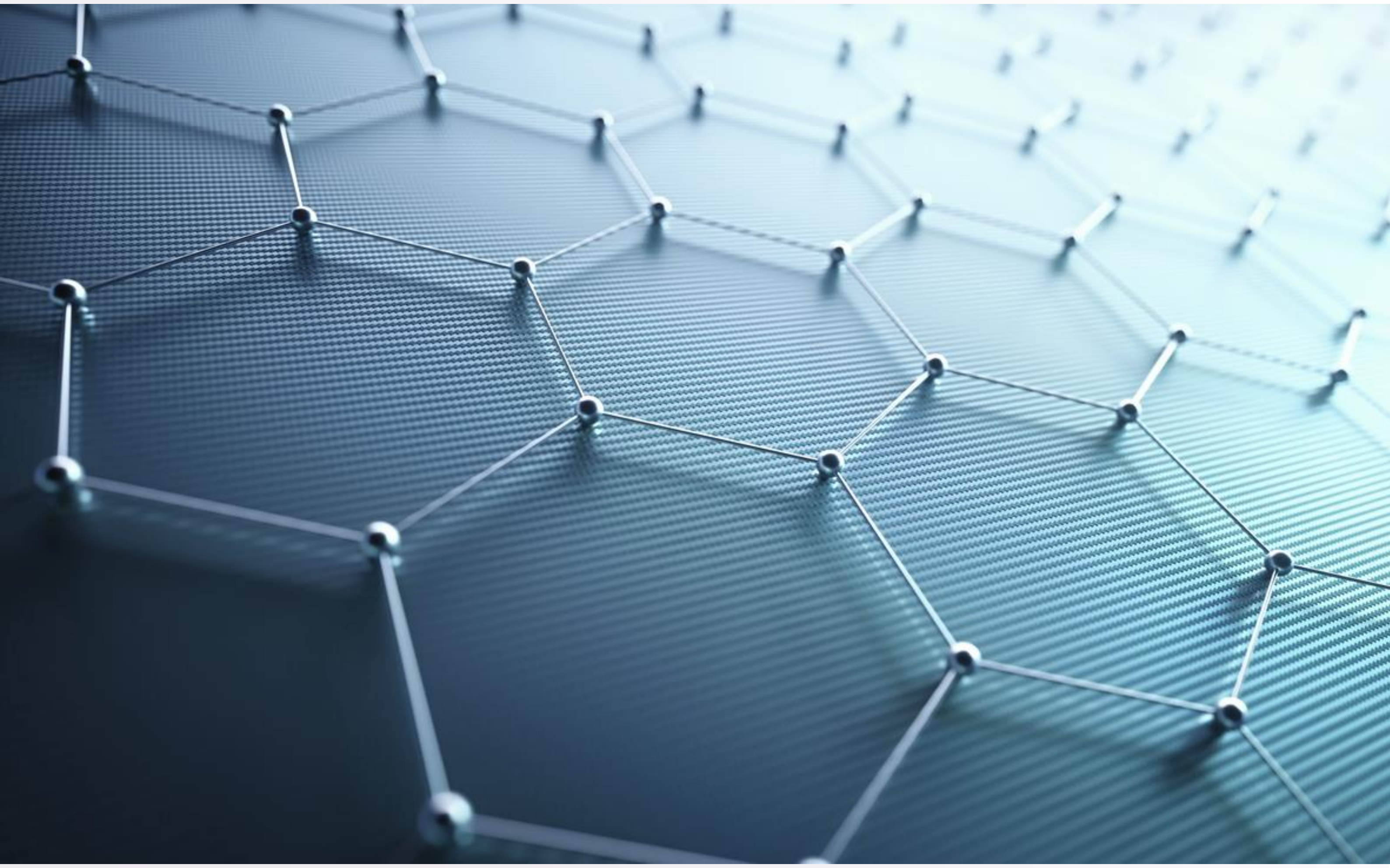
Graphene Technologies

Understanding the State-of-the-Art from a Patent Perspective



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This report is commissioned by the National Research Foundation (NRF) Singapore and produced by IPOS International, a subsidiary of the Intellectual Property Office of Singapore (IPOS). We acknowledge the partnership of Xora Innovation, Professor Antonio Helio de Castro Neto, Centre for Advanced 2D Materials and 2D Materials Pte Ltd in this study.

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Executive Summary

First isolated in 2004, graphene is a single layer of carbon atoms arranged in a honeycomb-like pattern. This two-dimensional material is among the world's thinnest, strongest materials and the best conductors of electricity and heat. While graphene's unique properties and significance in fundamental physics are clear, its potential in commercial applications is still being realised. To understand the commercial landscape and players, IPOS International's patent analytics team reviewed patent data — a lead indicator of commercial adoption.

Over the last decade, more than 62,000 graphene-related inventions were published globally. Graphene research and development gained rapid traction in 2010-2014, with a compound annual growth rate (CAGR) of 76%. Worldwide innovation output peaked in 2018, with a decline in graphene innovations observed across all the major countries active in graphene research.

This global slowdown presents both challenges and opportunities for research and investment. Well-studied areas have been tightly ring-fenced by the top technology holders. On the other hand, the maturity of some of these areas, such as graphene-enhanced lithium-ion batteries, can be attractive for investors. Further research would be better directed to emerging areas and specific technology niches such as water treatment.

1. Graphene production is well-studied, congested and tightly ring-fenced

Mass production and commercial availability are prerequisites for viable applications of graphene. Since its initial isolation, large-scale graphene production techniques have been a prime focus for innovation. Overall, graphene production is a well-studied, congested space tightly ring-fenced by the leading academic institutions and commercial players. While the top institutes are mainly from China, commercial entities range from graphene manufacturers like Global Graphene Group and Chengdu New Keli to technology giants such as Samsung, Sinopec, and BOE Technology. Each has built strong patent portfolios around specific graphene product types.

The maturity of these technologies and commercial availability of graphene products suggest that additional R&D investments in graphene production are unlikely to yield a strong return.

2. Graphene applications in Lithium-ion (Li-ion) battery technology are more mature than those in lithium-sulphur (Li-S) battery technology

Graphene-enhanced Li-ion battery technology is mature and ready for commercial adoption. The top 10 lithium battery manufacturers in the world have accumulated strong capability. Mass production of graphene-enhanced batteries is imminent. While this suggests diminishing returns for basic research, opportunities for technology consolidation and commercialisation are substantial. In-licensing, partnerships, mergers and acquisitions between universities, research institutes, technology giants and start-ups are likely to follow. Smaller companies with strong niche technologies sought after by the larger companies may stand to benefit.

Far fewer inventions relate to applying graphene to Li-S batteries. The portfolios of top applicants are much smaller compared to those related to graphene-enhanced Li-ion battery technology. Furthermore, the top battery makers are also significantly less present amongst top applicants in this area.

3. Graphene technologies for display and coating may not be the best areas for spin-offs or start-ups

Technologies related to graphene for display are heavily guarded by world-leading display panel makers, such as BOE Technology, Samsung, and LG. The difficulty associated with the manufacture of large, defect-free graphene films could be a high technical barrier that is difficult to overcome. On the other hand, many small commercial entities are active in applying graphene in coating. The fragmentation of this space suggests that graphene for coating would be challenging to commercialise, unless driven by a strong technology niche or product differentiation.

4. Sensor and biomedical applications are emerging

In sensor and biomedical applications, academic institutes account for about 70% and 60% of the related inventions respectively. The application focus of these two areas, however, is highly scattered. This suggests that research has not been systematically applied to address the challenges of these two areas: quality control and scaling for sensor applications, and safety for biomedical applications. These two areas remain nascent spaces for graphene R&D.

5. Graphene in water treatment and purification holds potential for Singapore

Graphene for water purification is growing rapidly, from seven inventions in 2010 to 544 in 2019. While top technology holders in graphene for water treatment comprise largely of academic institutes. Singaporean entities have had a headstart in adopting these technologies through strategic partnerships with commercial players. Continued research and investment in the commercialisation of these technologies could enable Singapore to establish a first-mover advantage in the market.

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Introduction

Imagine "crystals one atom or molecule thick, essentially two-dimensional planes of atoms shaved from conventional crystals," said Nobel Laureate Andre Geim in *New Scientist*. "Graphene is stronger and stiffer than diamond, yet can be stretched by a quarter of its length, like rubber. Its surface area is the largest known for its weight."[1] These are part of the many extraordinary properties possessed by graphene, a one-atom-thick film of carbon whose strength, flexibility and electrical conductivity have opened up new horizons for pure physics research as well as for high-tech applications.

To many experts, graphene is considered the material of the future. It has a special combination of superior properties that sets it apart from any other materials. It is the strongest material known to mankind, harder than diamond yet more elastic than rubber, and tougher than steel yet lighter than aluminium. Its electrical conductivity is 13 times higher than copper; it conducts heat two times faster than diamond; it is so impervious that even the smallest atom (helium) cannot pass through. Graphene has an extremely high specific surface area for interaction with molecules, electrons, ions, photons and phonons, making it ideal for applications in sensors, energy storage, biomedical, and other uses.

The unique set of properties has excited researchers and businesses around the world, as graphene offers a fascinating material platform for the development of next-generation technologies in various industries – flexible wearable technologies, superfast electronics, ultrasensitive sensors, multifunctional composites and coatings, membranes, medicine and biotechnology, energy harvesting and storage, and more.

As the world strives to maintain its pace of innovation, graphene has much to offer. It is a credible starting point for disruptive technologies; one that could open up new markets and even replace existing technologies or materials.

[1] New Scientist, "Andre Geim: Why graphene is the stuff of the future".

Scope of the study

This report examines the landscape of graphene technologies based on graphene-related patent applications published in the last decade (2010-2019). Specifically, this study covers domains relating to graphene product types, methods of production, properties, and applications (Exhibit 1). In addition to the macro-level assessment of the different domains, this study takes a deep dive into various sub-domains and specific areas as part of our detailed analysis.

Patent data represents an important and well-structured source of information on scientific and technological advancements. It is also a lead indicator of commercial adoption. When combined with other information, such as policies of different countries as well as market and business intelligence, the analysis of graphene-related patenting activities provides a multi-faceted and holistic assessment of current graphene technologies. The data enables us to assess the maturity of different graphene technology domains, allowing us to derive insights relating to research and investment opportunities.

Exhibit 1: Scope of the patent analytics study

Graphene Technologies

Products & methods of production

Product Types	Production methods
- Single layer - Few layers - Nanoplatelets - Graphene Oxide (GO) - Reduce graphene oxide (rGO) - Other film or layers	- CVD - Epitaxy - Hydrothermal - Hummers - Exfoliation - Electrochemical - Supercritical - Flow exfoliate

Properties & applications

Properties	Energy Storage	Separation
- Electrical - Thermal - Structural - Anticorrosion - Antifouling	- Li-ion batteries - Lead-acid batteries - Li-sulfur batteries - Supercapacitors - Fuel cells	- Desalination - Water purification - Fuel purification

Electronics	Composite & coatings
- Sensors - Printable electronics - Displays - Solar panels - Optical devices - Other devices	- Coating - Soundproof - Biomedical - 3D printing - Packaging barrier - Footwear - Armor

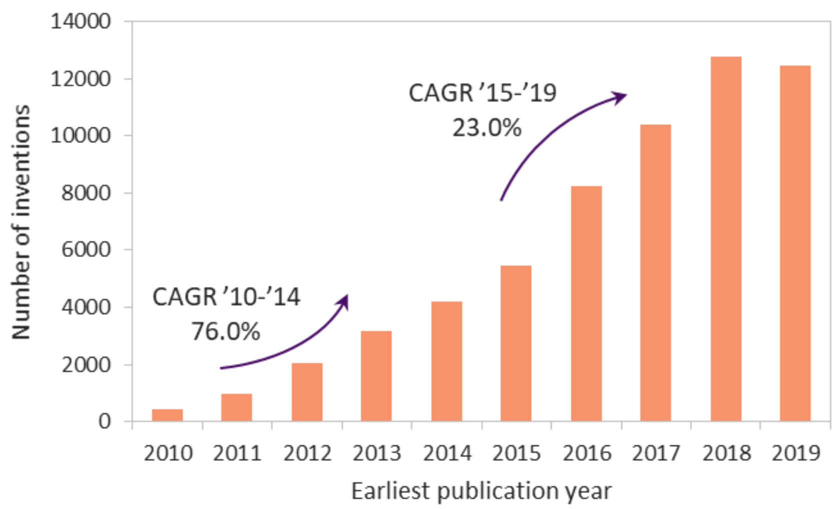
Global innovation trends

Since its discovery and isolation in 2004 by Sir Andre Geim and Sir Konstantin Novoselov, graphene has attracted worldwide attention due to its unique properties and potential impact on interdisciplinary materials research.

Globally, there were more than 62,000 graphene-related inventions[2] published in the past decade. In particular, graphene research and development had gained rapid traction in 2010-2014, giving rise to an astounding compound annual growth rate (CAGR) of 76% (Exhibit 2). The growth had since slowed down; the worldwide innovation output had peaked in 2018 with close to 13,000 inventions before the decline in 2019. Nevertheless, the CAGR in 2015-2019 was about 23%, which is nearly five times the growth rate of worldwide patent filings during the same period.[3]

The high volume of inventions underscores the significant push-and-pull at play for graphene technologies. It reflects not only the substantial resources invested in research and development but also the strong market demand, which is estimated at US$ 78.7 million in 2019, and expected to reach US$1 billion by 2027.[4]

Exhibit 2: Worldwide innovation trend of graphene technologies



[2] See Annex A: Methodology for the counting of inventions.
[3] World Intellectual Property Organization, “World Intellectual Property Indicators 2019”. The annual growth rate in 2014-2018 was used in this case since the worldwide 2019 data is not available at the time of this study.
[4] Grand View Research, “Graphene market size, share & trends analysis report by application, by product, by region, and segment forecasts, 2020 - 2027”.

While the interest in graphene is global, innovations in graphene technologies across the last decade are highly concentrated in only a handful of countries. China is the clear leader and has produced close to 47,000 inventions, more than 3 times the output from the rest of the world combined (Exhibit 3). The second and third spots were occupied by South Korea and the U.S., with about 4,700 and 3,300 inventions, respectively. Other countries or regions that are active in graphene innovations include Taiwan, the U.K., and Germany, each with more than 400 inventions published in the last decade.

The enormous filings from China are largely a result of its strategic focus on new materials, though state sponsorship towards patent filings plays a part.[5] Materials science has been a key focus of China as it aims to transform into a high-tech economy. The world's second-largest economy has been investing heavily in materials research with funding nearly quadrupled since 2008.[6] Various programmes at the national level such as New Materials Development Guide 2012, Key Technology Tech Roadmap for Made-in-China Plan 2025, and Guideline in Accelerating Graphene Development have all placed a strong focus on graphene.

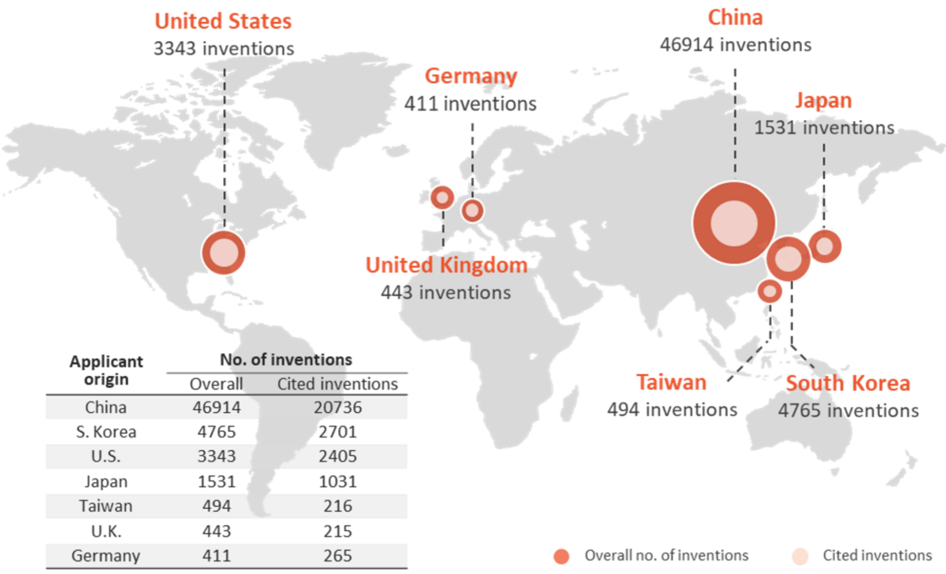
China has contributed close to 47,000 graphene inventions, more than three times the output from the rest of the world combined.

Chinese researchers are reaping the benefits of carefully built programmes and strong funding support. They are dominating the field of graphene research, in terms of both the invention quantity and the number of high-impact inventions, i.e. inventions that have been subsequently cited.[7] Consortia such as the China Innovation Alliance of the Graphene Industry are bringing together universities, institutes and companies to accelerate the technology transfer from research to product development and commercialisation.

[5] NS Tech, "Why China's impressive patent rates don't tell the whole story", 2019
[6] Nature, "Materials science is helping to transform China into a high-tech economy", March 2019
[7] A high degree of citation strongly indicates that the invention often forms the technological foundation upon which other players make further improvements.

Exhibit 3: Top countries/regions active in graphene research

China is dominating graphene research in terms of both the total number of inventions and the number of high-impact inventions, i.e. inventions that have been subsequently cited.



Applicant origin	No. of inventions	
	Overall	Cited inventions
China	46914	20736
S. Korea	4765	2701
U.S.	3343	2405
Japan	1531	1031
Taiwan	494	216
U.K.	443	215
Germany	411	265

Graphene innovations are slowing down globally

China's strong dominance in graphene research is the main driver of the global graphene-related innovation output. The world's emerging superpower has been sustaining the relentless upward trend of the worldwide graphene innovation before the drop in 2019, a decline that is widely believed to be a result of the sharp decrease in its investment in 2018.[8]

The drop in graphene innovation output is not limited to just China but a global phenomenon that has been observed across all the top countries/regions active in graphene research (Exhibit 4). For example, graphene inventions from South Korea and the U.S. have peaked in 2017, whereas Japan had its maximum output in 2013.

The global slowdown is a strong indication that some areas of graphene research are better established. This presents both challenges and opportunities for basic research and investment. For research and development, it is important to avoid well-studied or mature technologies so as not to re-invent the wheel. The focus should instead be on identifying emerging areas and building strong technology niches around them.

Exhibit 4: Publication trend of graphene-related inventions by top countries/regions

The number in the table refers to the number of published inventions, whereas the colour of the heatmap corresponds to the year-over-year growth as indicated by the colour scale.

	Earliest publication year									
	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
China	137	424	1166	1803	2654	3963	5995	8654	11182	10936
South Korea	77	231	357	578	612	567	641	676	497	529
U.S.	116	181	233	325	413	348	380	449	446	452
Japan	48	70	140	227	195	188	182	173	181	127
Taiwan	1	9	21	35	70	84	64	65	74	71
U.K.	15	17	38	36	70	54	73	54	64	22
Germany	14	26	38	45	52	51	39	55	55	36

Year-on-year growth: -50% | 0 | 50% | 100%

[8] Drop in the graphene investment in 2018 is 64% compared to that in 2017 according to "2020 年中国石墨烯产业发展形势展望" by CCID Consulting.

Strong competition to be expected

The discovery of graphene provided an immense boost and a new dimension to materials science and nanotechnology. Graphene has been an area of research actively pursued by universities, institutes, as well as different industrial players around the world since its first isolation in 2004.

Many of them have made significant breakthroughs and accumulated strong technology portfolios relating to both the production and application of this wonder material.

Exhibit 5: Top graphene technology holders

The number in the brackets denotes the number of published inventions by the entity in the last decade.

	China	Rest of the world
Universities/Institutes	CAS [2187]	KAIST, KR [253]
	Zhejiang Univ. [455]	Sungyunkwan Univ. [237]
	Harbin Inst of Tech [406]	KIST, KR [166]
	Jiangsu Univ. [371]	Hanyang Univ., KR [144]
	Tsinghua Univ. [362]	UNIST, KR [129]
	Southeast Univ. Nanjing [334]	Univ. California [97]
	Univ. of Jinan [325]	Korea Electronics Tech Inst [86]
	Tianjin Univ. [315]	MIT [63]
	South China Univ. of Tech [305]	CEA, FR [46]
	Changzhou Univ. [299]	NIMS, JP [34]
Commercial entities	Oceans King Lighting [406]	Samsung [509]
	Chengdu New Keli [360]	Global Graphene Group [316]
	Shengquan Group [186]	LG [252]
	Hangzhou GaoxiTech [165]	IBM [151]
	TCL [154]	Toshiba [111]
	Sixth Element [150]	Semiconductor Energy Lab [88]
	BOE Technology [132]	Nokia [88]
	Chenzhou Botai [129]	Fujitsu [76]
	Hunan Gonsion Graphite Tech [116]	Sekisui Chemical [76]
	Sinopec [113]	Lockheed Martin [60]

Extensive technology accumulation from academia

The simple “Scotch tape method” to peel graphene flakes off a chunk of graphite offers an extremely low-cost synthesis. It has enabled universities and research institutes to embark on their studies of graphene with relative ease. With strong government support, universities and institutes have gained a good understanding of the multidisciplinary characteristics of graphene in the initial years. The modern graphene research in academia has been directed towards the exploration of new graphene derivatives and their utilisations for different industrial purposes. Universities and research institutes are therefore strong players in this field and have patent portfolios that can rival top commercial players.

Academic graphene research has been particularly active in the Chinese and South Korean universities and research institutes, which dominate 16 spots of the top 20 list (Exhibit 5). The Chinese Academy of Sciences (CAS) tops the list with 2,187 inventions. Consistently ranked as the top research institution by *Nature Index* since its inception in 2016,[9] the world’s largest research organisation has been spearheading the nation’s graphene research. Along with its branch institutes (Annex C, Exhibit C-1), CAS has been making breakthroughs in both mass production and industrial applications.

Beyond China, the Korea Advanced Institute of Science and Technology (KAIST) leads the pack with 253 graphene inventions. The Daejeon-based research-oriented institute has been at the forefront of South Korea’s graphene research, with a strong focus on graphene synthesis and application in energy, electronic and optoelectronic devices.

[9] Nature Index 2020

New research needs to avoid well-studied, congested areas that have been tightly ring-fenced by the top technology holders.

Better explored areas could be more attractive for investment as they are closer to market adoption and may also set the next round of product advancement.

Established commercial players from different industry sectors

Despite the initial research and work on graphene taking place largely in university labs under government investment programmes, the series of technological breakthroughs has triggered the steady progress in graphene commercialisation. Graphene synthesis has transitioned from mostly university-based lab-scale experimental production to multiple commercial companies producing this nanomaterial on a large scale. Top graphene suppliers such as Sixth Element and Global Graphene Group have accumulated extensive knowledge in graphene mass production, as reflected in their large patent portfolios (Exhibit 5), and are churning out graphene and its derivatives in tonnes per annum.

The unique combination of superior properties of graphene has made it an ideal material for different applications, including flexible wearable technologies, superfast electronics, ultrasensitive sensors, and various medical, chemical and industrial processes.

Among the top commercial entities of graphene technologies, there are multinational conglomerates such as LG, Samsung, and technology giants like IBM and Toshiba developing graphene technologies for applications across different industry sectors. Big organisations, for example, BOE Technology, Sinopec, Sekisui Chemical, and Lockheed Martin, have also stepped up R&D efforts in graphene for specific applications in display, chemical, and aerospace. By focusing specifically on graphene technologies, young companies like Hunan Gonsion Graphite and Hangzhou Gaoxi Technology have also established themselves as strong players despite their relatively short history.

Aiming to secure the technological high-ground, these companies have amassed large patent portfolios and established strong footprints in graphene research. The formidable patent portfolios held by the top graphene players not only reflect their extensive expertise and know-how but also signify a high level of competition. With the fast-growing market demand for graphene technologies, they are expected to strengthen their lead through continued innovations, making the already crowded space even more competitive.

An accurate understanding of the overall technology landscape is essential for both R&D and investment. New research needs to avoid well-studied, congested areas that have been tightly ring-fenced by the top technology holders with strong patent portfolios. By identifying emerging but important areas and building strong technology niches around them, a new entrant may be able to establish itself as an important player providing graphene technologies not matched by others. Better explored areas could be more attractive for investment as they present lower risks. As the technologies are more established, they are closer to market adoption and may also set the next round of product advancement.

Spotlight: Singapore

Broad Spectrum of Local Expertise and Commercialisation Opportunities

Research, innovation and enterprise are cornerstones of Singapore's national strategy to develop a knowledge-based, innovation-driven economy and society. The city-state has been increasing its public investment in research and innovation over the last 25 years.

Materials science has been a strong research focus that is actively pursued by local universities and institutes. In particular, the Centre for Advanced 2D Materials, formerly the Graphene Research Centre, within the National University of Singapore was created for the research and development of transformative technologies based on two-dimensional materials, such as graphene.

With strong support from the government and world-class scientists, the island country has placed herself on the map of graphene research and is among the top 15 most innovative countries in the world. Despite being a small country, the city-state has close to 100 graphene inventions in the past decade. Singapore's graphene research has been largely led by the local universities and research institutes, as compared to more established economies such as Japan and the Western countries who have more innovations from commercial players (Annex C, Exhibit C-2).

Exhibit 6: Publication trend of graphene-related inventions by Singapore applicants

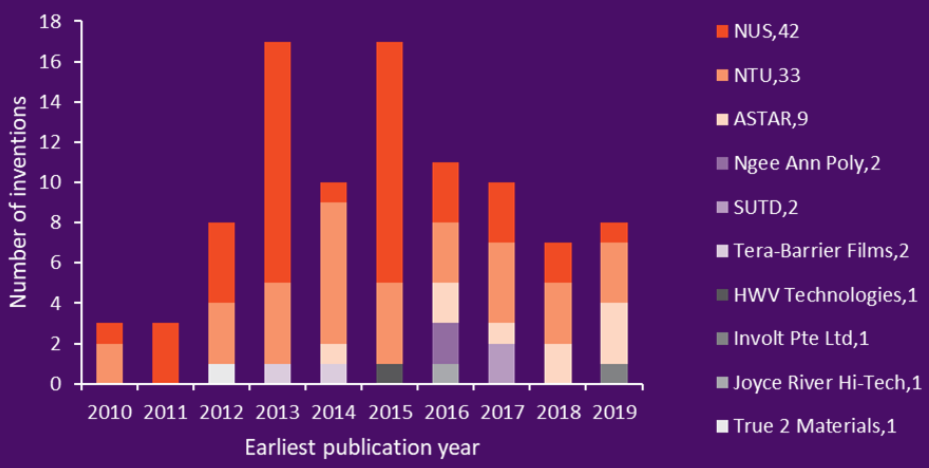
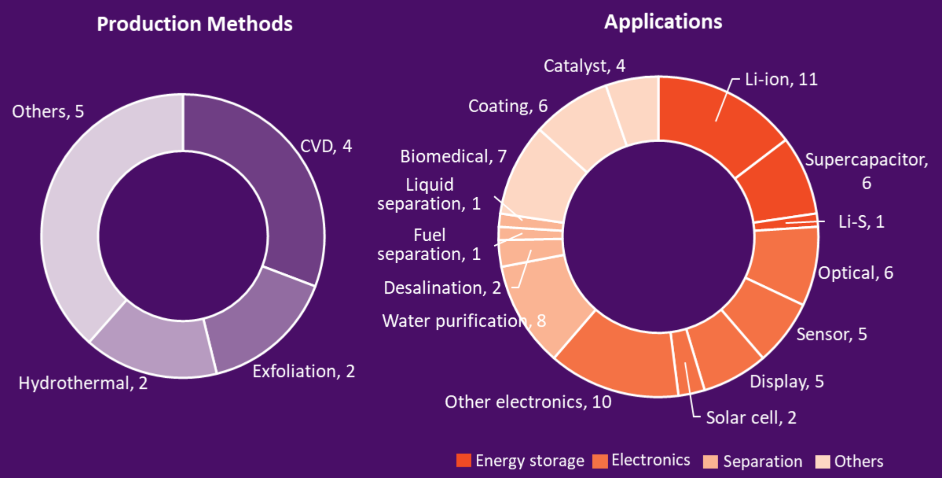


Exhibit 7: Breakdown of graphene-related inventions by Singapore applicants.



As one of the pioneers in graphene research, Singapore has accumulated strong know-how in many areas. Based on the inventions published in the last 10 years, the city-state has built capabilities across different production methods and applications. Strong expertise, in particular, exists in graphene technologies for energy storage, water purification, and biomedical applications.

While the overall number is modest, the quality of Singapore-originated inventions is unparalleled. About 83% of its inventions have been subsequently cited by other inventions (Annex C, Exhibit C-3), higher than any other country in the world. The high degree of citation strongly indicates that Singaporean inventions often form the technological foundation upon which other players make further improvements. This also implies a strong commercial potential, be it for direct exploitation, e.g. making products, or licensing to others.

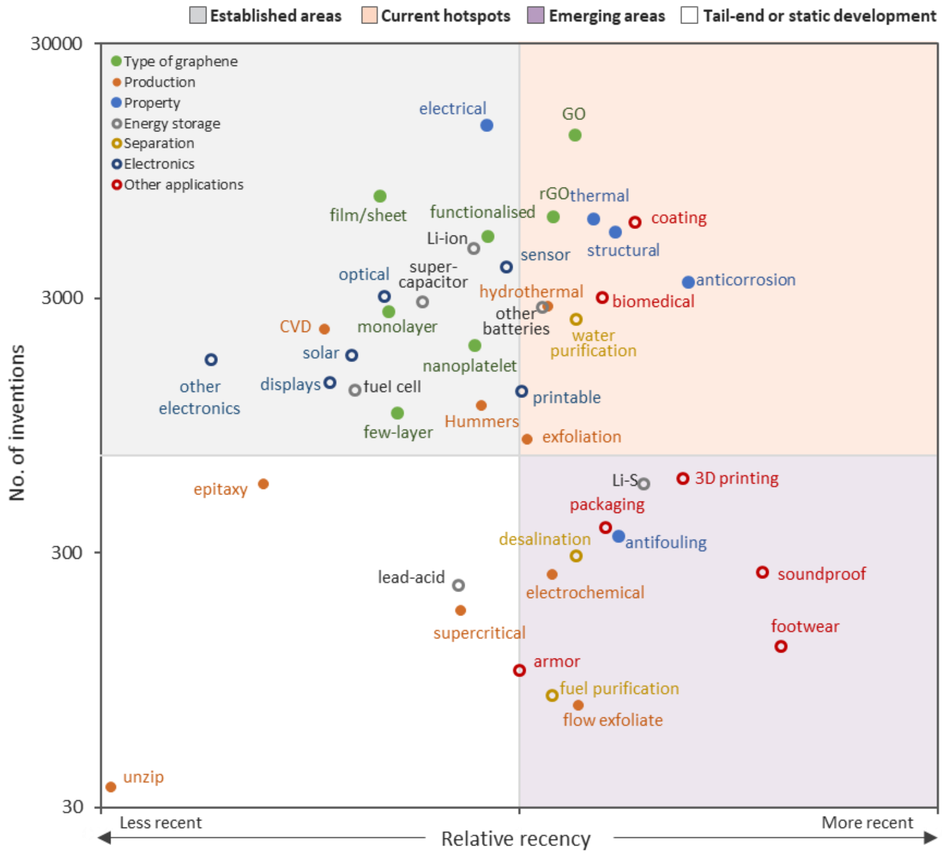
As graphene is increasingly adopted in commercial applications across different industries, it is an opportune time for local universities and research institutes, the owner of the majority of the local inventions, to explore commercial exploitation of their research outcome.

State of graphene innovations

By categorising the 62,000 graphene-related inventions published in the past decade into their corresponding domains and sub-domains (Exhibit 1) and calculating their respective recency - a measure of how recently the technologies were developed, this report assesses the relative technology maturity of each graphene domain and sub-domain through the analysis of an Innovation Maturity Matrix.[10]

Exhibit 8: Innovation Maturity Matrix of graphene technologies

The Innovation Maturity Matrix categorises all the 62,000 graphene-related inventions into their corresponding domains and sub-domains. It helps identify emerging interests, the current research hotspots, established areas, and technologies that either remain static or are at the tail-end of development.



[10] See Annex C, Exhibit C-4 for a detailed explanation of the four-quadrant innovation maturity matrix.

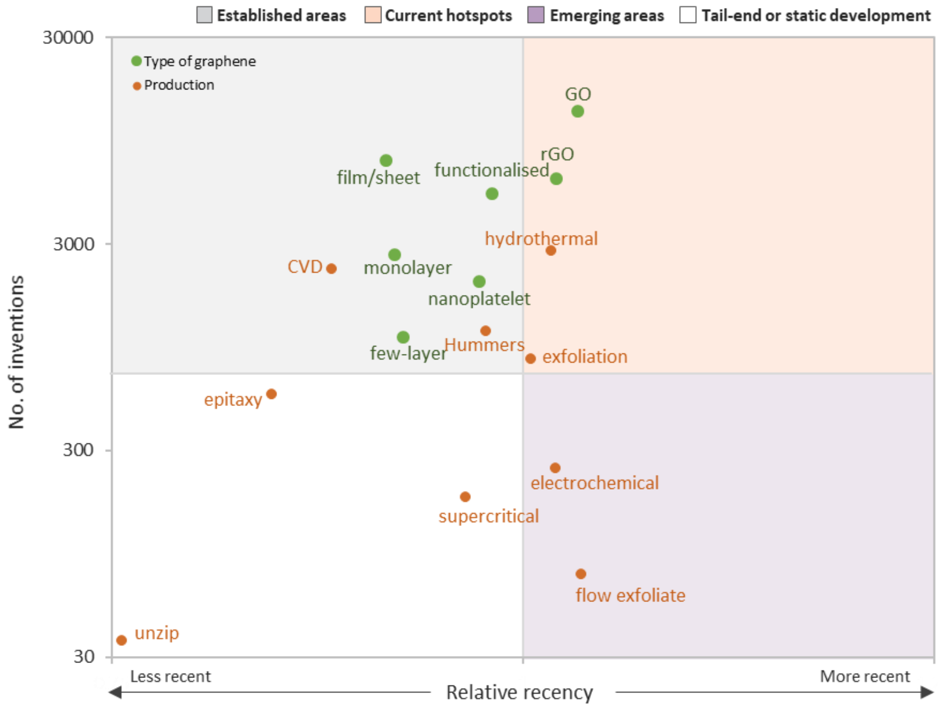
Graphene production

Since the first isolation of graphene, techniques that are capable of large-scale synthesis have been a prime focus, as mass production and commercial availability are prerequisites for the viability and wide application of graphene. Overall, graphene production techniques are well studied and have been used for the mass production of various graphene product types, most of which are already commercially available on a large scale.

Among the different production approaches, hydrothermal and chemical vapour deposition (CVD) are better explored. Each of them has seen more than 2,000 inventions (Exhibit 9). CVD appears to have lost its traction given its low relative recency. Extending from its success in the semiconductor industry, this traditional deposition method has been extensively studied to produce high-quality graphene. It, however, suffers from the relatively high cost arising from the need for specialist equipment and is a rather sensitive process easily influenced by parameter changes.

Synthesis through Hummers method or exfoliation, i.e. peeling from the bulk graphite layer by layer, represents the more recent approaches. They are promising ways to achieve large-scale, low-cost production, particularly for graphene oxide (GO) or reduced graphene oxide (rGO) (Exhibit 10). Flow exfoliation, in particular, is fast emerging albeit a lower number of inventions.

Exhibit 9: Innovation Maturity Matrix of graphene production methods and product types

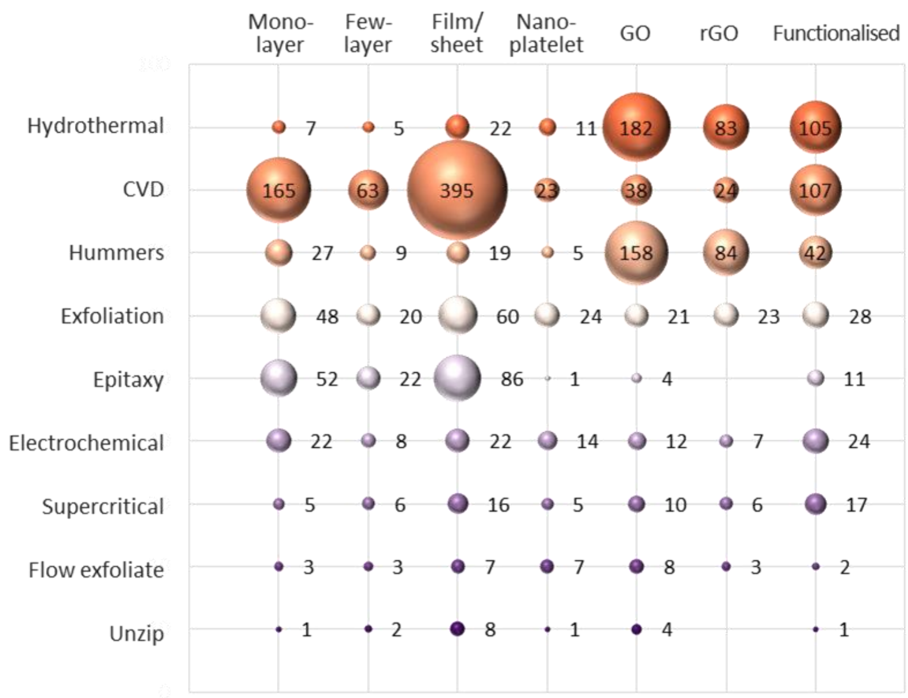


Among the different derivatives of the graphene family, graphene oxide and reduced graphene oxide are the current product focus. Together they have accounted for about 50% of all the product-related inventions. Another well-studied product type is functionalised graphene, e.g. hydrogenated or fluorinated graphene. One key reason behind the high level of innovation activities of these three graphene derivatives is the relative ease of manufacture. They commonly come in powdered form or as a solution that enables straightforward applications downstream as they can be easily mixed, directly deposited or applied as a coating.

Graphene films, mono- or few-layer graphene have also seen a high level of innovation. They have been long explored through traditional methods such as CVD and epitaxial growth (Exhibit 10). Despite the immense efforts and resources invested in research, the industry is still facing difficulties in producing large-size, high-quality or defect-free mono-or few-layer graphene films.

Exhibit 10: Graphene production methods and their use in the manufacture of graphene products

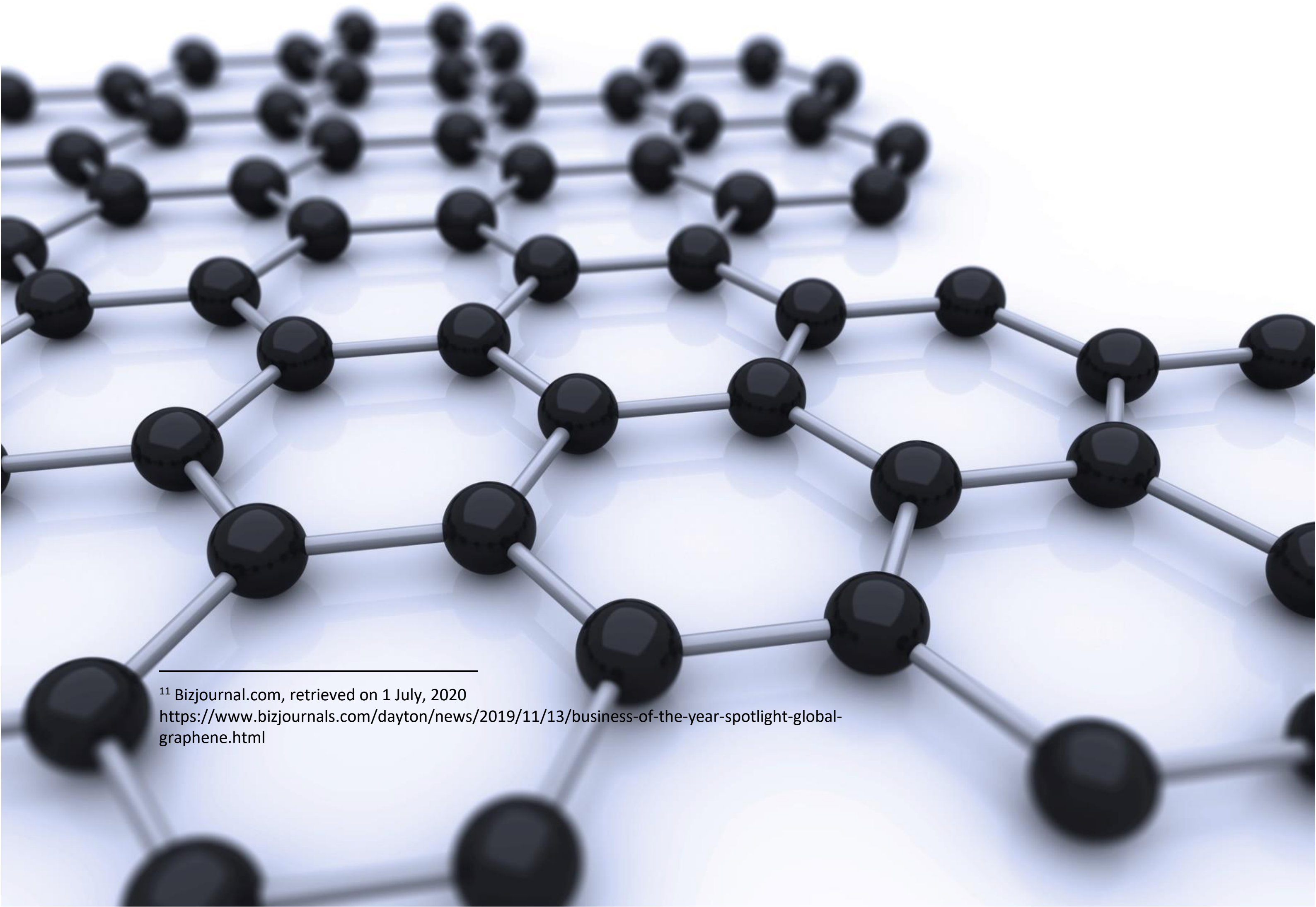
Among well-studied methods, hydrothermal and Hummers are more for GO, rGO, and functionalised graphene production, whereas CVD and epitaxial growth are utilised more for fabricating graphene films, mono- or few-layer graphene. Exfoliation, the more recent technique, is more versatile and can be used to manufacture all major graphene product types.



For most of the graphene product types, institutes and companies have built strong patent portfolios from their research (Annex C, Exhibit C-5). While the top institutes are mainly from China, commercial entities leading in the space are from all over the world. Top commercial entities comprise graphene manufacturers like Global Graphene Group (G3) and Chengdu New Keli and companies such as Samsung, Sinopec, and BOE Technology looking at specific applications. Graphene production techniques, similarly, are well-explored and have seen many universities and companies establish a strong foothold (Annex C, Exhibit C-6).

The establishment of graphene production implies that the technologies are relatively mature and products are readily available in the market. For example, G3, the leader in different graphene product types, produces roughly 300 metric tons of graphene per year.[11] Overall, graphene production constitutes a well-studied, congested space that is tightly ring-fenced by the leading universities/institutes and commercial players. Additional R&D investments directed here are unlikely to yield a strong return.

Graphene production constitutes a well-studied, congested space that is tightly ring-fenced by the leading universities, institutes and commercial entities.



[11] Bizjournal.com, retrieved on 1 July, 2020 https://www.bizjournals.com/dayton/news/2019/11/13/business-of-the-year-spotlight-global-graphene.html

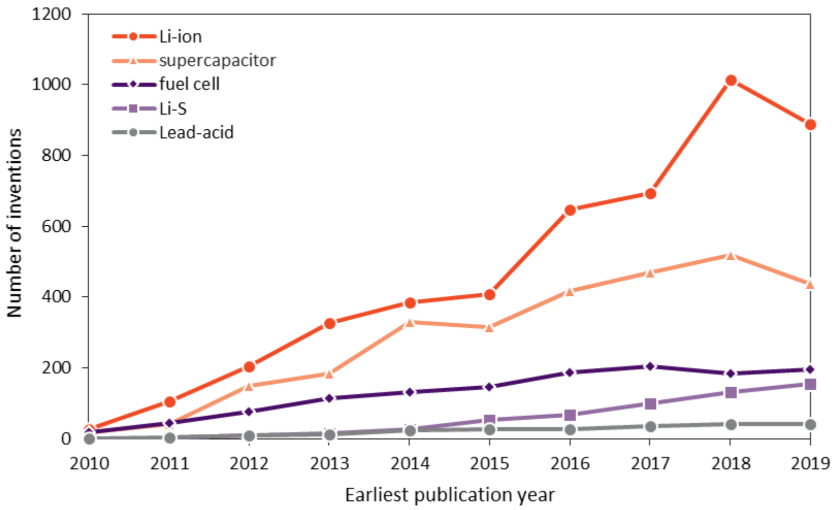
Graphene for energy storage

The large surface areas, theoretically up to 2600 square meters per gram, have made graphene an ideal candidate for energy storage applications such as supercapacitors and batteries. Early in 2015, researchers in South Korea demonstrated a graphene-based supercapacitor that reaches 131Wh/Kg,[12] nearly four times the previous record for graphene-based supercapacitors of around 35Wh/Kg in lab prototypes. Graphene could also significantly improve the performance of batteries, allowing for increased electrode density, faster cycle times, better thermal management, as well as enhanced charge retention and thus improved lifespan.

Overall, graphene for energy storage is considered well-explored as evinced from the Innovation Maturity Matrix (Exhibit 8). Graphene applications in Li-ion batteries, supercapacitors and fuel-cells have thousands of inventions published in the last decade and are no longer a current research focus. Indeed, these three areas have all showed a decline in the most recent years (Exhibit 11). The emerging use of graphene is seen more towards Li-S battery, a promising candidate that is often touted to succeed Li-ion because of its higher energy density and reduced cost.

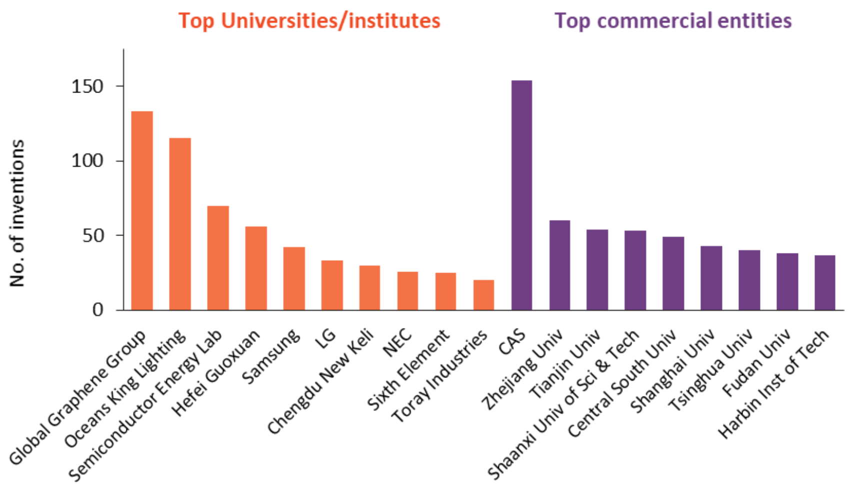
Exhibit 11: Publication trend of graphene application in energy storage

Applications in Li-ion batteries, supercapacitors, and fuel-cells all showed a decline in the most recent years. Graphene for Li-S, on the other hand, has shown consistent growth in the last decade albeit a smaller number of inventions published.



[12] Hao Yang et al., Journal of Power Sources, Volume 284, 15 June 2015, Pages 146-153

Exhibit 12: Top technology holders in graphene-enhanced Li-ion batteries



The improvements in Li-ion battery made achievable via graphene addition have catalysed efforts by universities, research institutes, technology giants and start-ups alike, many of which have amassed large technology portfolios in the field (Exhibit 12). The top 10 Li-battery manufacturers[13] in the world have also shown an increasing interest and accumulation of strong know-how in this area, as reflected in their related patent filings (Annex C, Exhibit C-7).

Graphene-enhanced Li-ion batteries are considered mature enough and are poised for mass commercial adoption.

Many commercial entities, such as G3 and Chengdu New Keli, are already looking at the mass production of graphene-enhanced batteries. Graphene-enhanced batteries are emerging in the market. Notable examples include Huawei's adoption of graphene to enable high-temperature Li-ion battery[14] and conduction cooling for the batteries in its Mate 20 mobile phones, [15] and G3's Li-ion batteries with graphene/silicon anode materials that are offered commercially.

[13] Top 10 Li battery makers are identified in a separate study on Battery Technologies. They are: Panasonic, LG, Samsung, Toyota, Hitachi, Bosch, Sumitomo, CATL, Hefei Guoxuan, and NEC.
[14] Huawei, retrieved on 1 July 2020, https://www.huawei.com/en/news/2016/12/Graphene-Assisted-Li-ion-Batteries
[15] Graphene-info, retrieved on 1 July 2020, https://www.graphene-info.com/huaweis-new-mate-20-x-uses-graphene-film-cooling-technology

As graphene-enhanced Li-ion batteries are considered mature for mass commercial adoption, the remaining window of opportunity for research is finite. It is expected that the technology may soon start to consolidate and big players in the field will be seeking different means, such as in-licensing and partnership, to enhance their technology and maintain a competitive edge. This presents opportunities to commercialise the local inventions relating to the graphene application in Li-ion batteries built up within the local universities in Singapore (Exhibit 7). It is also an opportune time to invest in start-ups and small companies with a strong relevant technology niche, who may become the target of potential mergers and acquisitions, similar to that of Tesla's $218 million acquisition of energy storage company Maxwell.[16]

The industry is seen moving away from Li-ion and playing an increasing focus on applying graphene for Li-S batteries. Graphene is an ideal candidate to overcome the key technical challenges faced by Li-S batteries, arising from the quick capacity decay and short lifespan. Given the small number of inventions, graphene-enhanced Li-S batteries appear to be in their infancy. This could be in part due to Li-S batteries as a whole still being at the exploratory stage. The portfolios held by the top applicants on graphene/Li-S batteries are much smaller as compared to that of graphene-enhanced Li-ion batteries. There is also a significantly smaller presence from the top 10 battery makers. Graphene-enhanced Li-S batteries, therefore, present a higher degree of uncertainties in terms of commercialisation potential.

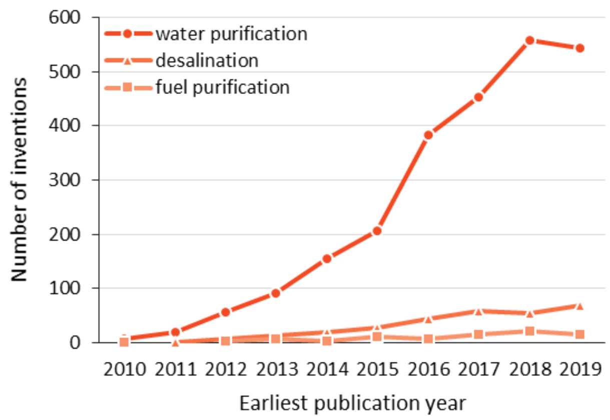
Graphene applications in separation

Graphene-based materials, particularly graphene oxides, have excellent advantages in the filtration and separation process. Their large specific surface areas, stacked structures, as well as the functional groups and defects in the monatomic layers enable a porous microstructure with engineerable channels that is ideal for selective transport of water, ions, and gases.

Despite the use of graphene for filtration and separation being a relatively new area, as reflected by its high relative recency (Exhibit 8), graphene for water purification is making strong headway. This is hardly surprising given that water shortage and contamination are one of the most daunting challenges the world is facing. This fast-growing interest in graphene technologies for water purification has resulted in a surge in related inventions (Exhibit 13). From merely seven inventions in 2010, the global invention output has reached 544 inventions in 2019. Despite the fast growth, applying graphene to decontaminate water is still at the basic phase, as evident in the profile of top technology holders which comprises largely universities and institutes.

[16] CNBC, retrieved on 1 July 2020, https://www.cnbc.com/2019/02/04/tesla-to-but-maxwell-technologies-for-4point75-a-share.html

Exhibit 13: Publication trend of graphene applications in separation, and the top technology holders in water purification.



Top 10 technology holders in water purification
CAS [64]
Jiangsu Univ. [39]
South China Univ. of Tech [39]
Changzhou Univ. [39]
Donghua Univ. [36]
Tsinghua Univ. [28]
Univ. of Jinan [26]
Shaanxi Univ. Sci & Tech [19]
Tianjin Polytech Univ. [19]
Tongji Univ. [18]
Chengdu New Keli [18]

Singapore has a vested interest in and is on a strong footing to develop graphene technologies for water purification. As a small island country with limited natural water resources, Singapore has always placed a strong focus on water technologies and has produced 8 inventions relating to graphene technologies for water treatment (Exhibit 7) in the last decade. Local entities have got off to a good start in the real-life adoption of graphene-enhanced water purification technologies. The National University of Singapore has partnered with Grafoid to launch a spin-off named Graphite Zero in 2013 for the development and production of a graphene-based platform called MesoGraf™, which was subsequently incorporated for industrial-scale water treatment through Grafoid's strategic collaboration with Liquinex. HWV Technologies, a young local start-up founded in 2012, is exploring the use of graphene in its water technologies. It has partnered with Graphene Nanochem, a UK-based company with Malaysian ties, to commercialise its graphene-enhanced water treatment systems for the oil and gas industry.

Singapore entities have got off to a good start in commercial exploitation of graphene for water treatment and purification.

Continued research and investment could allow further relevant expertise to be built within the island country. At the same time, the city-state could continue expanding the commercialisation of its technologies to establish a first-mover advantage in the market.

Other applications

Graphene's exceptional properties such as superior mechanical strength and high electrical and thermal conductivity have been extensively investigated for different electronics applications. It is a strong candidate to replace indium tin oxide, a widely used transparent conductor in touch screens on tablets and smartphones. Graphene has also been used in printable, flexible electronics where it can enable conductive inks, as sensors that provide ultra-high sensitivity and as an electrode in solar cells and optical devices such as OLEDs, among others.

Overall, inventions utilising graphene's electrical properties seem to be well-explored. In particular, applications in optical devices, solar, and display are relatively well-established whereas sensors and printable electronics are the more recent areas. The current research focus is more on exploiting graphene's superior thermal, structural and anticorrosion properties (Exhibit 14). This has led to two research hotspots, coating and biomedical applications, and emerging applications such as 3D printing, packaging, and the novel use of graphene in armour, footwear, and for soundproof purposes.

Exhibit 14: Innovation Maturity Matrix of graphene inventions utilising different properties, use of graphene in electronics and other applications.

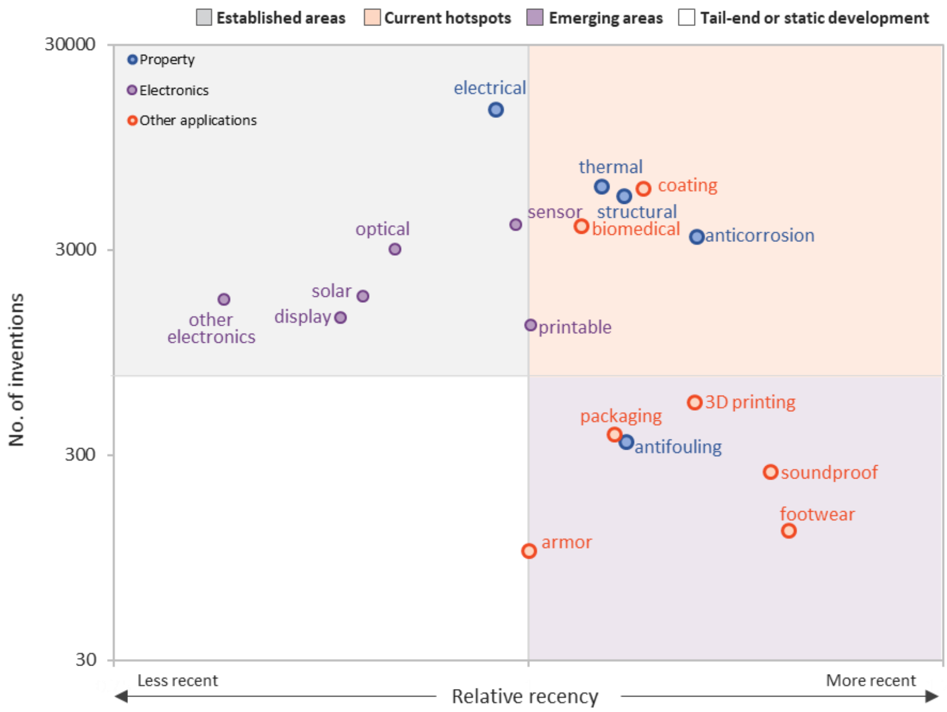
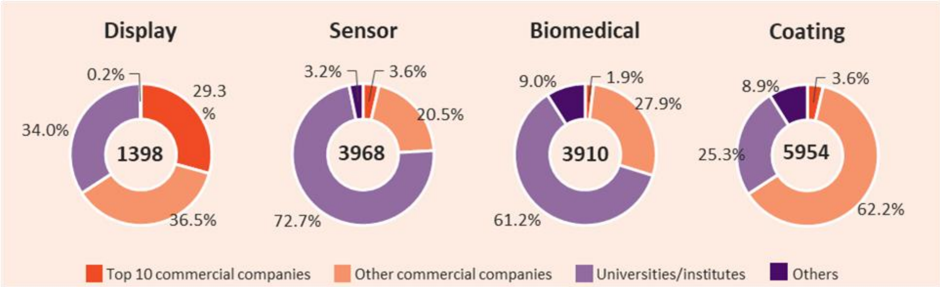


Exhibit 15: Applicant profile of graphene technologies for display, sensor, biomedical, and coating.



Top 5 Enterprise Applicants

TCL [109]	Nokia [37]	Chengdu New Keli [15]	Chengdu New Keli [50]
BOE Technology [104]	Samsung [33]	Samsung [11]	Global Graphene Group [31]
Samsung [68]	IBM [13]	Lockheed Martin [11]	Hunan Gonsion Graphite [22]
LG [44]	Sixth Element [11]	Nanomedical Diagnostics [9]	Samsung [20]
Chongqing Graphene Tech [23]	Fujitsu [8]	Shengquan Group [7]	LG [17]

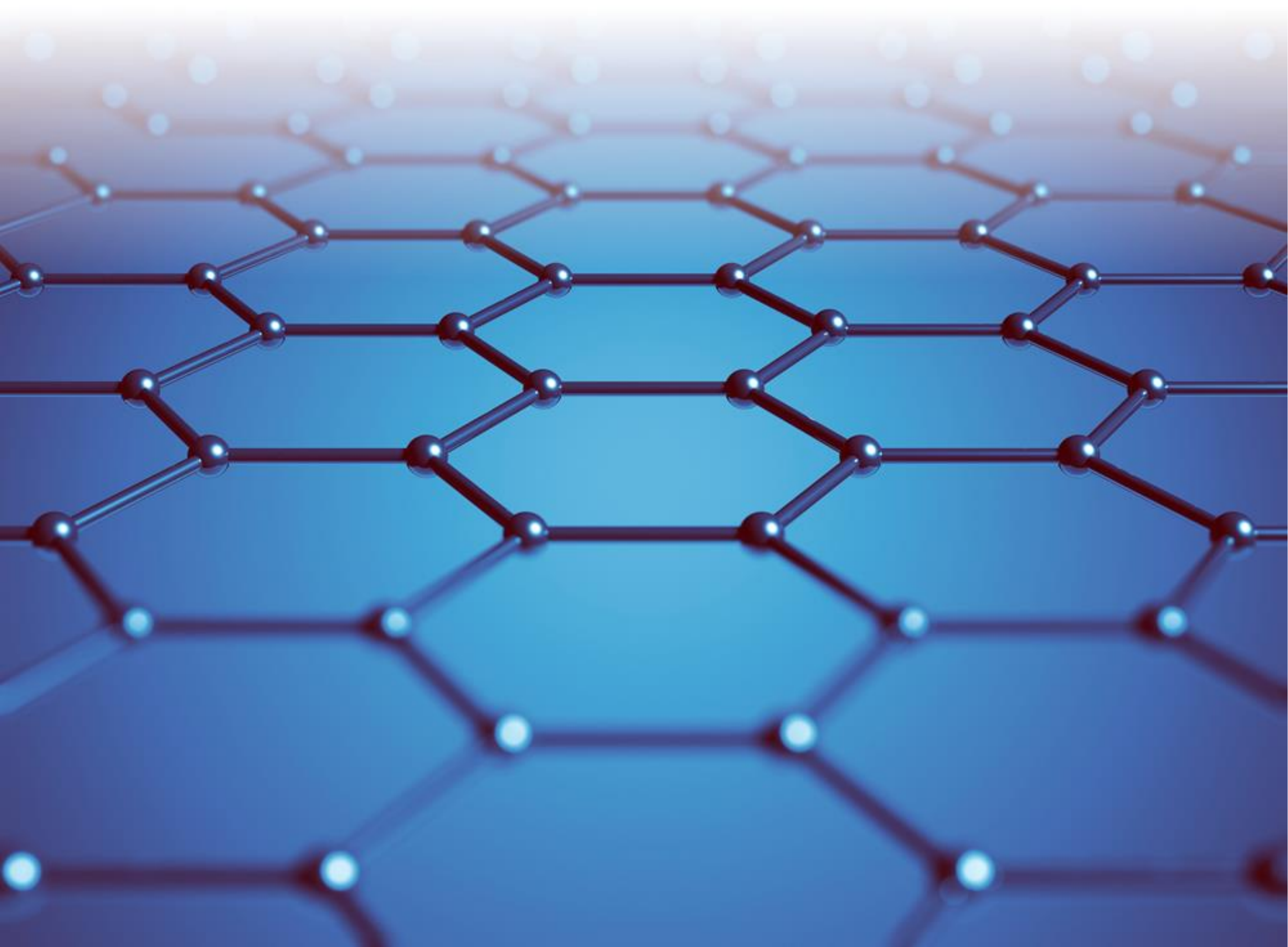
Despite existing local capabilities (Exhibit 7), graphene technologies for display, sensor, biomedical and coating may not be the best areas for technology spin-offs or start-ups at the current stage.

Graphene for display has received the lowest level of interest and has less than 1,400 inventions. Its low relative recency indicates that the related inventions have stagnated. The difficulty associated with the manufacture of large-size, defect-free graphene films could be a high technical barrier that is difficult to overcome, particularly for new entrants without a strong technology foundation and financial support. Indeed, close to 30% of the inventions were filed by the top 10 commercial companies, including world-leading display panel makers, such BOE Technology, Samsung, and LG, who have amassed large patent portfolios in the area.

Graphene technologies for display, sensor, biomedical and coating may not be the best areas for technology spin-offs or start-ups despite existing local capabilities.

Universities and institutes are the main contributors to the breakthroughs in sensor and biomedical applications, accounting for about 70% and 60% of the related inventions, respectively. Compared to commercial players, universities and institutes typically engage in more fundamental research. Their technologies are therefore often at lower technology readiness levels. Based on the inventions published, the application focus of these two areas is highly scattered and seems to stem from opportunistic approaches rather than systematic research. Sensor applications are facing challenges in production scale-up and quality control due to the need for high-quality graphene, whereas graphene for biomedical applications has yet to address all the safety concerns. As a whole, sensor and biomedical applications represent a nascent space for R&D.

Coating is the best-studied among the four areas as evinced by the high overall number of inventions (close to 6,000). It represents a more commercialised area where more than 65% of the inventions are filed by commercial entities. It is however a highly fragmented space filled with many small commercial entities. The presence of a large amount of small commercial players could imply a high level of competition, making graphene for coating a challenging space for new entrants unless there are strong technology niche and product differentiation.



Conclusion

Graphene is an exciting wonder material that has been extensively studied since its first isolation in 2004. Its rapid rise to popularity in scientific and technological communities can be attributed to its exceptional properties. The substantial resources that have been invested in research and development and the strong market demand have made graphene a major innovation hotspot, predominantly led by China.

Technological breakthroughs have enabled mass production of graphene and its derivatives, allowing graphene to successfully make the leap from the lab to the marketplace. Overall, graphene production constitutes a well-studied, congested space, which has been tightly ring-fenced by the leading universities/institutes and commercial players. Additional R&D investments directed here are unlikely to yield a strong return.

The unique set of superior properties has excited researchers and businesses around the world, as graphene offers a fascinating material platform for the development of next-generation technologies in various industries. Graphene-enhanced Li-ion batteries are considered mature enough for mass commercial adoption and the industry is seen paying an increasing focus on applying graphene for Li-S batteries.

With strong support from the government and world-class scientists, Singapore has placed herself on the graphene map. The city-state has built a broad spectrum of graphene technologies and is among the top 15 most innovative countries. As graphene is increasingly adopted in commercial applications, it is an opportune time for local universities and research institutes, the owners of the majority of the local inventions, to explore commercial exploitation of their research outcome. Given the relatively weaker presence of local enterprises in the field, there are also opportunities in technology transfer from the universities/institutes to address the existing gaps in local enterprises.

Graphene applications in water purification are a promising area for further R&D and investment, as compared to highly competitive areas such as display and sensors and nascent spaces relating to sensors and biomedical. In addition to the expertise built within the local universities and institutes, local entities have got off to a good start in the real-life adoption of graphene-enhanced water purification technologies through strategic partnerships with other commercial players. Continued research and investment could allow further relevant expertise to be built within the island country. At the same time, the city-state could continue expanding the commercialisation of its technologies to establish a first-mover advantage in the market.

Annex A: Methodology

Dataset

The final dataset relating to graphene technologies was retrieved on 1 May 2020. The dataset consists of graphene-related patent applications published worldwide from 2010-2019.

Search string

To ensure optimal recall and accuracy of the dataset retrieved, the search strings used in this study were formulated incorporating keywords (and their variants) and patent classification codes and indexing, e.g. International Patent Classification (IPC) and Cooperative Patent Classification (CPC). Detailed lists of the main keywords and the patent classification codes used are presented in Annex B.

Grouping by patent family

The innovation intensity, i.e. the no. of inventions in this study is measured by counts of patent families. A patent family is a group of patents related to the same invention. Analyses based on unique patent families reflect the innovation output more accurately; considering individual patent applications will inevitably involve double counting as a patent family may contain several patent publications if the applicant files the same invention for patent protection in multiple destinations.

In this study, the representative of a patent family, i.e. an invention, is chosen to be the earliest published family member.

Data cleaning

Systematic data cleaning and manual review were carried out to

1) remove non-patent specification, e.g. utility model, and
2) ensure the relevance of the dataset prior to carrying out the analyses.

Refinement of the applicant field

IPOS International's in-house proprietary patent data cleaning platform and automated algorithms from commercial tools were used to refine applicants' information, e.g. by removing various spelling and punctuation mark discrepancies. The refined results were manually checked for accuracy.

Grouping of technology domain and sub-domains

Grouping of patent families of the retrieved dataset into the respective technology domains and sub-domains was carried out based on patent classifications codes, text-mining and semantic analysis of the patent specifications, in particular, the titles, abstracts, and patent claims, as well as a manual review of the individual patent applications.

Recency

Recency used in this study measures quantitatively how recently the technologies were published (developed). It is calculated by a weighted average of the inventions whereby a higher weightage is given to inventions published in more recent years.

Formula

$$\overline{\mathrm{R}} = \frac{\sum_{i=1}^{n}(w_i \times i)}{n \times \sum_{i=1}^{n} w_i}$$

where
i = 1 for the first year of the survey period, and i increases by 1 for every subsequent year in chronological order.
n = total no. of years of the survey period, and
w_i is the no. of inventions published in the year.

Relative recency

Relative recency in this study refers to normalised recency by taking the recency of the entire graphene dataset to be 1.

Annex B: Search string

Graphene types and production

Main keywords used

- Graphene, graphene oxide, reduced graphene oxide, single layer, mono-layer, bi-layer, few layers, film, sheet, nanoplatelets, pellet, nano-plate, nano-flake, nano-composite, dispersion, suspension
- Preparation, manufacture, grow, production, fabrication, synthesis, chemical vapour deposition, hydrothermal, solvethermal, Hummer, expanded graphite, atomic layer deposition, epitaxy, silicon carbide, copper, exfoliation, intercalation, delamination, peeling, stripping, shearing, flow exfoliation, shear flow, Taylor-Couette, pneumatic, super-critical, sub-critical, electrochemical exfoliation

Main IPC/CPC used

- C01B 32/00, C01B 31/00, C01B 2204/00, C23C 16/00

Industrial applications and properties

Main keywords used

- Battery, cell, lithium ion, Li-ion, lithium sulphur, lead acid, lead carbon, supercapacitor, fuel cell; water desalination, seawater, water purification, water treatment, sewage, waste water; fuel, gasoline, petrol, hexane, methane, hydrogen, desulphurisation; paint, coating, pigment; sound-proof, noise reduction, acoustic isolation; bio-medical, medicine, pharmaceutical, drug, disease, cancer, therapy, immune, enzyme; 3D printing, additive manufacture; packaging, lubricant
- Mechanical strength, structural, toughness, tenacity, Young's modulus, fatigue, flexible, compressive; electrical conductivity, electrical resistance, anti-static; thermal conductivity, heat transfer, heat dissipation, heat spread; anti-fouling, anti-scale; anti-corrosion, anti-rust; electronics, sensor, detector, transistor, touch-sensor, pressure sensor, gas sensor, photodetector, UV sensor; optical, photonic, optoelectronic, photo-emission, photo refraction, photo split, photo amplifier; photovoltaic, solar cell, solar panel, solar energy; printable electronics, graphene ink, PCB; display panel, screen

Main IPC/CPC used

– C01B 2204/00, H01M 10/00, H01M 04/00, Y02E 60/00, H01G 11/00, H01M 8/00, H01M 2008/00, C02F, Y02W 10/00, B01D 61/00, B01D 71/00, B01J 20/00, B01J 35/00, C09D, A61, B33Y, B29C 64/00, C10M, C10N, G02, G03, H01S, G09G, H02S, Y02E 10/00, Y02E 10/00, Y02P 70/00, C09D 11/00

Annex C: Additional Information

Exhibit C-1: Key branch institutes of Chinese Academy Sciences and their key research focus of graphene technologies

中國科學院
CHINESE ACADEMY OF SCIENCES

Ningbo Inst of Materials Techn & Engr.	Shanghai Inst of Micro-system & Info Tech	Suzhou Inst of Nano-Tech & Nano-Bionics	Inst of Metal Research, Shenyang	Inst of Metal Research, Chongqing
Institute's research focus				
Energy materials, anticorrosive coatings	Semiconductor materials, microelectronic devices	Nano materials, nano- and bio-chemistry devices	Metallic materials, carbon-based materials	Green energy, 3D printing, advanced manufacturing, graphene mass production
Graphene-related innovations				
Graphene BN nano-dots in anti-corrosive coating	CVD preparation of graphene film on Cu/Ni wafer	Large-scale production of graphene on Cu substrate, 3D porous graphene aerogels for batteries	Green and large-scale production of graphene oxide	High quality large-scale graphene preparation; Graphene-based flexible touch sensors

Exhibit C-2: Percentage of inventions filed by universities/institutes vs. commercial entities

More established economies such as Japan and the western countries have more innovations from industrial players, whereas Singapore's research output is largely contributed by the local universities and research institutes.

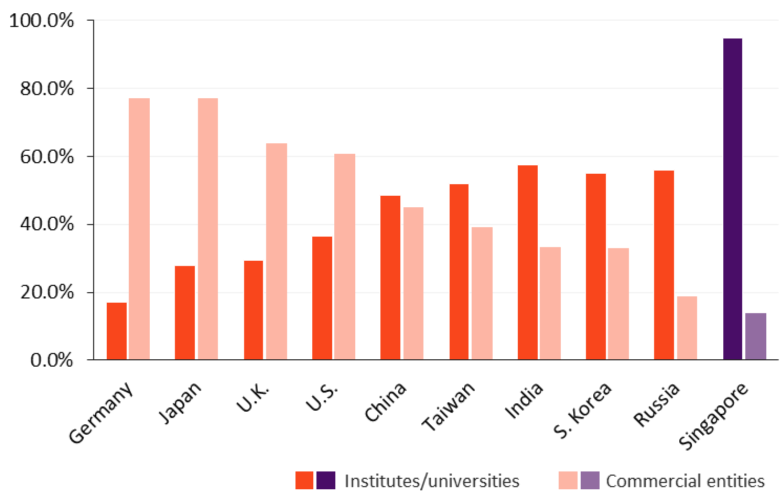


Exhibit C-3: Top 10 countries/regions with the highest ratio of number of cited inventions to the total number of inventions

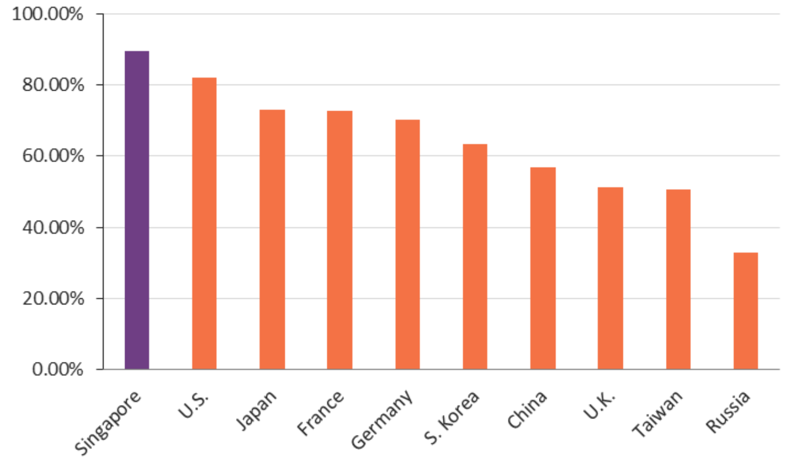
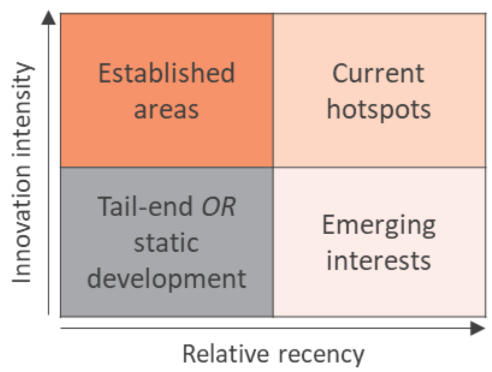


Exhibit C-4: Innovation Maturity Matrix

The Innovation Maturity Matrix studies the innovation intensity as well as the relative innovation recency of a particular technology area based on the relevant inventions published worldwide.



where

Innovation intensity is measured by number of related inventions.

Recency is a quantitative indicator of how recently the technologies were developed and published (see Annex A: Methodology).

Relative recency refers to the normalised recency by taking the recency of the entire dataset to be 1.

The four-quadrant matrix helps identify

1) **Emerging interests**: areas with related inventions that occurred most recently but have not reached a large volume. These areas are emerging and gaining rapid traction from the industry.

2) **Current hotspots**: areas that are the current industry focus and have achieved a high level of accumulation of inventions.
3) **Established areas**: areas with a high number of inventions but are no longer the key focus, as most of the inventions were published relatively in the past.
4) **Tail-end or static development**: areas that are not of recent focus and with low filings. They could already be at the tail-end of the technology development at the time of the patent analytics study, or areas that have been (relatively) long explored but have not gained traction.

Exhibit C-5: Top technology holders of different graphene product types

	GO/rGO	Functionalised	Mono/few layer	Film/sheets
Universities/Institutes	CAS [670]	CAS [264]	CAS [224]	CAS [384]
	Jiangsu Univ. [224]	Changzhou Univ. [81]	Peking Univ. [48]	Univ. Electronic Sci & Tech [79]
	Donghua Univ. [187]	Jiangsu Univ. [63]	Univ. Electronic Sci & Tech [41]	Zhejiang Univ. [78]
	Shaanxi Univ. Sci & Tech [177]	Nanjing Univ. Sci & Tech [62]	Tsinghua Univ. [33]	Peking Univ. [68]
	Univ. of Jinan [177]	Univ. of Jinan [55]	Zhejiang Univ. [33]	Tsinghua Univ. [56]
Commercial Entities	Global Graphene Group [224]	Global Graphene Group [216]	Samsung [51]	Samsung [194]
	Oceans King Lighting [145]	Oceans King Lighting [72]	Global Graphene Group [45]	IBM [69]
	Hangzhou GaoxiTech [115]	Samsung [37]	IBM [34]	Oceans King Lighting [62]
	Chengdu New Keli [77]	Shengquan Group [33]	Hon Hai Precision [30]	BOE Technology [54]
	Chenzhou Botai [75]	LG [21]	Sinopec [26]	Hon Hai Precision [49]

Exhibit C-6: Top technology holders of different graphene production techniques.

	Hydrothermal	CVD	Hummers	Exfoliation
Universities/Institutes	CAS [100]	CAS [203]	CAS [39]	CAS [82]
	Shaanxi Univ. Sci & Tech [78]	Peking Univ. [63]	Jiangsu Univ. [26]	Peking Univ. [14]
	Jiangsu Univ. [71]	Harbin Inst Tech [41]	Southeast Univ. Nanjing [22]	Beihang Univ. [7]
	Zhejiang Univ. [68]	Southeast Univ. Nanjing [24]	Tianjin Polytech Univ. [17]	Southeast Univ. Nanjing [7]
	Nanjing Univ. Sci & Tech [48]	Zhejiang Univ. [23]	Shanghai Univ. [16]	Tsinghua Univ. [6]
Commercial Entities	Chengdu New Keli [11]	Samsung [59]	Chengdu New Keli [10]	Chengdu New Keli [50]
	Oceans King Lighting [7]	Oceans King Lighting [51]	Hunan Gonsion Graphite [7]	Global Graphene Group [24]
	Nanjing Xinyue Material [5]	Sixth Element [17]	Oceans King Lighting [7]	Nantong Qiangsheng [19]
	SGCC [5]	LG [16]	Hefei Guoxuan [6]	Sixth Element [11]
	Shengquan Group [4]	Chongqing Graphene Tech [11]	SGCC [5]	IBM [8]

Epitaxy	Electrochemical	Supercritical	Flow exfoliate
CAS [58]	CAS [41]	Yancheng Teachers College [13]	Chengdu New Keli [22]
Fudan Univ. [15]	Nantong Qiangsheng [11]	Chengdu New Keli [6]	Korea Electronics Tech Inst [4]
Peking Univ. [14]	Chongqing Graphene Tech [9]	Hanwha Chemical, KR [5]	Soulbrain, KR [3]
Hon Hai Precision [11]	Global Graphene Group [6]	Global Graphene Group [3]	Gachong Univ., KR [3]
Samsung [11]	Zhejiang Univ. [4]	Showa Denko [3]	Jiangyin Tangu Tech [3]
IBM [11]	BASF [4]	Oceans King Lighting [3]	Thoms Swan, UK [2]

Exhibit C-7: Publication trend of inventions relating to graphene-enhanced Li-ion batteries by top 10 Li-battery makers.

Note that this chart relates to inventions specific to Li-battery. It does not cover other graphene inventions by the same player. For example, Panasonic has quite a number of patents relating to graphene synthesis, and application in Fuel cells

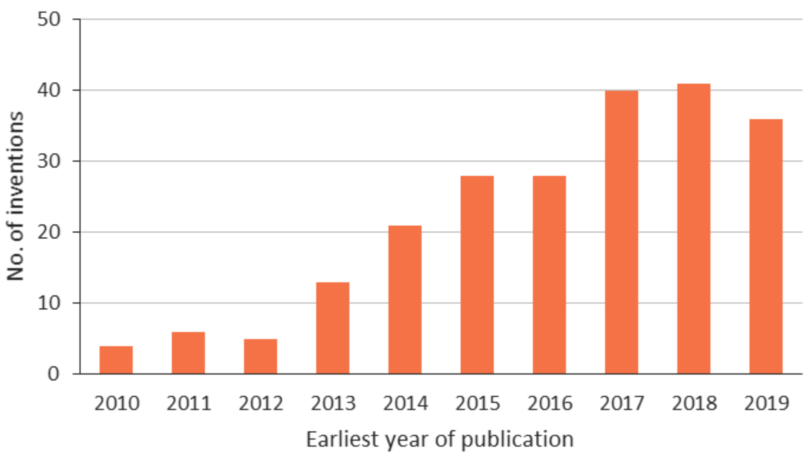


Exhibit C-8: Top technology holders of graphene-enhanced Li-S batteries.

Universities/institutes	Commercial entities
CAS [42]	Global Graphene Group [46]
Harbin Inst. Tech [17]	LG [27]
Central South Univ. [14]	Hunan Gonsion Graphite Tech [6]
Tsinghua Univ. [12]	Chengdu New Keli [5]
Beijing Univ. Tech [10]	Hon Hai Precision [4]

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