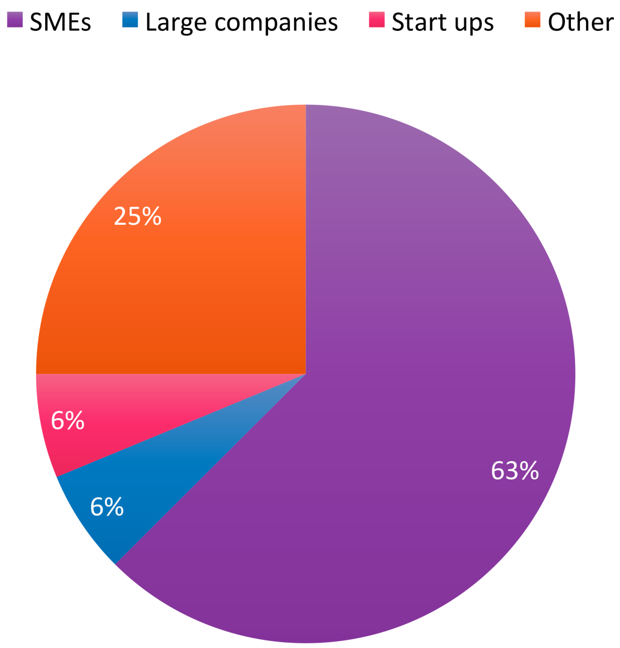
Small and Medium Enterprises	Votes
1. Support economies of scale (e.g. cost, scale-up) for graphene	11
2. Opening up international markets for UK Innovators	10
3. Promoting consumer confidence	9
4. Improving safety in deployment of graphene/graphene products	7
5. Fostering collaboration and openness of supply chains	7
6. Strengthening the knowledge and intellectual property (IP) by UK organisations	6
7. Providing a supporting to regulation	6
8. Attracting inward investment	5
9. Supporting infrastructure development	5

Large companies	Votes
1. Promoting consumer confidence	10
2. Improving safety in deployment of graphene/graphene products	7
3. Support economies of scale (e.g. cost,scale up) for graphene	5
4. Opening up international markets for UK Innovators	4
5. Fostering collaboration and openness of supply chains	4
6. Strengthening the knowledge and intellectual property (IP) by UK organisations	3
7. Supporting infrastructure development	3
8. Providing a supporting to regulation	2
9. Attracting inward investment	1

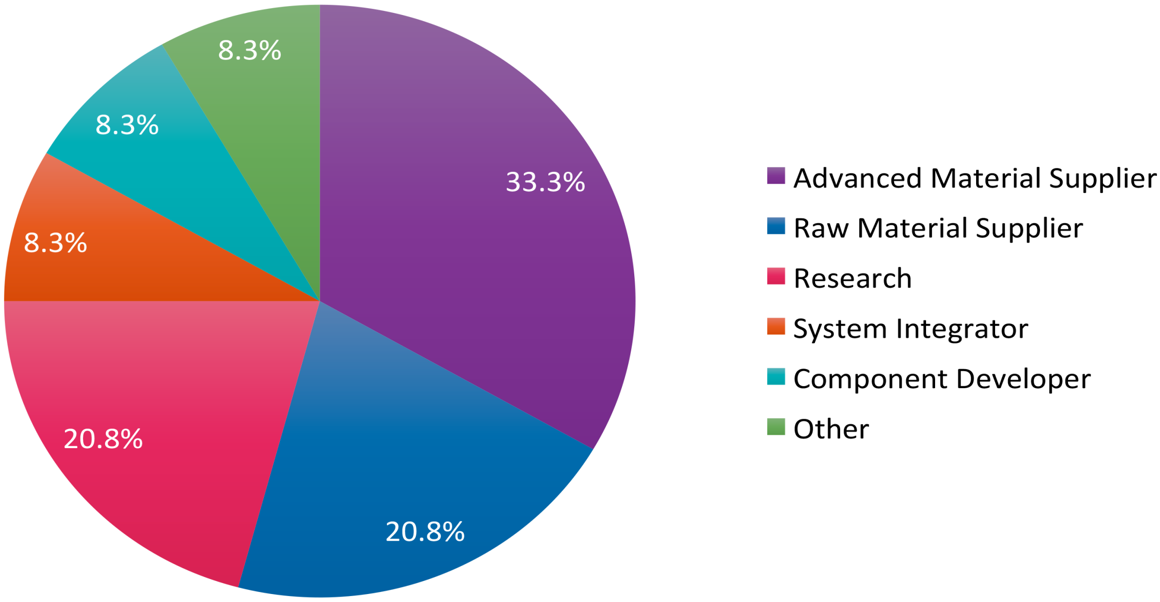
Appendix 6 – One-to-one Interviews

17 one to one interviews have been carried out with different UK businesses across the graphene value chain.

Question 1: What is the size of your organisation?



Question 2: What best describes your organisation's core business in relation to graphene?



Question 3: How can standards advance the commercialisation of graphene?

Question 4: In which ways do you consider standards development could impact the commercialisation and innovation of graphene?

British Standards Institution

The British Standards Institution (BSI) is a global leader in the development of standards of good practice for business and industry. Formed in 1901, BSI was the world's first National Standards Body (NSB) and a founding member of the International Organization for Standardization (ISO). Over a century later, BSI is focused on business improvement across the globe, working with experts in all sectors of the economy to develop codes, guidance and specifications that accelerate innovation, increase productivity, boost international trade and support economic growth. Research funded by the Department for Business, Innovation and Skills (BIS) and published by BSI in 2015 concluded that 37.4% of UK productivity, 28.4% of UK GDP growth and £6.1 billion of UK exports can be attributed to standards.

Renowned as the originator of many of the world's best known business standards, BSI's activity spans multiple sectors including aerospace, automotive, built environment, energy, food, healthcare and ICT.

Over 95% of BSI's work is on international and European standards. In its role as the UK National Standards Body, BSI represents UK economic and social interests across the international standards organisations ISO, IEC, CEN, CENELEC and ETSI, providing the infrastructure for over 11,000 experts to work on international, European, national and Publicly Available Specification (PAS) standards development in their chosen fields.

BSI operates in accordance with a Memorandum of Understanding with the UK Government and offers Government a business-led tool for delivery of its policy objectives. BSI's robust standards development process requires open and full consultation with stakeholders to build consensus-based outcomes. BSI, as the UK National Standards Body, has a public interest responsibility to develop and maintain the standards infrastructure to support UK emerging industries at home and internationally.

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KTN helps businesses get the best out of creativity, ideas and the latest discoveries, to strengthen the UK economy and improve people's lives. As a network partner of Innovate UK, KTN links new ideas and opportunities with expertise, markets and finance through our network of businesses, universities, funders and investors.

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