Institution: The University of Manchester		
Unit of Assessment: 9 (Physics)		
Title of case study: Influence on graphene policy and global market growth		
Period when the underpinning research was undertaken: 2001 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Konstantin Novoselov	Professor (2013 – present) Research Fellow (2001 -2013)	January 2001 – present
Andre Geim	Professor	November 2001 – present
Cinzia Casiraghi	Professor (2016 – present) Reader (2014 – 2016) Lecturer (2010 – 2014)	2010 – present
Ursel Bangert	Reader (2009 – December 2013) Senior Lecturer (1993 – 2009)	1993 – December 2013
Rahul Nair	Professor (2016 – present) Research Fellow (2012 – 2016) Research Associate (2011 – 2012)	March 2011 – present
Period when the claimed impact occurred: October 2013 - July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The isolation and characterisation of graphene by The University of Manchester (UoM) has led to disruptive technological change across a broad range of industries. Continued UoM expertise, provided to governments and industry about how to best translate graphene research into commercial success, has resulted in:

- Influence on EU policy to secure GBP198Million of funding within the impact window and a further GBP130Million grant extension to further assist graphene commercialisation;
- Two international standards and co-authorship of a good practice guide for graphene analysis. The setting of international standards helps mitigate supply chain risks whilst reducing costly in-house testing, providing confidence to investors, and ultimately stimulating market development;
- A consistent growth (40% year-on-year between 2014 and 2020) in the revenue for global production of graphene and graphene-related materials (not including products containing graphene). Estimates for total cumulative graphene production revenue within the window 2013 to 2020, range from GBP48Million and GBP480Million.

Cumulatively, this has enabled approximately USD600Million in investment and market growth for graphene production across the impact window.

2. Underpinning research

In 2004, research conducted at The University of Manchester (UoM) by Geim and Novoselov demonstrated the existence of free-standing two-dimensional crystals, including graphene, boron nitride and an array of dichalcogenides and complex oxides **[1]**. Isolation techniques, initially achieved by rubbing layered nano-crystals against a solid surface **[1]**, and later by mechanical exfoliation **[2]**, offered a simple, cheap and reliable approach for isolation of these 2D materials. This, combined with the promise that the new class of 2D materials would offer a wealth of new physical phenomena for application across a range of industries, led to significant interest in the field. Interest in graphene was further accelerated when Geim and Novoselov **[2]** demonstrated that graphene's electrical properties offered ballistic transport (negligible resistivity to the passage) of charge, a linear current-voltage (I-V) relationship, and the ability to sustain huge currents. These properties made graphene a target for research in semi-conductor related industries where performance improvements in silicon-dominated technologies were plateauing **[2]**.

Building on previous UoM research into likely challenges and opportunities facing industrialisation of graphene, a 2012 review 'A roadmap for graphene' **[3]**, provided an overview of graphene research, a critique of advances in, and challenges of, production, and, most importantly, a critical analysis of the feasibility of various graphene applications. The work acknowledged that challenges in mass production of high-quality graphene would hinder the emergence of markets dependant on it (such as electronics and biocompatibility applications). Finally, the work suggested that technologies that can be improved with lower grade and cheaper to produce graphene-related materials (GRMs; graphene oxides, bilayer graphene, few-layer graphene, and graphene nanoplatelets) would likely be the first to appear on the market **[3]**. In 2015, three UoM authors contributed to the '*Science and technology roadmap for graphene, related two-dimensional crystals, and hybrid systems*' **[4]**, a 214-page review that presented the science and technology roadmap for research and commercialisation of graphene and related two-dimensional crystals. The roadmap was developed within the framework of the European Graphene Flagship (detailed below) and outlined priority research areas, and multiple short-, medium- and long-term targets for the flagship to follow "that might lead to impacts and benefits reaching into most areas of society".

In 2008, in collaboration with the STFC Daresbury Laboratory, UoM researchers demonstrated experimentally that scanning transmission electron microscopy (TEM) could be used to characterise free-standing graphene layers **[5]**. Not only could films be identified but low-loss Electron Energy Loss Spectroscopy (EELS) could distinguish between single-, two- and few-layer graphene as a result of spectral redshifts in the energies of π and π+σ plasmons with film thickness. The opportunity for accurately determining the film thicknesses of few-layer graphene and their defects in relation to their physical properties helped categorise the distinction between the different forms of graphene material.

In collaboration with FU Berlin (The Free University of Berlin) in 2013, building on previous UoM research into the Raman spectra of graphene, UoM research demonstrated that regardless of the nature of the defect, a two-stage disordering evolution is observed in the Raman spectra of imperfect graphene **[6]**. Specifically, Raman spectra identify the ratio of *sp2* (non-graphitic carbon) to *sp3* (graphitic carbon) within a sample, providing a measure of the quality of the film. The wavelength of the *sp2* signal is also indicative of the nature of the disorder. Outcomes from **[5, 6]** demonstrate that TEM and Raman spectroscopy are effective non-destructive tools for unambiguous identification of graphene materials.

3. References to the research

Citations counts are from Web of Science (February 2021):

[1] **Novoselov K.S., Jiang D., Schedin F., Booth T.J., Khotkevich V.V**., Morozov S.V., & Geim A.K., "Two dimensional atomic crystals", *Proceedings of the National Academy of Sciences*, 102, 10451 (2005) DOI: 10.1073/pnas.0502848102. (8,082 citations)

[2] **Novoselov K.S., Geim A.K.**, Morozov S.V., **Jiang D., Zhang Y**., Dubonos S.V., Grigorieva I.V. & Firsov A.A. "Electric field effect in atomically thin carbon films", *Science* 306, 666, (2004) DOI: 10.1126/science.1102896. (43,099 citations)

[3] **Novoselov, K.,** Fal′ko, V., Colombo, L. et al. "A roadmap for graphene", *Nature,* 490, 192–200 (2012). DOI: 10.1038/nature11458 (5,760 citations)

[4] Ferrari, A. et al. "Science and technology roadmap for graphene, related two-dimensional crystals, and hybrid systems", *Nanoscale*, 7, 4598-4810 (2015). DOI: 10.1039/C4NR01600A (1,678 citations)

[5] Gass M., **Bangert U.,** Bleloch A., Wang P., **Nair R.R., Geim A.K.**, "Free-standing graphene at atomic resolution", *Nature Nanotech* **3**, 676–681 (2008). DOI: 10.1038/nnano.2008.280. (484 citations).

[6] **Eckmann A.**, Felten A., Verzhbitskiy I., Davey R., **Casiraghi C.**, "Raman study on defective graphene: Effect of the excitation energy, type, and amount of defects", *Phys.*

Rev. B. 88 (2013) 035426. DOI: 10.1103/PhysRevB.88.035426. (174 citations).

The quality of the research is shown through the award of the Nobel prize in Physics in 2010 to Geim and Novoselov for **[1, 2]**; the use of **[3, 4]** as guides for the European flagship programme, the EU's largest single-field research initiative; and the use of **[4 – 6]** in setting international standards.

4. Details of the impact

UoM research **[3, 4]** has had influence (directly and indirectly) on public and private policy makers, to nurture the graphene production market and the resulting economic growth. Whilst the rapid growth of the graphene market and its impacts come from the concerted efforts of many people around the world, its genesis and foundations are based on the initial graphene isolation and characterisation work from UoM **[1, 2]**. The input into international standards and best practice **[5, 6]**, have supported confidence in this market.

Pathway to impact

Established industries, such as the semiconductor industry and the International Technology Roadmap for Semiconductors (ITRS), have used working groups, road mapping and calculative practices to set international research agendas. Using lessons from these industries, Novoselov and Geim from UoM, alongside other experts in the burgeoning field, aimed to strategize and provide key expertise to successfully nurture the development of the graphene market **[A].** This began in 2007 with the production of a definitive outline of the current state of graphene research. In 2012, Novoselov and a wider pool of experts delivered the first graphene roadmap **[3]**. The roadmap outlined developments in graphene production, took stock of the challenges facing commercialisation of graphene into key industries and provided a critical analysis of the feasibility of various graphene applications. These roadmaps have been influential in guiding the development of a large range of technologies based on graphene and GRM, and increasing investor confidence in expanding the graphene production market. Within the European market, this culminated in UoM's contribution to 'Science and technology roadmap for graphene, related two-dimensional crystals and hybrid systems' **[4]**, which set goals for the European Union's (EU) graphene flagship programme.

4.1 Shaping policy and investment budgets

The Graphene Flagship, launched in October 2013, is the EU's largest single-field research initiative with a EUR1,000,000,000 (GBP830,000,000) planned budget **[B]**. The flagship is *"tasked with bringing together academic and industrial researchers to take graphene from the realm of academic laboratories* ***into European society*** *in the space of 10 years, thus generating* ***economic growth, new jobs and new opportunities***" **[C]**. A seven-person strategic advisory panel **[D]** that, by virtue of their expertise and insight in the field, included Novoselov and Geim **[1-3]** initially shaped the flagship's agenda. From 2015 onwards, the 'Science and technology roadmap for graphene, related two-dimensional crystals and hybrid systems' **[4]**, provided further direction through expert insight on how to best pursue academic and commercial success with graphene technologies, assuring government confidence in continued investment. The flagship has therefore helped to continue to leverage European funding, and direct research and development policy towards international innovation and market impact. The flagship formalised in 2013 with 142 academic and industrial research partners across 23 countries. In 2020, the flagship has 146 partners split between research centres (22%), academic institutions (42%), and industry, including ***12 spin-off companies (36%)*** with over 1,200 current members **[B]**.

The flagship's initial "ramp-up" phase (1 October 2013 – 31 March 2016) received EUR54,000,000 (GBP43,000,000) in funding from the European Commission (EC). The secondary phase was divided into two-year "cores". The approximate value of these cores between 2016-2018 and 2018-2020 is EUR89,000,000 (GBP77,000,000) and EUR88,000,000 (GBP77,000,000), respectively. Cumulatively this represents EUR231,000,000 (GBP198,000,000) funding within the impact window, with 50% coming from the EC and 50% through its 53 industrial partners and its 82 associated members **[E]**. In February 2020 the EC signed a EUR150,000,000 (GBP130,000,000) grant agreement to continue funding the Graphene Flagship up to March 2023 with a keen focus on **advancing industrial applications [F]**.

[Text removed for publication].

4.2 Established international standards for the graphene market: improving market competition and confidence

To address investor concerns over the quality and consistency of graphene material sold in the open market, UoM has demonstrated its continued commitment since 2014 to the growth of the graphene market by working closely with the (UK) National Physical Laboratory (NPL) on the development of international standards for graphene **[H]**. Since 2013, NPL has been the global lead in developing international graphene standards within the nanotechnologies technical committee (ISO/TC229), which oversees the formation of international standards work encapsulating all graphene and related 2D materials. ISO standards are globally adopted, especially in countries at the forefront of graphene production (China, USA, South Korea, India, Taiwan and Japan, and several European countries) **[H]**. NPL has developed the definitive terminology standard: '*Nanotechnologies — Vocabulary — Part 13: Graphene and related two-dimensional (2D) materials'* (ISO/TS 80004-13:2017), which was published by ISO in 2017) **[H]**. UoM research **[5]** was key to defining the thickness of different forms of graphene, and in characterising graphene defects.

In 2017, NPL and UoM co-authored good practice guide NPL GPG 145: *'Characterisation of the structure of graphene'*, which provides analytical protocols for determining the structural properties of graphene **[H]**. TEM and Raman techniques defined in the guide have developed from research conducted at UoM **[5, 6]**. This guide served as the template for the second international standard **[H],** *'Nanotechnologies — Structural characterisation of graphene from powders and liquid dispersions'* (ISO/PDTS 21356-1:2020), currently in publication. This standard informs how a company should approach characterising either their product or a product they have bought, for quality assurance against the terminology standard. NPL Good Practice Guide 145 has been downloaded from the NPL website around 1,600 times. In the month of its publication, it was the second most popular NPL guide and it continues to consistently feature in the top 50 downloads from the NPL website **[H]**. Use of product standards has been shown to (i) streamline or eliminate the need for internal company assurance testing and (ii) mitigate the risk companies face introducing new product lines. These factors increase revenue by up to 5% and 33%, respectively **[H]**.

4.3 Economic impact of the global production of graphene

An independent review in 2019 summarised 20 market studies for the global production of graphene and GRMs (not products containing graphene) between 2010 and 2025 **[I]** (see Figure 1 below, reproduced from this study). The market studies estimated the global market based on the current market prices and production volumes of producers, along with estimates from market experts. Overall, the studies all infer an annual 40% growth rate in the revenue for global graphene production between 2014 and 2025 (all between 36% and 44%), which is equivalent to a doubling in value every two years, or a factor of ten growth during the seven years of the REF impact window. The estimated revenues from these studies range from USD20,000,000 to USD200,000,000 (GBP16,000,000 to GBP160,000,000) in 2020. The most conservative and bold estimates for total cumulative graphene production revenue within the impact window were USD60,000,000 and USD600,000,000 (GBP48,000,000 to GBP480,000,000) respectively **[I].**

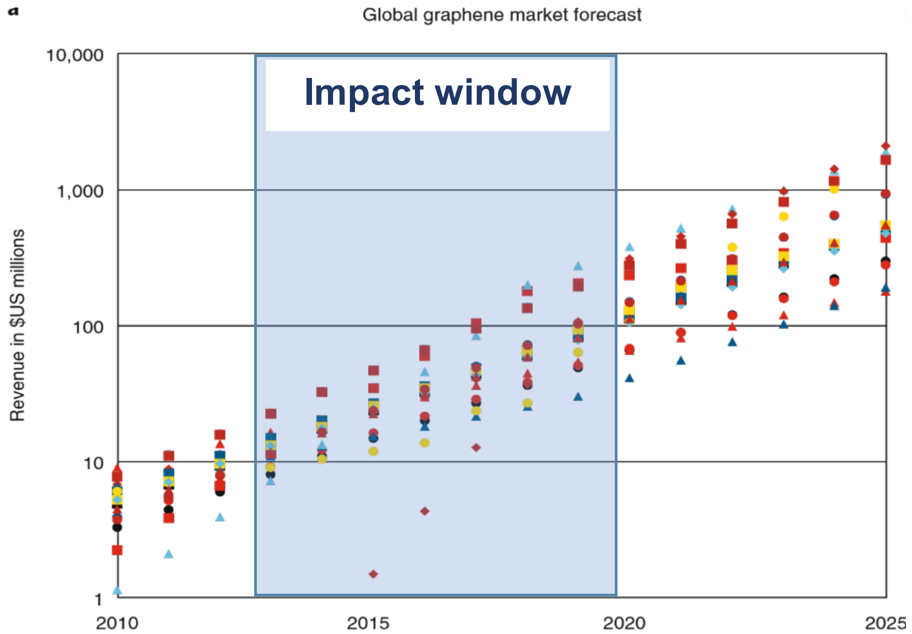

Figure 1 Historic and predicted revenue of the global graphene market **[I]**. The different coloured data points refer to each of 20 independent market studies.

5. Sources to corroborate the impact

[A] Alvial-Palavicino, C., and Konrad, K. (2019) The rise of graphene expectations: anticipatory practices in emergent nanotechnologies, *Futures*, 109, p192–202 DOI: 10.1016/j.futures.2018.10.008

[B] EU Graphene Flagship Annual Summary Reports for 2015 and 2019

[C] Graphene Flagship web-page "About Graphene Flagship" (14 March 2019). [Archived website, pdf on file].

[D] UoM Press Release "Graphene Flagship has set sail" (14 October 2013). [Available at https://www.manchester.ac.uk/discover/news/article/?id=10857]

[E] Graphene Flagship web-page "Funding Systems" (2 March 2018). [Archived website, pdf on file].

[F] Graphene Flagship Press Release "European Commission Signs 150M Grant Funding the Graphene Flagship" (25 February 2020) [Available at https://graphene-flagship.eu/graphene/news/european-commission-signs-150m-grant-funding-the-graphene-flagship/]

[G] [Text removed for publication]

[H] Letter of support (co-signed) from Science Area Leader and Chief Scientist, National Physical Laboratory, 23 July 2020

[I] Reiss, T., Hjelt, K. & Ferrari, A.C. (2019) Graphene is on track to deliver on its promises. *Nat. Nanotechnol*. 14, p907–910 DOI: 10.1038/s41565-019-0557-0