GRAPHENE
FLAGSHIP

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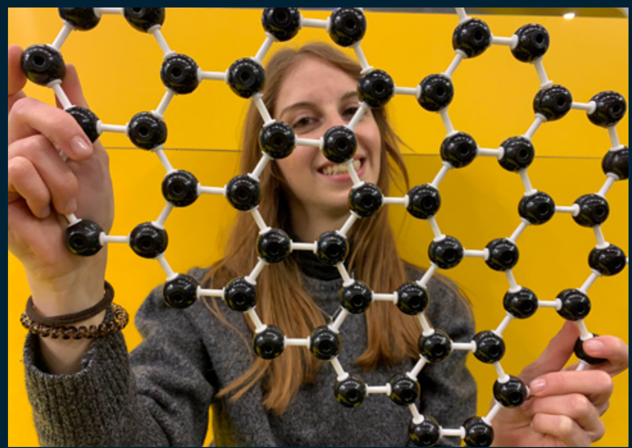
Ten years of research, innovation and collaboration: the Graphene Flagship and the 2DM community

Graphene is ...

... strong

... flexible

... conductive



... transparent

Graphene is strong: The Graphene Flagship has facilitated the creation of a European 2DM community with over 170 partners and more than 90 associated members in 21 countries.

Graphene is conductive: The Graphene Flagship has enabled lightning-fast technology transfer from academia to industry helping to launch 20 spin-off companies, 108 products and 387 patent applications (84 of which have already been granted).

Graphene is flexible: The Graphene Flagship is helping Europe to create a resilient and sustainable 2DM ecosystem. Graphene can replace scarce materials and reduce Europe's reliance on outside suppliers.

Graphene is transparent: The Graphene Flagship facilitates knowledge transfer through its events, early career education initiatives and business development activities.

Contents

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This report was delivered at the end of the Graphene Flagship Core 3 project as part of Deliverable D16.8 to provide an analysis of the evolution of the 2DM landscape from 2013 to 2023, and beyond, within the context of the Graphene Flagship. The purpose of this cumulative report is to provide an overview of the first ten years of the Graphene Flagship and how one of the European Union's largest ever research initiatives was able to set up new networks and structures to enable successful research, innovation and collaboration on graphene and 2D materials.

Introduction

In 2011, when the Coordination Action for Graphene-Driven Revolutions in ICT and Beyond (GRAPHENE-CA) began, the European Commission (EC) made its most ambitious investment in the future of 2D materials. GRAPHENE-CA prepared the ground for the Future and Emerging Technologies (FET) Flagship Initiative 'Graphene-driven revolutions in ICT and beyond' (GRAPHENE), a €1 billion research project, spanning ten years. At this stage, much of the preparation centred on the material – graphene – something which was high-risk but that needed to be brought to market. Alongside the detailed technical planning of the research and innovation actions which would take place over the next ten years, there was careful consideration of how to create a new ecosystem and infrastructure for impactful growth of graphene and 2D materials in Europe. To bring graphene out of the lab and into the fab and close the large gap between academic success and market breakthrough, the project would need to reduce risk and put into place new structures which could foster long-lasting research, innovation and collaboration.

In 2014, as the Graphene Flagship was launching its ramp-up phase in the Seventh Framework Programme (FP7), a Commission Staff Working Document[1] on the FET Flagships was published, citing the following objectives for the Graphene Flagship:

1. Establish Europe as a global leader in the field of graphene research, attracting talent and establishing collaborations across the globe, while at the same time acting as a centre of gravity for other, like-minded initiatives in Europe and beyond.
2. Develop new talents and skills – including the education of hundreds of researchers in the next generation of materials science – while nurturing creativity in order to attract the best minds in Europe and beyond.
3. Create a long-lasting research structure in Europe which fosters and sustains collaboration beyond the project's duration, while creating synergies with national and regional activities and contribute to the completion of the ERA.
4. Deliver a significant impact on competitiveness and society to bridge the gap between fundamental research and innovation, facilitate long-term collaboration between academia and industry leading to an efficient translation of science to concrete innovation opportunities while addressing societal challenges.

Now, nearly ten years after the publication of the Staff Working Document, and as will be demonstrated throughout this report, the Graphene Flagship and its five successive projects (GRAPHENE, GrapheneCore1, GrapheneCore2, GrapheneCore3 and the 2D Experimental Pilot Line) has achieved, and in some cases exceeded, the above objectives. The Key Performance

> To take graphene and related layered materials from a state of raw potential to a point where they can revolutionise multiple industries. This will bring a new dimension to future technology – a faster, thinner, stronger, flexible and broadband revolution. Our program will put Europe firmly at the heart of the process, with a manifold return on the EU investment, both in terms of technological innovation and economic growth."

Graphene Flagship mission statement

Indicators of the project have shown not only the high-quality of the Graphene Flagship's research and its researchers but have gone well beyond what was initially expected in terms of outputs. The cutting-edge activities and unique collaborations between academia and industry, combined with the community building events such as Graphene Week, Graphene Study and numerous industry outreach events, have indeed produced a network of highly skilled and well-trained researchers who will lead the way in the coming decades of 2DM research and innovation. The new structures made possible by the Graphene Flagship, such as cross-cutting support functions in research management; innovation support; validation, standardisation and roadmapping activities; dedicated Health and Environment work; and countless others, have created a community that will outlast the project – as evidenced by the establishment of numerous related initiatives and collaborations which would not have existed without it. Finally, the Graphene Flagship has left a measurable impact, not only on the research community and industrial innovation, but also on the society and economy of Europe, via the creation of jobs, career opportunities and contributions to sustainable development.

[1] SWD(2014) 283 final of 16.9.2014 – "FET Flagships: A novel partnering approach to address grand scientific challenges and to boost innovation in Europe". Accessed: https://era.gv.at/public/documents/2254/FETFlagshipsStaffWorkingDocument-Sep.pdf

Neelie Kroes, Vice-President of the EC in charge of Digital Agenda announces the winners of the FET Flagships R&D projects. Credit: European Commission.

Ten years of Graphene

1. Graphene Flagship Director, Jari Kinaret, and Nobel Laureate Konstantin Novoselov recreate the original "sticky-tape experiment" by which graphene was first isolated. Credit: Graphene Flagship

2. Graphene Flagship Director, Jari Kinaret, Nobel Laureate Andre Geim and Herre van der Zant of Delft University of Technology take time out from the grand opening of the Graphene Exhibition in Gothenburg's Universeum to explore the gravity defying properties of Velcro. Credit: Graphene Flagship

3. On a quick trip to Manchester, Prince William took to the cockpit of the single-seater BAC Mono at The University of Manchester's National Graphene Institute. A graphene composite makes up the rear wheel arches of the Mono for weight-saving and body-strengthening benefits. Credit: The University of Manchester

4. Graphene Flagship students and researchers conducted two exciting experiments in 2017 in collaboration with the European Space Agency (ESA) to test the viability of graphene for space applications including light propulsion and thermal management. Meganne Christian, researcher at the Graphene Flagship Partner CNR (pictured on the right) has gone on to be selected as part of the 2022 class of ESA astronauts. Credit: Graphene Flagship

5. The Graphene Flagship has supported hundreds of early career researchers in launching their careers in graphene through resources like our career days and our Graphene Study events (pictured). Many of these students are in leadership positions in the Graphene Flagship today. Credit: Graphene Flagship

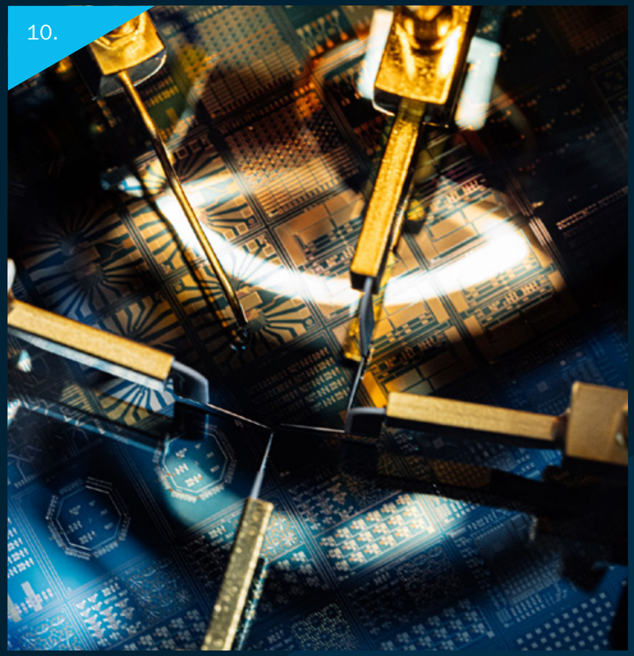
6. Researchers from the Graphene Flagship partner ICN2 displayed their work on a deep brain sensor at Mobile World Congress in 2016. The work has continued to mature, leading to the launch of spin-off company INBRAIN Neuroelectronics, which will use this graphene-enabled technology to detect seizures moments before they happen, with greater precision than current technologies. Credit: Graphene Flagship

7. Mark Viebrock began incorporating graphene into his research on gas sensors during his postgraduate studies at the University of Bundeswehr Munich.As a volunteer firefighter, he is exploring the possibilities for an easy to operate gas sensor capable of detecting all gases and acids equally. Credit: Mark Viebrock

8. Graphene Flagship's Work Package for Energy Generation combined graphene and related materials to perovskite cells and reached record levels of performance and stability. The project resulted in the first graphene-perovskite solar farm on Crete. Graphene Flagship Spearhead Project GRAPES is pushing solar cell technology a step ahead by reducing the levelised cost of energy to below €20 per MWh. Credit: Graphene Flagship

9. Graphene Flagship Associated Member Nanografen is producing graphene from waste tyres with the goal of improving recycling systems and making automotive vehicles more eco-friendly. The company is developing prototypes for graphene-reinforced lightweight automotive parts made from their upcycled graphene for use in modern electric vehicles. Credit: Nanografen

10. The 2D Experimental Pilot Line is a Graphene Flagship project created to address the challenges of establishing reliable fabrication processes for high-volume production of graphene and related materials-based electronics, photonics and sensors. As part of this process the 2D-EPL has launched multi-project wafer runs in which customer designs are included as dies on joint wafers. Applications are open for the fourth run now. Credit: AMO GmbH.



Evolution of the 2DM community over the past ten years

A key success factor in the Graphene Flagship has been its longevity[2], which has created not only an ecosystem in Europe, but built momentum for continued research and innovation within future EC framework programmes and beyond. This timeframe has seen a significant evolution of the 2DM community, one in which the presence of the Graphene Flagship has created a network and the trust necessary for cocreation and development.

> By 2016, the Graphene Flagship had already "created an international profile for Europe's researchers at the forefront of science and technology developments, and arguably triggered significant investment internationally in these domains."
>
> FET Flagships – Interim evaluation – Final report[3]

EUROPEAN FUNDING LANDSCAPE

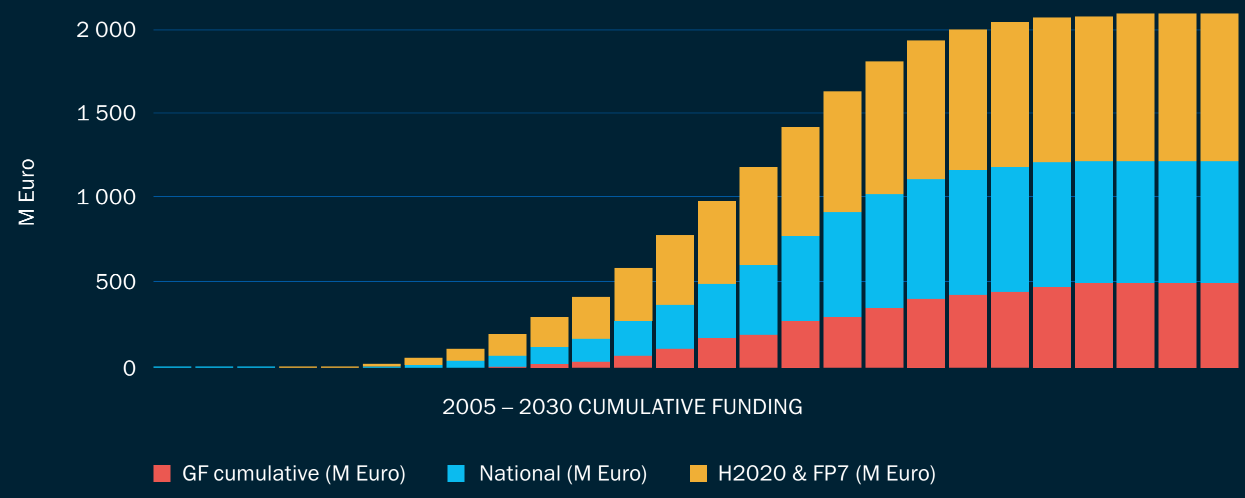
Due to the remarkable properties of graphene, which made it a promising material for the development of different technologies, extensive funding was anticipated shortly after its isolation in 2004. The 2DM funding landscape has evolved in line with the growing interest in graphene research (fundamental and applied) and progressive industrialisation. As early as 2009, graphene research attracted substantial funding both from national and European sources. Examples of European research networks on graphene include several EU projects (GRAND, ConceptGraphene, RODIN, GRENADA) with a total funding of well over € 15 million, ESF Eurocores program EuroGraphene (€ 7 million in 2010-2013), the GDR GNT (France, € 200 k in 2009–2013), different projects funded by the ANR (France, € 2.2 million in 2009–2013), DFG Specific Priority Program (Germany, € 15 million in 2011–2016) and EPSRC Infrastructure Science and Innovation Awards (United Kingdom, € 15 million in 2009–2014). All the above-mentioned initiatives were proof of very early significant interest focused on graphene, due to its great potential for application. However, it was only when the FP7 Coordination Action GRAPHENE-CA started that a long-term strategic vision of graphene research in Europe began to be shaped, together with the creation of a unified network between academic research and industrial innovation. The launch of the Graphene Flagship has been one of the main driving forces for the unification of initially scattered, diversified research initiatives related to graphene.

At the outset of the Graphene Flagship during the ramp-up phase in FP7, an ambitious goal of € 1 billion of research funding was announced. When comparing the total funding provided by both the EC, through the FP7 and H2020 work programs, and national funding agencies, there is good evidence that the initial funding target dedicated to graphene and related materials research and innovation activities at European level has been reached. Indeed, there are strong indications that the initial target has been exceeded, reaching about € 2 billion public funding for the period 2005–2022. From our analysis of the European funding landscape in the field of GRM (graphene and related materials) based on information retrieved directly (provided by the FLAG-ERA funding agencies) and by desk-research (from information publicly available online), it is shown that, by 2027, about € 400 million will have been granted to the Graphene Flagship project (including the FP7 ramp-up phase, the H2020 funding and the 2D-EPL project) – as well as another approximately € 95 million granted to projects in Horizon Europe under the umbrella of the Graphene Flagship initiative. Over € 850 million will be granted through other EC funding schemes under FP7 and H2020 work programmes, and over € 700 million through national funding.

[2] European Commission, Directorate-General for Research and Innovation, Budraitis, M., Pranckevičius, P., Dėlkutė, R. et al., Evaluation study of the European framework programmes for research and innovation for excellent science – Horizon 2020 – Annexes, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2777/353383

[3] European Commission, Directorate-General for Communications Networks, Content and Technology, FET Flagships – Interim evaluation – Final report, Publications Office, 2017, https://data.europa.eu/doi/10.2759/26136

EC AND NATIONAL FUNDING ON GRM RESEARCH



Cumulative funding in GRM between 2005 and 2027. Graphene Flagship (including the projects funded under Horizon Europe) funding in red, EC H2020 and FP7 funding (excluding the Graphene Flagship) in yellow, and national funding in blue. To have an overview, we consider funding of research projects (by the European Commission and nationally) as well as for infrastructures and investments in companies. We note that i) an overestimation for the EC funded projects is likely as all projects which included the keyword graphene in the title or objective were considered for this report and ii) an underestimation for the national projects is likely, as the information on the number of projects and funding amount was not available for all countries. Note that this data does not include other EC funded projects in Horizon Europe that may have to do with graphene or other 2DM, rather only the projects under the "Graphene: Europe in the Lead" calls.

The Graphene Flagship has been constantly engaged in the alignment of 2DM research and innovation activities at the European level by setting up an association mechanism that further contributed to a unification of graphene-related research across Europe, bringing together projects and institutions addressing complementary topics of interest relevant to the Graphene Flagship initiative. Since 2013, this harmonisation of graphene-related research activities has involved not only EC-funded projects, but also initiatives funded by national and regional agencies. The most notable example is the FLAG-ERA initiative. FLAG-ERA unites a consortium of national and regional funding agencies from more than 20 European countries, with the aim of supporting the objectives of the Graphene Flagship by implementing calls for transnational research projects in research areas related to graphene and 2DM (and complimentary to those already found in the Graphene Flagship core projects). This mechanism is further described in Section 1.3.

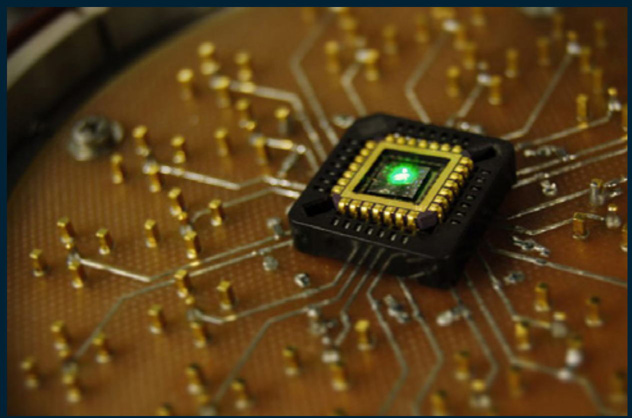
We have identified over 2600 nationally funded projects, 440 projects funded by the European Commission (EC), 30 centres working on GRM in Europe and over 165 European-based companies that are active in the field. We could assess that the overall budget spent on GRM research support has reached the envelope of two billion euros, and that additionally over € 450 million have been spent on GRM infrastructures, and over € 250 million have been invested in companies working with GRM. Institutions involved in GRM research are evenly distributed across Europe and include organisations that are part of the Graphene Flagship, as well as other organisations, indicating that the overall GRM community is widely spread. The combined EC (comprising Graphene Flagship and other projects) and national funding data shows that there is a linear increase in funding per year in the field of GRM from 2008 up to 2021, most recently with an average of € 200 million spent per year.

200

Million € yearly combined European funding for GRM

BUSINESS DOMAINS

During the ramp-up phase of the Graphene Flagship, the project had not yet developed the horizontal structures for innovation and business development which are described in section 3. Instead, the bulk of the work required to clarify the business domains fell on the technical work packages. During Core 1, the key business domains of the Graphene Flagship became more defined, namely, Photonics and Optoelectronics, Electronics, Biomedical Technology, Energy, Flexible and Wearables, Composites, and Coatings. The creation of the Business Developer function in Core 2, followed by the creation and anchoring of Spearhead projects in Cores 2 and 3, fostered even more outputs from these fields. Below is an overview of the business domains which the Graphene Flagship has focussed on.



Close-up photograph of a graphene-based photodetector.
Credit: ICFO

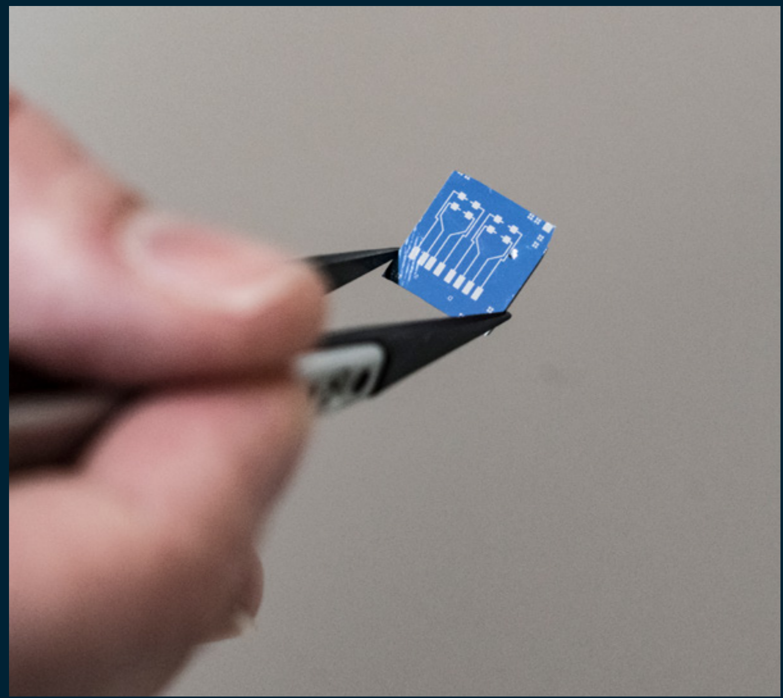
PHOTONICS AND OPTOELECTRONICS

Graphene-based technologies are proving integral to the new generation of communications, such as 5G, enabling high performance optical communication systems through ultra-fast and compact optoelectronic devices. From lasers and optical switches to wireless communication and energy harvesting, graphene will play an important role within the optoelectronics field.

GRM bring unique physical properties to photonic and optoelectronic applications such as high carrier mobility and broadband absorption, which translate to performance of photodetectors and optical modulators compatible with high-speed optical data communication applications, such as those required for 5G and 6G datacom. Integrating GRM in CMOS manufacturing lines brings the possibility to achieve a cost structure compatible with the conventional silicon industry, along with the same levels of miniaturisation and low-power consumption demonstrated over the years by CMOS electronic devices.

At the outset of the Graphene Flagship, innovative technological application fields in long-haul optical communications, inter- and intra-chip optical interconnects, wireless communications, security and surveillance applications, environmental monitoring and energy harvesting were envisioned in this field. After the project's first ten years, the innovation outlook for graphene and related materials (GRM) in the fields of photonics and optoelectronics is exceptionally promising, with numerous industrial applications driving research and development efforts. These innovative industrial applications highlight the significant impact that graphene could have in transforming photonics and optoelectronics, pushing the boundaries of technology and opening doors to a wide range of advanced applications.

The commercialisation of the technologies is expected to have a substantial economic impact. As these technologies mature and become commercially available, they have the potential to drive significant market growth and create a range of new business opportunities, all while improving the performance and price point offered to customers. Industries such as telecommunications, consumer electronics, healthcare and energy will benefit from the improved performance, efficiency and cost-effectiveness offered by graphene-based photonics and optoelectronic devices.



An early chip produced by the Electronic Devices Work Package.
Credit: Johan Bodell, Chalmers University of Technology

ELECTRONICS

As the electronics industry strives to maintain its pace of innovation, graphene – being flexible, strong, thin and highly conductive – has much to offer. Graphene can help to facilitate the next generation of technology from chips and interconnects for data communication to flexible screens for wearable technology. With miniaturisation a major driving factor of the electronics industry, graphene's thinness coupled with its high room temperature conductivity shows great promise. Electronic devices have evolved to become smaller, more multifunctional and increasingly integrated. The incorporation of graphene into electronic and photonic components can enhance their performance in terms of size, power and energy efficiency. Graphene has the potential to create the next generation of electronics even though currently most of this work is limited to the lab. The industry is now shifting focus on developing the tools and processes necessary to manufacture high quality graphene at an industrial scale, leading to a wider adoption by the semiconductor industry.

In the wireless domain, first prototypes of flexible near-field communication antennas based on graphene have been built, providing a very competitive solution for flexible radio frequency identification tags. Coupling graphene's ability to be integrated into electronics with its excellent sensing ability means that it can also be used to provide the building blocks for the internet of things.

The initial hype around graphene in the electronics industry was for transparent conductive films (TCF) and revolutionising the semiconductor industry. The commercial reality is very different; in TCFs, CVD graphene struggles to compete with the incumbent materials (such as indium tin oxide), and the lack of bandgap limits their use as a semiconductor.

Rather than TCFs and semiconductors, the initial commercial activity has shifted to focus on sensors and photonics, where early success and demand is now being seen. Taking advantage of graphene's conductivity, surface area and other unique properties, a wide range of sensor applications are gaining significant momentum in numerous sectors.

After the first ten years of the Graphene Flagship, the main concentration within electronics is on reproducibility, uniformity, stability, yield and scalability to move the devices to higher TRLs. Over time, the focus has also moved from graphene to other layered materials, such as semiconducting transition metal dichalcogenides (TMDs), especially molybdenum disulphide (MoS_2), which have great potential for electronic applications. Efforts have also been made to enhance the wafer-scale growth and integration of graphene and other 2D materials. It is expected that in 2023, the initial growth of 2D material on 200 mm and 300 mm substrates will be demonstrated, and CVD growth of graphene on 200 mm and 300 mm wafers will enable mass manufacturing for applications such as biosensors, sensors, IR cameras and telecommunications. As the technologies created within the 2D-EPL project mature, our next challenge will be to turn the "Experimental Pilot Line" into a "Pilot Line", and finally to enable technology transfer into foundry and semiconductor manufacturers.

Neural interface device to record neuron activity.
Credit: ICN2

BIOMEDICAL TECHNOLOGY

When the Graphene Flagship moved into its Horizon 2020 phase, graphene and 2DM had attracted much attention for their potential to offer alternative options in a variety of biomedical and biological applications, including delivery systems and imaging agents, as well as biosensors and neuroprosthetics, or the combination of the above. The small size and tuneable surface chemistry of graphene and 2DM sheets promised a very efficient interaction with cells, eventually enabling their facile transport within tissues, into individual cells and their intracellular compartments. The ability to fabricate electrically- and biochemically-functional graphene devices furthermore had great promise for a new generation of biosensors and body-implantable electronics. The aim of the project was then to design, fabricate and pre-clinically and clinically test graphene devices based on the following emerging technology platforms: biosensors, electrically-functional implants, devices, matrices and vehicles for transport of therapeutics, and diagnostics and theranostics.

Now, as the demand for healthcare services continues to increase, so does the demand for novel healthcare solutions. These solutions should be more effective, cost less, prevent and cure disease and should be equally effective throughout the world. Graphene is paving the way for novel diagnosis and treatments, thanks to its unique properties, such as high surface area, electron mobility and functionalisation potential, all favourable for biomedical technologies.

For instance, the surface area of graphene makes an excellent platform for drug delivery and the conductivity makes for effective biosensors. The ability of graphene to be made into scaffolds whilst maintaining the inherent conductivity can be put to use in tissue engineering. New research has shown that graphene can be incorporated with a polymer to make very sensitive electromechanical sensors, and that it can be used to make improved deep brain implants.

The biological compatibility of graphene also sees it being used in biological sensors capable of sensing molecules such as DNA and many different analytes, like glucose, glutamate, cholesterol, haemoglobin. Graphene sensors might enhance our lives, for example through wearable sensors that can monitor health in real time.

Market considerations envisage a constant growth for medical devices, for both neuromodulation/neuroprosthetics and biosensing, with the latter having received a recent push by the COVID-19 outbreak. Start-ups and SMEs already involved in these areas have been consolidating during recent years and are heading toward product launches in the coming years, while healthcare corporations monitor graphene advancements in their areas, to be ready for mergers and acquisitions (M&As) or in-licensing opportunities when technologies have been sufficiently de-risked.

The world's first outdoor demonstration of a solar farm with 4.5 m^2 graphene–perovskite panels. Credit: Nature Energy

ENERGY

As the global population expands, the demand for energy production and storage constantly increases. Graphene and related materials (GRM), with their high surface area, large electrical conductivity, light weight nature, chemical stability and high mechanical flexibility have a key role to play in meeting this demand in both energy generation and storage. The field of energy storage has been one of the areas that has seen intense development activity from the early days of graphene research, even at high TRL, and strong patent application activity.

Solar cells, batteries, supercapacitors, hydrogen storage and fuel cells are all areas where GRM can make a difference. These could be used to produce unique, novel devices or integrate into current devices to boost their performance. For example, activated graphene enables supercapacitors for energy storage and also increases their lifespan, energy capacity and charge rate for lithium-ion batteries. For energy generation, GRM, such as molybdenum disulphide, can be used to extend the lifetime of perovskite solar cells. Graphene-based products are already found on the market, especially in the field of energy storage, and they prove that 2D materials can be effectively scaled up in industrial environments and they can reach the requirements in terms of cost, performance and reliability.

In the early years of the Graphene Flagship, a focus was put on batteries and electrochemical capacitor storage as the most common means of storing energy, with fuel cells in association with hydrogen storage tanks also coming into their own. In addition, solar cells manufactured with graphene and other 2DM could offer better sustainability (eliminating the use of scarce materials) and higher conversion efficiencies along with lower cost. Systems for saving wasted thermal energy were also considered at this stage (e.g., thermoelectric devices). After ten years of the Graphene Flagship, various graphene-based innovative products have entered the market, such as graphene-enhanced lithium-ion batteries where graphene is mainly used as an additive to improve their electrical conductivity, charge-discharge rates and overall energy storage capacity; and graphene-based supercapacitors, where graphene-based products have been gaining momentum in the last years. The next wave of graphene-enabled products will probably include advanced perovskite photovoltaic modules and Silicon-perovskite tandem solar cells, while post-lithium-ion batteries and graphene-based hydrogen electrolysers are still at a lower TRL. In order to promote their adoption in the relevant market, there is a need for higher TRL projects involving graphene manufacturers, mainly dedicated to the assessment of the commercial potential of these technologies, including the comparison at industrial scale with competing technologies.

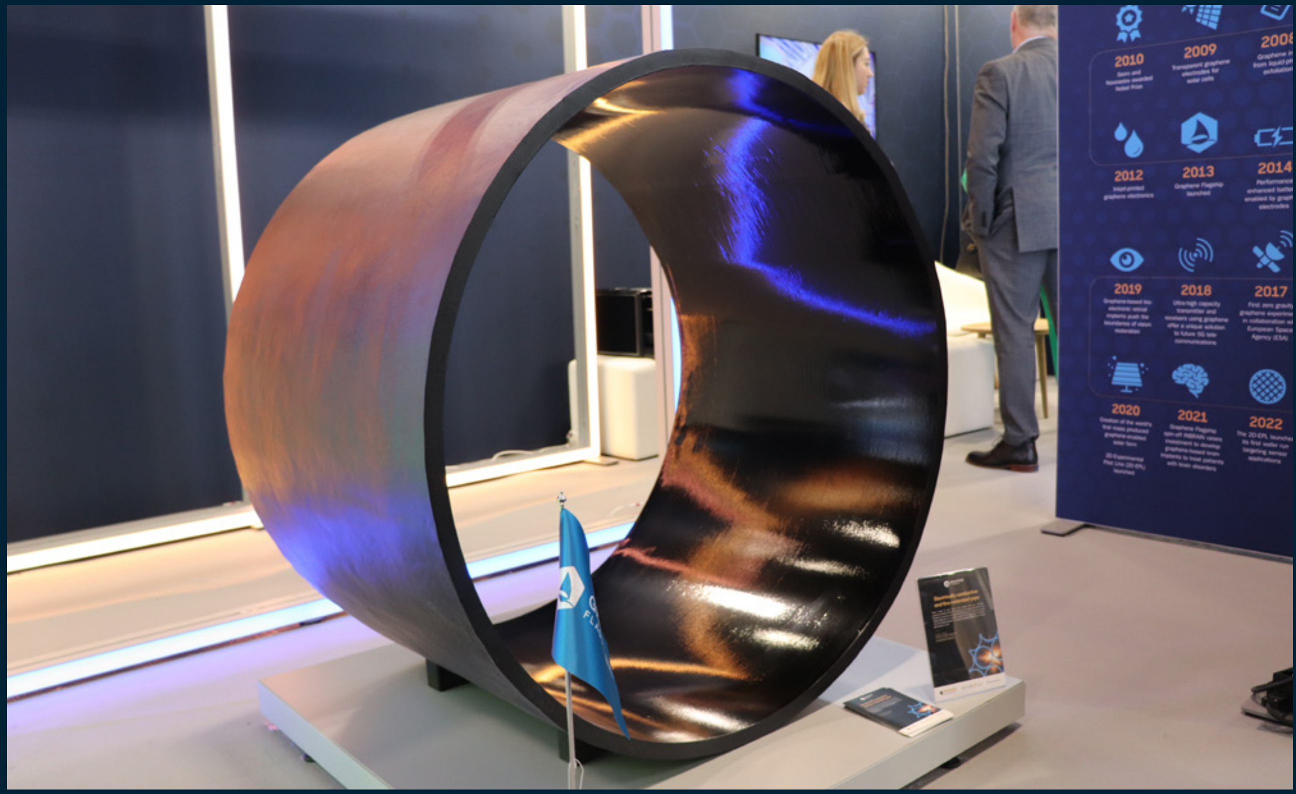
The skin-contact sensors and printed wiring harness in this T-shirt are made from inks that are washable, resilient and stretchable. Credit: Graphene Flagship

FLEXIBLE AND WEARABLES

Wearable technologies have been used to augment our capabilities for centuries, dating back to the invention of the mechanical watch in the 15th century. Today's smart watches are accompanied by a range of wearable gadgets such as smart bracelets, jewellery, patches and similar devices. Ubiquitous computing and its integration with accessories such as bands, watches, glasses, clothing and implants, have resulted in an enhanced intra- and interconnectivity among humans and their environment. From measuring vital signs to sensing environmental conditions, all are part of a future where wearables play a key role in our decision making and life choices.

This future is on our doorstep thanks to recent technological advancements but requires a step-change in the building blocks of wearable technologies. Metals can be expensive, toxic and their performance degrades when subjected to mechanical stresses, while traditional semiconductors are rigid with limited optoelectronic properties. There is a demand for unobtrusive, soft and light smart devices that could be worn un-noticed. Graphene and other 2D materials are, due to their inherent properties, extremely suitable for such devices. They offer an alternative material platform for the creation of low-cost and multifunctional wearable products with unique form factors. Prototypes of health tracking devices, environmental sensors, durable e-textiles and flexible power sources, to name a few, have been developed and demonstrated additional functionalities beyond the limits of the state-of-the-art.

The flexible and wearable domain comprises a sub-area of multiple other technological domains, especially as the 2D materials enable lightweight and often flexible solutions to traditionally rigid applications. Both the market and the producers of the technology and applications see huge potential in this field. Advancements are happening in many areas simultaneously, including health and regulation related aspects especially for skin contact wearables and devices tracking personal information. The main target for the Graphene Flagship in the field of flexible and wearables was to create flexible, intelligent devices built on the platforms of flexible wireless connectivity, sensors, large area sensing surfaces and energy storage and harvesting solutions. In the area of flexible electronics (for wearables or other flexible applications) the progress has been the most rapid in material development. This is natural as e.g. printing inks are not dependent on too many other components. Materials and deposition technology is also a prerequisite for applications to be developed. We are now at the stage where materials and manufacturing technology allows devices to be integrated into wearable systems and gadgets.



Graphene makes this pipe strong and fire-resistant, furthermore, graphene's conductive properties make it possible to place sensors along its surface to detect damage, making it idea for oil and gas transport. Credit: Graphene Flagship

COMPOSITES AND COATINGS

The next generation of composites and coatings can be enhanced by graphene. Its excellent strength, conductivity, flexibility, light weight nature and barrier properties are useful for a wide range of applications. From anti-static and anti-corrosion coatings through to ultra-strong and ultra-lightweight composites, graphene can not only enhance the performance of current materials, but also enable new application fields. Graphene can play a key role in the automotive, aerospace and building industries, where it can be used to enhance the properties of car panels, aerospace wings or concrete. As an additive in coatings, graphene could be used to weatherproof houses or prevent ships from rusting. The conductivity and flexibility of graphene also makes it a promising additive for thermoforming plastics. Soon after the start of the Graphene Flagship, graphene-based sports equipment was already being commercialised on a large scale. However, those early applications were based on few-layer graphene. Early predictions for extensive applications of GRM composites were in the aerospace sector where, due to high end-value and small production scale, the cost of using graphene would be justified allowing for new technologies to become rapidly competitive for small to medium scale production.

Composites represent the largest single application area for graphene. The Graphene Flagship Technology and Innovation Roadmap (TIR) for graphene composites confirms large, growing and strong (European) markets (automotive, aerospace, medical technologies, renewable energy, energy transmission, advanced textiles, defence, packaging). Sporting goods, automotive, aerospace and renewable energy predominate in the commercial up-take of graphene in composites. Further and more specific applications include desalination, air filtration and anti-corrosion paints.

The multifunctional benefits of graphene, coupled with the alignment to corporate environmental, social and governance (ESG) policies, have been key. Concrete has emerged as a primary driver of enquiries and a significant potential market for graphene materials, green polymers and upcycling waste polymers into graphene composites.

As we near the end of the first ten years of the Graphene Flagship, there are a notable number of start-ups and SMEs seeking to develop and accelerate graphene and 2D materials into existing and new products, processes or services. We anticipate that sustainability and NET-ZERO will be the predominant issues affecting the innovation outlook for graphene in composites over the next – five to ten years. Graphene will increasingly be seen as an enabling technology for companies seeking to align with their ESG obligations, be it environmental and social sustainability, managing risks, meeting shareholder expectations, or driving long-term value creation. It also holds huge potential to reduce manufacturing costs by creating versions of existing products that can be produced with less material and less energy-intensive processes. Importantly, whilst the focus for graphene tends to be on material properties, an equally important benefit is cost reduction to the composite manufacturer. Graphene can reduce the amount of material required, lower energy costs and result in faster production – saving time and money.

The Dallara Stradale sportscar uses graphene composites in the body for fire retardancy and better shock absorption during collisions. Credit: Graphene Flagship

The Graphil water filter can be fitted and the point of use to guarantee in-line access to clean water. Credit: Juliane Haerendel, Graphene Flagship

OTHER APPLICATION AREAS

The technologies created within the Graphene Flagship have not been limited to the six domains described above. Rather, there have been concerted efforts towards the development of other, very relevant applications as described below.

Water filtration

Europe consumes billions of cubic metres of water each year. Several Graphene Flagship initiatives study new solutions for water purification, using graphene-enabled filters helps remove contaminants, pesticides, heavy metals and dangerous pathogens.

The water treatment systems market is growing and is estimated to reach $ 35.5 billion by 2027, growing at a CAGR of 6.9% over 2020–2027, with Europe as the second-largest market after North America. This sector usually incorporates new technologies because of its high sales volume, lower capital cost and small scale. This is particularly important because the EU is considering introducing new guidelines for contaminants and limits for water. Various brands of water purifiers are trying to meet the standards set by regulatory bodies to provide clean and pure drinking water across the globe. The GRM-coated membrane is a promising technology that could fulfil the new regulations, due to high contaminant removal, and create a strong market pull within the next five to six years.

Automotive

Graphene has the potential to drive significant advancements in the automotive industry – from strengthening structural components to improving electrochemical energy storage (i.e., batteries) efficiency and safety in electric cars as well as enhancing the performance of the self-driving car. The Graphene Flagship has orchestrated a number of projects researching the benefits of graphene in automotive applica-tions and how vehicles can be improved. The Graphene Flagship is now seeing this research and development come to fruition.

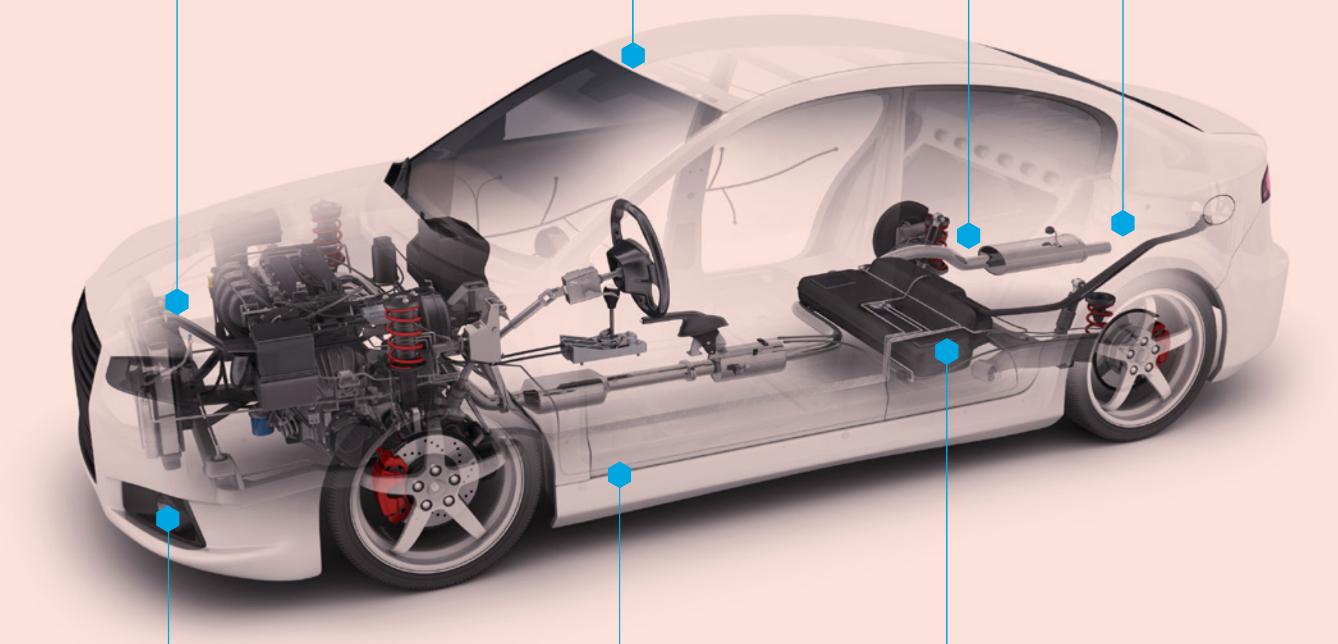
Graphene for automotive

HEAT DISTRIBUTION
Loop heat pipes, previously only tested for aerospace applications, dissipate heat in computer electronics or radiators.

ENERGY EFFICIENCY
Increased energy extracted from new-generation solar cells, enhancing vehicle performance and efficiency.

SAFER PIPES AND TANKS
Graphene-based resin used for corrosion-resistant tanks and pipes, for storage and transport of volatile chemicals.

REDUCED POLLUTION
Smog consuming catalysts are enhanced, and increased levels of CO_2 are captured.



SAFER SENSORS
Graphene-based sensors enable the detection of light from ultraviolet to infrared, improving obstacle detection.

ROBUST COMPONENTS
Panels manufactured using graphene carbon fibre composites are lightweight and stronger than traditional panels.

INCREASED MILEAGE
A new generation of lithium ion batteries with increased capacity and potential.

Graphene for aeronautics

Aeronautics & Space

Graphene and related materials show great promise for aeronautics and space applications and are already being tested thanks to the innovative research carried out by Graphene Flagship partners. Our most recent results clearly suggest that graphene will be a true revolution in these fields. Leading Graphene Flagship partners such as Airbus, Lufthansa Technik and Leonardo have demonstrated the possibilities of graphene and related materials in aeronautics. Graphene improves the mechanical properties of plane parts, enabling their construction to be thinner and lighter, while maintaining or improving functionality. This results in significant fuel savings, reducing costs and greenhouse gas emissions.

Graphene will also lead manufacturers towards producing safer aircraft – one of the Core 3 Spearhead projects funded by the Graphene Flagship, GICE, has developed graphene-based thermoelectric ice protection systems. These new devices will keep aircraft parts ice free without affecting aerodynamic properties, leading to safer and more environmentally friendly flights.

Graphene's properties make the material ideal for a myriad of applications in human space exploration. This led to numerous joint European Space Agency (ESA) – Graphene Flagship workshops and other activities, such as the Zero Gravity Graphene campaign which saw researchers and students in the Graphene Flagship conducting two exciting experiments in collaboration with ESA to test the viability of graphene for space applications, including light propulsion and thermal management.

Further collaborations between the Graphene Flagship and ESA led to participation in a sounding-rocket launch in collaboration with the Swedish Space Corporation (SSC) in 2019. The experiment aimed to test the possibilities of printing graphene inks in space. Studying the different self-assembly modes of graphene into functional patterns in zero-gravity will enable the fabrication of graphene electronic devices during long-term space missions, as well as help understand fundamental properties of graphene printing on Earth. This mission is also a first step towards the investigation of graphene for radiation shielding purposes, an essential requirement of manned space exploration.

ECO-CONSCIOUS DESIGN
Integrating graphene and related materials (GRMs) into fibre-reinforced composites can improve weight and strength, reduce fuel usage and CO_2 emissions, and help to mitigate environmental damage.

FIRE RETARDANCY
Graphene is an extremely effective, non-toxic fire-retardant solution. Graphene foams and coatings are highly synergistic and can be used to enhance fire retardancy in aircraft interior elements such as luggage racks.

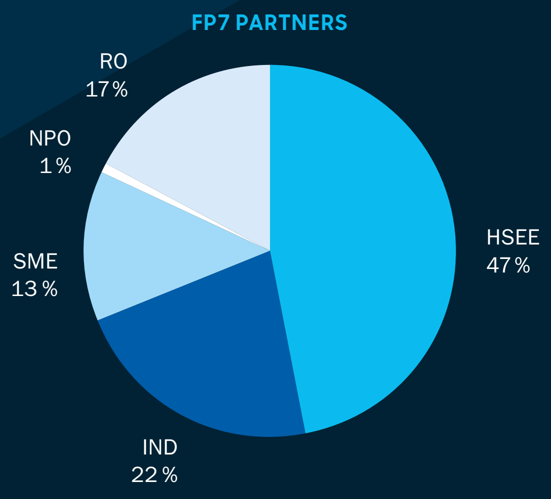
THERMAL MANAGEMENT
Graphene coatings or composites can improve the efficiency of heat transfer applications. An ad-hoc thermal management is necessary for allowing the most efficient operational conditions of electrical engines, batteries, or fuel cells.

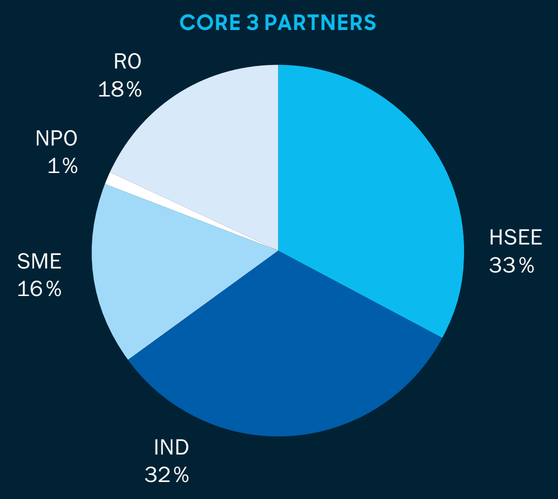
IMPACT RESISTANCE
Graphene's high aspect ratio, flexibility and mechanical strength enable it to strengthen weak points in currently used composites. Aircraft wings coated with graphene-enhanced skin show levels of impact resistance of up to 60% higher than conventionally-skinned carbon fibre wings.

DAMPING VIBRATIONS
Graphene composite foams can dampen vibrations, reducing noise inside the cabin and improving mechanical properties and heath endurance.

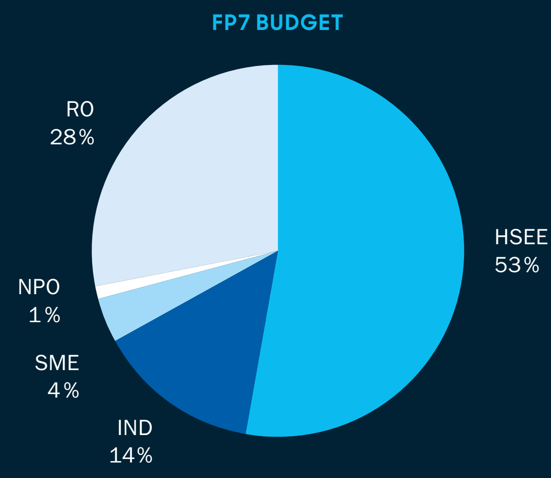
DE-ICING
Graphene-based electrical ice protection systems prevent the accumulation of ice on critical components of the aircraft. This enables the overall energy consumption of an aircraft to be reduced without compromising safety.

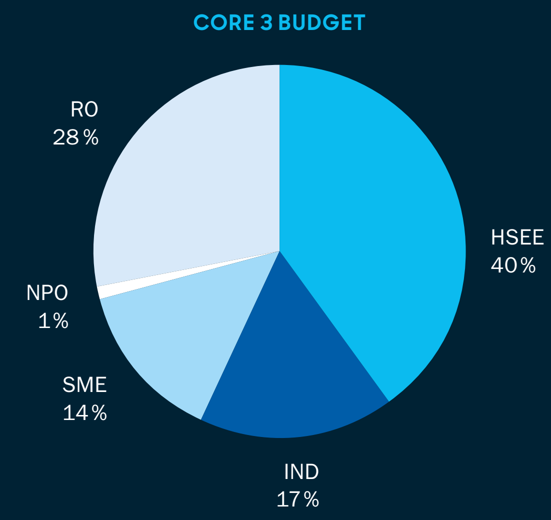
AIR FILTRATION
Heatable foams made from low-density aerographene are used in cabin air filters to provide smart self-cleaning functions, reduce maintenance costs, and enable all air filter surfaces to be consistently and equally cleaned. Graphene air filters could even remove impurities more effectively than HEPA filters.





The evolution of the consortium in terms of partner type, showing the increase in industrial partners over time. RO= Research Organisation, NPO= Non-Profit Organization, SME= Small- and Medium-sized Enterprises, IND= Industry, HSEE= Higher Secondary Education.





Budget share per organisation type in FP7 and Core 3. RO= Research Organisation, NPO= Non-Profit Organization, SME= Small- and Medium-sized Enterprises, IND= Industry, HSEE= Higher Secondary Education.

GRAPHENE FLAGSHIP CONSORTIUM

Since its inception, the Graphene Flagship consortium has evolved in terms of number and types of partners, as well as in terms of expertise among partners, facilitating a shift towards more applied topics and higher technology readiness levels which is also reflected in the distribution of budget as show above. The Graphene Flagship began with the Coordination Action for Graphene-Driven Revolutions in ICT and Beyond (GRAPHENE-CA) in the European Commission's Seventh Framework Programme (FP7). Following a two year ramp up phase in FP7 (GRAPHENE), the Flagship sailed into Horizon 2020 with three successive Core projects, adding the 2D Experimental Pilot Line after the start of Core 3.

Evolution of the Graphene Flagship consortium.

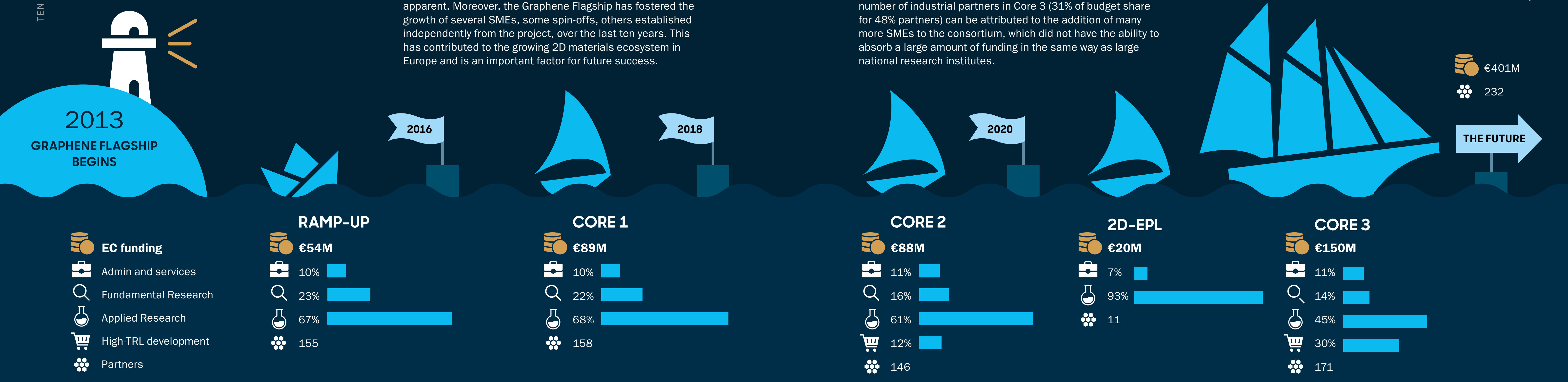
The evolution of the consortium in terms of number of partners during different phases (FP7, Core 1, Core 2, Core 3, 2D-EPL) is visualised below. There were large jumps when 65 new partners joined the consortium in Core 1 as a result of a competitive call in 2014 and smaller changes when Core 1, Core 2 and Core 3 were launched, or proposals submitted. The smallest jumps are due to individual partners reorganising themselves, or due to researchers moving to new organisations. The increase in the number of partners in Core 3 relative to Core 2 is largely due to the expansion of our industrially focussed spearhead programme and reflected in the larger project budget for Core 3 where one third of the project's funding was invested in these ventures.

In terms of types of partners – academic institutes, industry or research organisations – the Graphene Flagship also changed in composition from FP7 to the close of Horizon 2020. An increase in industrial partners as the consortium grew was apparent. Moreover, the Graphene Flagship has fostered the growth of several SMEs, some spin-offs, others established independently from the project, over the last ten years. This has contributed to the growing 2D materials ecosystem in Europe and is an important factor for future success.

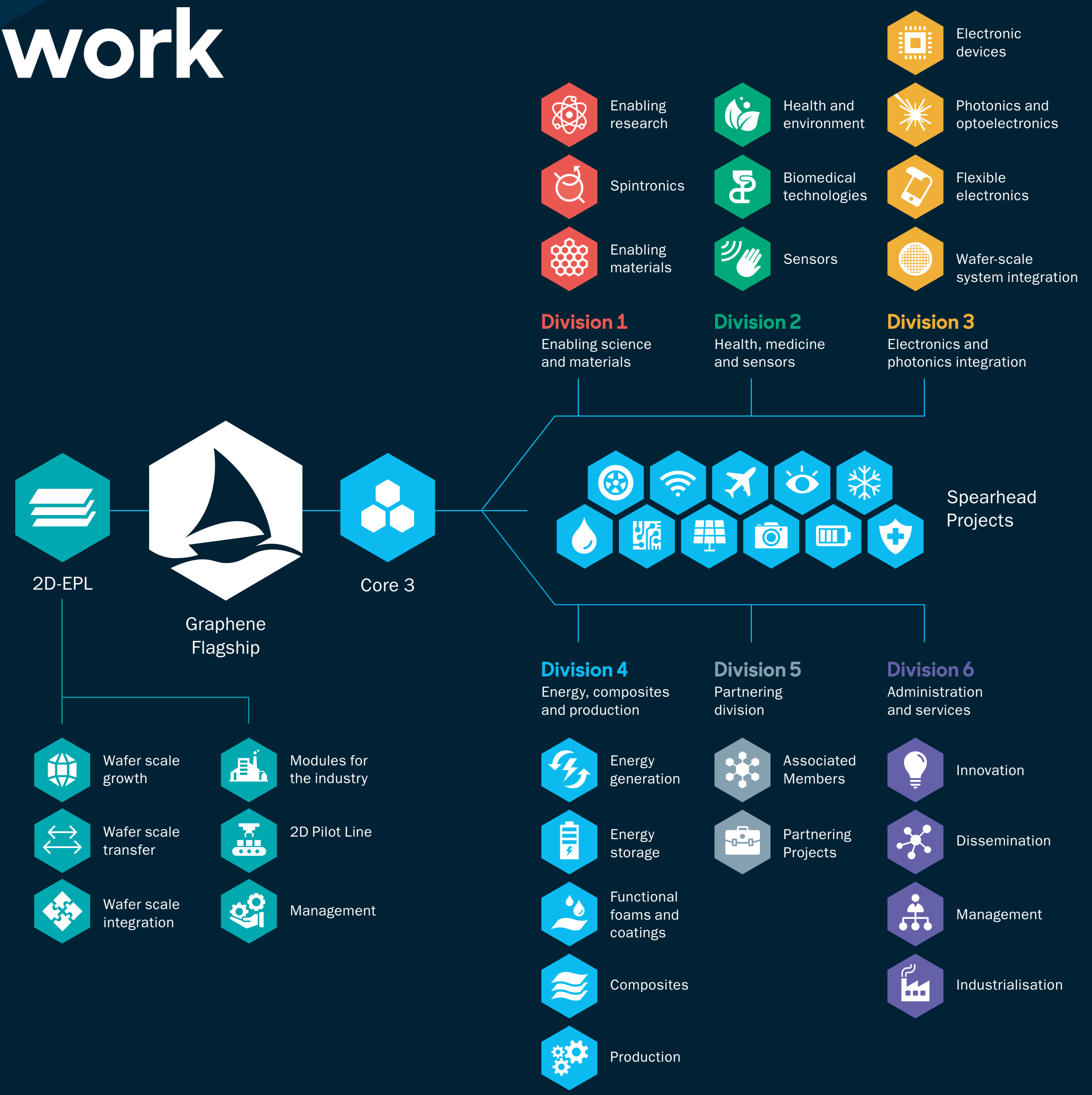
The difference between FP7 and Core 3 is apparent and reflects the explicit step towards higher technology readiness levels in Core 2 and Core 3 with the launch of Spearhead (SH) projects, which addressed market opportunities where graphene and related materials (GRM) provided significant advantages. These SH projects drew upon advances made in different work packages over the first two core projects and combined them to create concrete demonstrators close to market integration. This topic is discussed in more detail in Section 3.

The budgets of FP7 (€ 75 million of which € 54 million was co-funded by the EC) and Core 3 (€ 150 million) differed not only in size but in distribution across organisation types. The increase from 14% of the FP7 budget allocated to industrial partners (both large industry and SMEs) to 31% in Core 3 shows the clear shift in work done in the project. The slight mismatch in budget share per organisation type and overall number of industrial partners in Core 3 (31% of budget share for 48% partners) can be attributed to the addition of many more SMEs to the consortium, which did not have the ability to absorb a large amount of funding in the same way as large national research institutes.

The structure of the Graphene Flagship itself also evolved over the years, from 16 work packages (WPs) in FP7, to 19 work packages and 11 Spearhead (SH) projects in Core 3. This evolution is shown on the next page. The technical WPs were divided into four technical divisions – Enabling science and materials; Health, medicine and sensors; Electronics and photonics integration; and Energy, composites and production – with an additional external division for Associated Members and Partnering Projects, one administrative division, and finally, a division for the 2D-EPL project after its launch in 2020. The restructuring of WPs between FP7 and Core 1 into the stable structure of Cores 2 and 3 show the maturation of application areas, such as Biomedical technologies and diversification of certain applications, such as energy and composites. The structure of the 2D-EPL reflects its goal of an integrated pilot line working as one unit.



How we work



Core 1 Work Packages

- Fundamental science of graphene and two-dimensional materials
- Spintronics
- Materials
- Health and Environment
- Sensors
- High Frequency Electronics
- Optoelectronics
- Flexible Electronics
- Energy Applications
- Nanocomposites
- Production
- Innovation
- Dissemination
- Management
- Research Management
- European Programmatic Coordination and Alignment

Core 2 Spearhead Projects

- 5G
- RFID
- Solar farm
- CHEMSENS
- Batteries
- Weargraph

Final Graphene Flagship organisation vs original Work Packages and Spearhead projects. Note that the Core 2 Spearhead project budgets were inserted into WP budgets, while in Core 3, the SHs were treated as WPs.

> This partnering mechanism can be considered a successful mechanism to widen participation, promote alignment and contribute to the advancement of graphene and related material research in a coordinated way in Europe."

Evaluation study of the European framework programmes for research and innovation for excellent science – H2020

Although the players involved in the field of GRM at the national and European levels go well beyond the institutions formally part of the Graphene Flagship initiative, the latter, during ten years of activity, has managed to involve an impressively large number of organisations (research institutions as well as industrial companies) working with GRM to build a consolidated network of participants. These were affiliated either as partners in the Core projects or as Associated Members – any interested organisations working in the field of GRM associated to Graphene Flagship WPs either through their own initiative as Individual Associated Members (iAM) or via Partnering Projects (PPs), i.e., other EU or nationally funded projects.

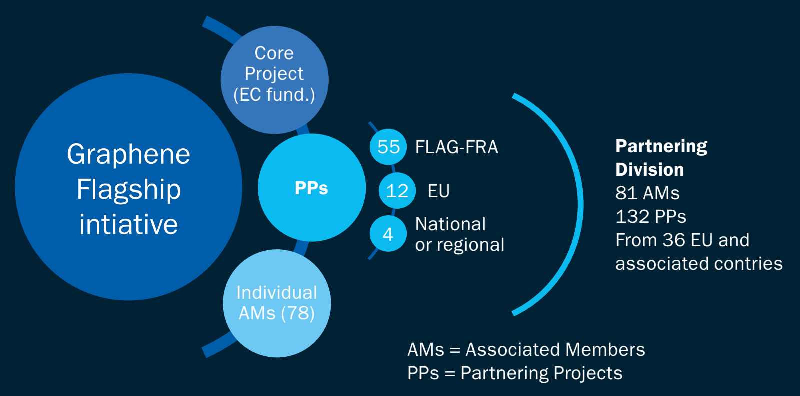
Besides the impact in terms of securing funding for research in GRM, the Graphene Flagship, over the past decade, was committed to attracting collaborative partnerships beyond the Core projects consortia. For this reason, an association mechanism was developed and was implemented since Core 1. Since the FP7 phase, a total of 213 organisations from 35 different EU Member States and Associated Countries were associated to the Graphene Flagship as AMs (figures updated through July 2023), either individually (81) or via a PP (132).

These Associated Members contributed to the overarching aims of the Graphene Flagship by performing research that was complementary to that covered by the Core projects, as well as by contributing to the outputs of the initiative with products released on the market and the translation of research from lab to market applications. Through this partnering mechanism, organisations from countries that were not involved in the Core projects were associated to the Graphene Flagship, thus effectively widening the participation, promoting alignment and contributing to the advancement of GRM research in a coordinated way in Europe.

The interaction between Core partners and Associated Members resulted in a quite heterogeneous variety of initiatives, ranging from strong scientific collaborations, joint projects and publications to more informal exchanges of information and materials, to participation in networking activities. Networking activities promoted by the Graphene Flagship, in particular by the Dissemination Work Package, were crucial in offering opportunities for AMs and PPs to connect and interact with successive Core projects and learn about the activities performed within. Based on the collected evidence, the association mechanism successfully supported the integration of AMs and PPs and contributed to increasing the overall output of the Graphene Flagship initiative. This mechanism also significantly increased the reach of the Graphene Flagship beyond its 232 beneficiaries in the FP7 and H2020 projects, nearly doubling the number of European organisations affiliated in some way with the project.

From the information gathered, it is evident that numerous collaborations of different types are still on-going between the AMs/PPs and the partners of the Core project. Nevertheless, these numbers are undoubtedly underestimated due to the lack of information provided systematically by the AMs/PPs. We note that, in cases where interest and pro-active approach was shown from both AMs/PPs and Core project sides, the interactions were efficient and resulted in very concrete joint outputs.

From the feedback gathered via surveys and face-to-face interviews, there is a clear need expressed both by the Core project partners and AMs to continue the partnering mechanism in the next phase of the Graphene Flagship under Horizon Europe.



Overview of Associated Members and Partnering Projects.

Overview of Graphene Flagship outputs

As illustrated above, the Graphene Flagship has been a unique opportunity for science and innovation in Europe. The long timeframe and huge network of the project resulted in many outputs beyond the typical Key Performance Indicators one may find in an EU-funded project.

In this section, we describe the success of the Graphene Flagship in delivering on its own promises, i.e., those objectives set out in 2013, as well as its exceptional outputs in terms of publications and intellectual property. These results are complemented by several external evaluations of the initiative over its lifetime, not to mention by the impressions of numerous Graphene Flagship personnel.

HAS THE PROJECT DELIVERED ON ITS PROMISES FROM 2013?

The Graphene Flagship began in 2013 with the ambition to, over ten years, bring together academia and industry to take graphene and other 2DM research out of the laboratory and onto the factory floor. As part of this cumulative analysis of the last decade of the Graphene Flagship, we reflect on the promises made at the outset of the project.

In 2013, the Graphene Flagship Framework Partnership Agreement (FPA), the legal agreement which governs the Core and 2D-EPL projects, set out 77 scientific and technical objectives and 29 systems-level targets ("promises") across eleven domains: fundamental research, health and environment, materials and production, electronic devices, spintronics, photonics and optoelectronics, sensors, flexible electronics, energy storage and generation, nanocomposites, and biomedical applications. These objectives were the basis of the work to be done over the next ten years and are reflected in the structure of the Graphene Flagship divisions and work packages as described above. At the same time, 11 specific roadmaps for each of those domains were devised to steer the initiative. Those roadmaps are themselves related to the broader Technology and Innovation Roadmap[4] published in Nanoscale in 2014 but are tailored to the specific scientific and technological objectives and systems-level targets of the Graphene Flagship.

Based on inputs from the majority of Graphene Flagship Work Package leaders during the last year of Core 3, the project has indeed delivered on its promises, and even delivered products, spin-offs, patents and prototypes not initially promised or envisioned. In total, 67 scientific and technological targets were reached, while 17 systems-level targets were achieved. In other words, after ten years of research, innovation and collaboration, the Graphene Flagship has delivered on 80% of its initial promises. While not every objective or systems-level target has produced a product on the market, it is important that each objective or target be considered within the context of its domain and the state-of-the-art – in other words, fundamental sciences will of course differ in outputs from more market-ready applications such as composites. The objectives set in 2013 and the promises delivered should also be viewed through the lens of a changing Graphene Flagship consortium (e.g., a shift to higher-TRL activities), as well as the development and growth of 2DM application areas. However, it is clear from the number of patents, spin-offs, prototypes and products which are outlined later in this deliverable, that the Graphene Flagship has also facilitated the further commercialisation and innovation within the 2DM field.

> Over the past nine years, the Graphene Flagship has successfully brought graphene out of the lab, creating a fruitful European industrial ecosystem that develops applications of graphene and layered materials."
>
> Evaluation study of the European framework programmes for research and innovation for excellent science, 2023

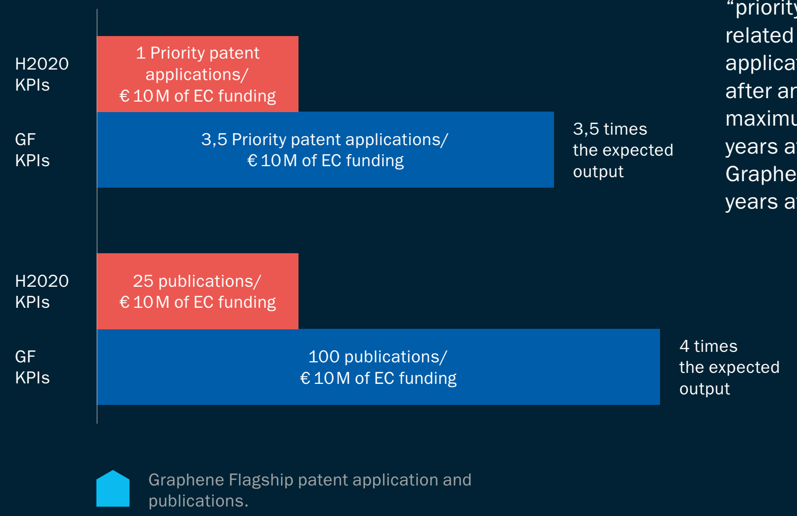
[4] E Nanoscale, 2015,7, 4598-4810, https://pubs.rsc.org/en/Content/ArticleLanding/2015/NR/C4NR01600A#!divAbstract

> The Graphene Flagship is money well spent!"
>
> Margrethe Vestager, European Commission Executive Vice President

HORIZON 2020 INDICATORS

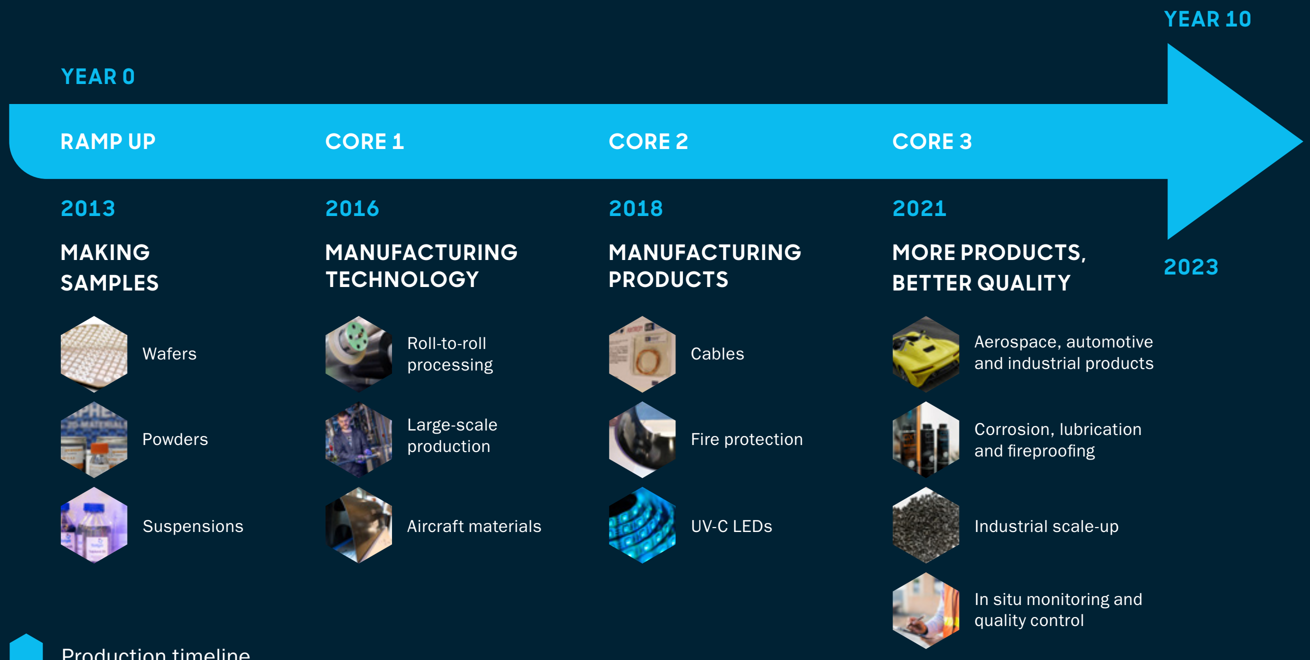
The legal basis of Horizon 2020 specifies a list of compulsory Key Performance Indicators (KPIs) to be considered in its evaluation and monitoring system. For Future and Emerging Technology projects, the EC has set a benchmark of one patent application per € 10 million of funding. By December 2023, the inventive output of the Graphene Flagship exceeded this benchmark, with 3.5 priority applications € 10 million. While not a H2020 KPI, the output of granted patents from Graphene Flagship activities is more than 80.

In terms of publications in peer-reviewed high impact journals, which is a key performance indicator for excellent science, the output of the Graphene Flagship has greatly exceeded the target of 25 publications per € 10 million funding. With over 5400 publications in December 2023, of which more than 70% were published in top 10% impact ranked journals, this result is 100 publications per €10 million.



> The case study results have shown that the Graphene Flagship has successfully delivered on the objectives as set out in the beginning of the FET programme of excellent science and excellent innovation."
>
> Evaluation study of the European framework programmes for research and innovation for excellent science, 2023

It should be noted that the scientific impact of the Graphene Flagship is still accumulating. For example, it takes years for a patent application to mature into a granted patent, and many patent applications are abandoned, are withdrawn, or expire. As a ten-year project, the Graphene Flagship tracks patenting metrics over a longer time than is typical, from the first-filed patent application describing an invention (the so-called "priority application") through to the subsequent "family" of related patent applications that "claim priority" to the priority application. Similarly, peak citation rate occurs several years after an article has been published. More specifically, the maximum citation rate is only reached approximately four years after publication. A clear estimate of the impact of the Graphene Flagship can therefore only be obtained several years after the project has ended.



Production timeline

PRODUCTION

Without scalable production methods, the products, prototypes and even spin-off companies, may not have been possible. In 2013, much of the material being worked on was produced by mechanical exfoliation and to a small part CVD graphene. Today large-scale production dominates the market, with many thousands of tonnes of graphene being produced worldwide. Additionally, in 2013 very little effort was put to 2D materials other than graphene, while today these new and emerging materials are maturing rapidly. Over the first ten years of the Graphene Flagship, Work Package (WP) Production has developed its capabilities in terms of production volumes, quality (and traceability) of material produced and range of product offering. Indeed, most manufacturing challenges for graphene and related materials (GRM) from the start of the project have now been overcome. As WP Production was largely driven by industrial partners, several products and prototypes have been released to the market over the course of the initiative.

In addition, as mentioned in the H2020 evaluation of the Graphene Flagship, an important success factor of the project has been the focus on creating various value chains for different application areas. This involvement of actors from every stage, including manufacturing and production, has reduced the risks in the project.[5]

In 2019, the Graphene Flagship produced a comprehensive guide that condenses the knowledge of graphene and 2DM production and processing acquired and developed by the Graphene Flagship over its first six years. Co-authored by 70 international experts and incorporating over 1,500 references, this open access review has benefitted the whole materials science community across both academia and industry. The handbook, published by the Institute of Physics in 2D Materials, is a source of information for companies wanting to incorporate graphene and layered materials into their products. Considering it has been downloaded more than 100,000 times since its publication, it is almost certainly the ultimate manual in the field of graphene and 2DM production and a testament to the power of the Graphene Flagship.

> For scientists looking to study graphene and layered materials, or companies that want to mass produce them, this knowledge is vital."

Mar García-Hernández, Graphene Flagship Work Package Leader for Enabling Materials and coordinator of the Handbook of Graphene Manufacturing

[5] European Commission, Directorate-General for Research and Innovation, Budraitis, M., Pranckevičius, P., Délkutė, R. et al., Evaluation study of the European framework programmes for research and innovation for excellent science – Horizon 2020 – Annexes, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2777/353383

Graphene Flagship Spin-off companies

PRODUCTS, PROTOTYPES, SPIN-OFFS

In addition to the numerous technical KPIs which were set by the Graphene Flagship over the ten years of the project, the numerical KPIs – common for all technical work packages – also tell a story. With such a long duration, we are able to see how the work begun in 2013 has transformed academic research into working prototypes, then into spin-off companies, and finally into products on the market.

> The Graphene Flagship has created a great environment for academics and industrial partners to work together, enormously shortening the time between scientific discovery and bringing products to the market."

Mar García-Hernández, ICMM – CSIC

In total, 20 companies spun-off from the Graphene Flagship. They have received an estimated € 170 million in private investments. A list of spin-off companies can be found here: https://graphene-flagship.eu/innovation/spin-offs/

Materials and Production

SPIN-OFF COMPANY
SIXONIA TECH - 2017

Production and processing of electrochemically exfoliated graphene for different applications, in particular conductive inks and formulations, functional coatings and polymer composite materials. Product example: E-Graphene Dispersion.

SPIN-OFF COMPANY
BEDIMENSIONAL - 2018

Industrial production of few atomic layers-thick flakes of graphene, hexagonal boron nitride and other two-dimensional crystals in liquid dispersion or powder form for solutions in the in the fields of functional paints and coatings and polymer composites. Applications range from energy storage and conversion, to lubricants, automotive, aerospace and additive manufacturing sectors. Product example: B-LEAF and G-LEAF coatings.

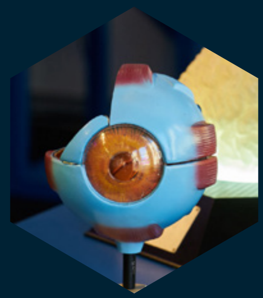
PRODUCT
COST-EFFECTIVE, LARGE-SCALE GRAPHENE- 2019

The Neutron is a roll-to-roll system capable of depositing large areas of graphene on metal foils under ambient conditions; and the CCS 2D system enables wafer-scale production of graphene on insulating wafers, a breakthrough that will speed up the development of new graphene electronics.

SCIENTIFIC PUBLICATION
HANDBOOK OF GRAPHENE MANUFACTURING - 2020

Encompassing more than 1,500 references and the knowledge of 70 co-authors from EU-funded Graphene Flagship partners and Associated Members, this handbook aims to provide a single source of knowledge on techniques for the production and processing of graphene and related layered materials.

Biomedical Applications

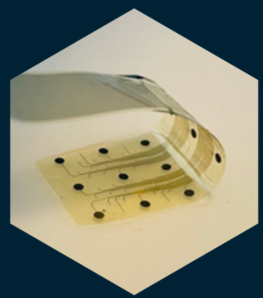


PROTOTYPE
BIOELECTRONIC RETINAL IMPLANTS - 2018

The electrode material interfacing with retinal neurons is based on graphene, which enables the use of more and smaller high-performing electrodes capable of bidirectional (recording and stimulation) communication with the retina.

SPIN-OFF COMPANY
INBRAIN - 2019

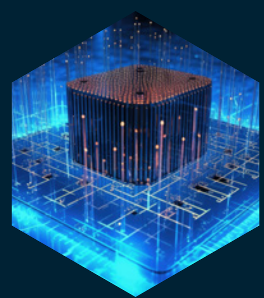
Harnessing the extraordinary material properties of graphene to build safe, non-invasive and highly efficient neural solutions. Prototype example: Graphene microtransistors are excellent devices for recording infraslow signals which can be very valuable for clinical diagnosis, prognosis and therapy in neurocritical care.



PRODUCT
NEURAL INTERFACE DEVICES - 2020

First graphene-based neural interface device, aimed at the neuroscience market. Commercially available neural headstages amplify, record and analyse data from the brain in vivo allowing neuroscientists around the world to use graphene for their own research and leading to new discoveries.

Fundamental Science



PRODUCT
TABLETOP QUANTUM HALL - 2015

Quantum Hall resistance measurements with metrological accuracy in a small cryogen-free system operating at a temperature of around 3.8 K and magnetic fields below 5 T demonstrated.

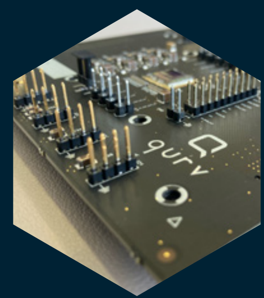
Photonics and Optoelectronics

SPIN-OFF COMPANY
EMBERION - 2016

Developing and producing revolutionary infrared cameras that disrupt and extend multiple imaging markets. Prototype example: Broadband camera based on a graphene-enabled image sensor that can detect visible, short-wave infra-red and mid-wave infra-red light using a single focal plane array for food processing and plastic waste sorting in industrial environments.

SPIN-OFF COMPANY
CAMBRIDGE RAMAN IMAGING - 2018

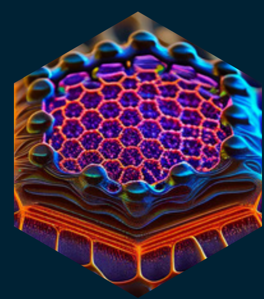
Bringing together ultra-fast fibre-based lasers and Coherent Raman scattering microscopy to make high-speed, truly label-free imaging possible, scanning tumour tissue in seconds.



SPIN-OFF COMPANY
QURV - 2020

Developing wide-spectrum image sensor technologies and integrated solutions to enable next-gen computer vision applications, addressing the expanding needs of an autonomous and intelligent new world.

Sensors



PROTOTYPE
WAFER-SCALE GRAPHENE MICROPHONES - 2022

An efficient transfer-less method to fabricate wafer-scale graphene drums with a high yield of 100% by using a CMOS-compatible process flow without any transfer steps. These graphene membranes are shown to operate as microphones, detecting sound with mechanical compliances greatly exceeding that of commercial MEMS microphones.

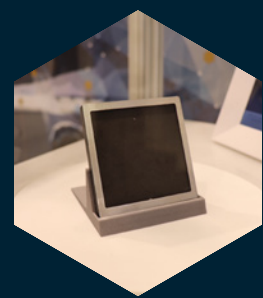
Nano-composites

PROTOTYPE
WATER FILTRATION - 2022

Production of a compact water filter that exploits the best of two materials: hollow fibre membranes to eliminate microbiological contaminants (i.e., bacteria, viruses, endotoxins) and graphene oxide to remove emerging contaminants (i.e., drugs, antibiotics, pesticides, heavy metals and personal care by-products) from water.

PROTOTYPE
ICE PROTECTION SYSTEM - 2022

Graphene-based thermoelectric ice protection technologies keep aircraft ice-free, without affecting aerodynamic properties. The system is compatible with Carbon Fibre Reinforced Plastic, flexible, light, consumes very little power, controls heat generation and could be process automated.



PROTOTYPE
AIRCRAFT CABIN AIR FILTRATION - 2022

Building a sustainable, innovative and active air filtration system for passenger aircraft with a novel system made of lightweight filter materials based on graphene foams, which possess a unique set of mechanical and electrical properties.

PROTOTYPE
STEERING WHEEL HEATING - 2022

An alternative solution to standard steering wheel heating systems based on electrothermal conductive graphene-polyurethane coatings on flexible supports for faster, more efficient and more uniform heating at low manufacturing costs.

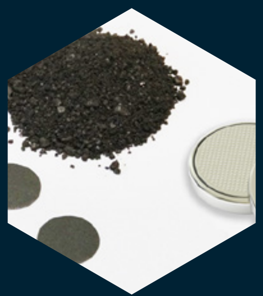
PROTOTYPE
SELF-LUBRICATING CIRCUIT BREAKERS - 2022

Metal-graphene composites to produce first-of-their-kind, grease-free, maintenance-free, low-voltage circuit breakers for fault protection in key parts of the electrical grid.

PROTOTYPE
SPORTS CAR - 2023

The Dallara Stradale sports car features a graphene-enhanced fire-resistant interior as well as other graphene-enhanced composites that improve resistance to deformation and improved energy dissipation capabilities.

Energy Storage and Energy Generation



PROTOTYPE
GRAPHENE ENABLED SILICON-BASED LITHIUM-ION BATTERIES - 2020

Graphene enabled silicon-based lithium-ion batteries for wireless headphones, hearing aids, wearables and small electronic devices developed.

PROTOTYPE
SOLAR FARM - 2022

Manufacturing of large-area (0.5 m2) perovskite solar panels, each containing 40 modules whose interfaces are engineered with two-dimensional materials and further integration in a stand-alone solar farm infrastructure with peak power exceeding 250 W.

Health and Environment

SCIENTIFIC PUBLICATION - 2018

A comprehensive view of human and environmental hazard assessment of graphene-based materials with the aim to understand the properties that underlie the biological effects of these materials.

POLICY REPORT - 2022

A systematic review to critically assess the health and environmental effects of graphene, graphene oxide and other two-dimensional (2D) materials, based on existing public information.

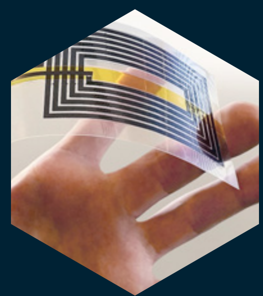
SCIENTIFIC PUBLICATION - 2023

Applying existing OECD Test Guidelines for testing 2D graphene nanoforms may require more attention, additional considerations and/or adaptations of the protocols, because graphene materials are often problematic to test due to their unique attributes.

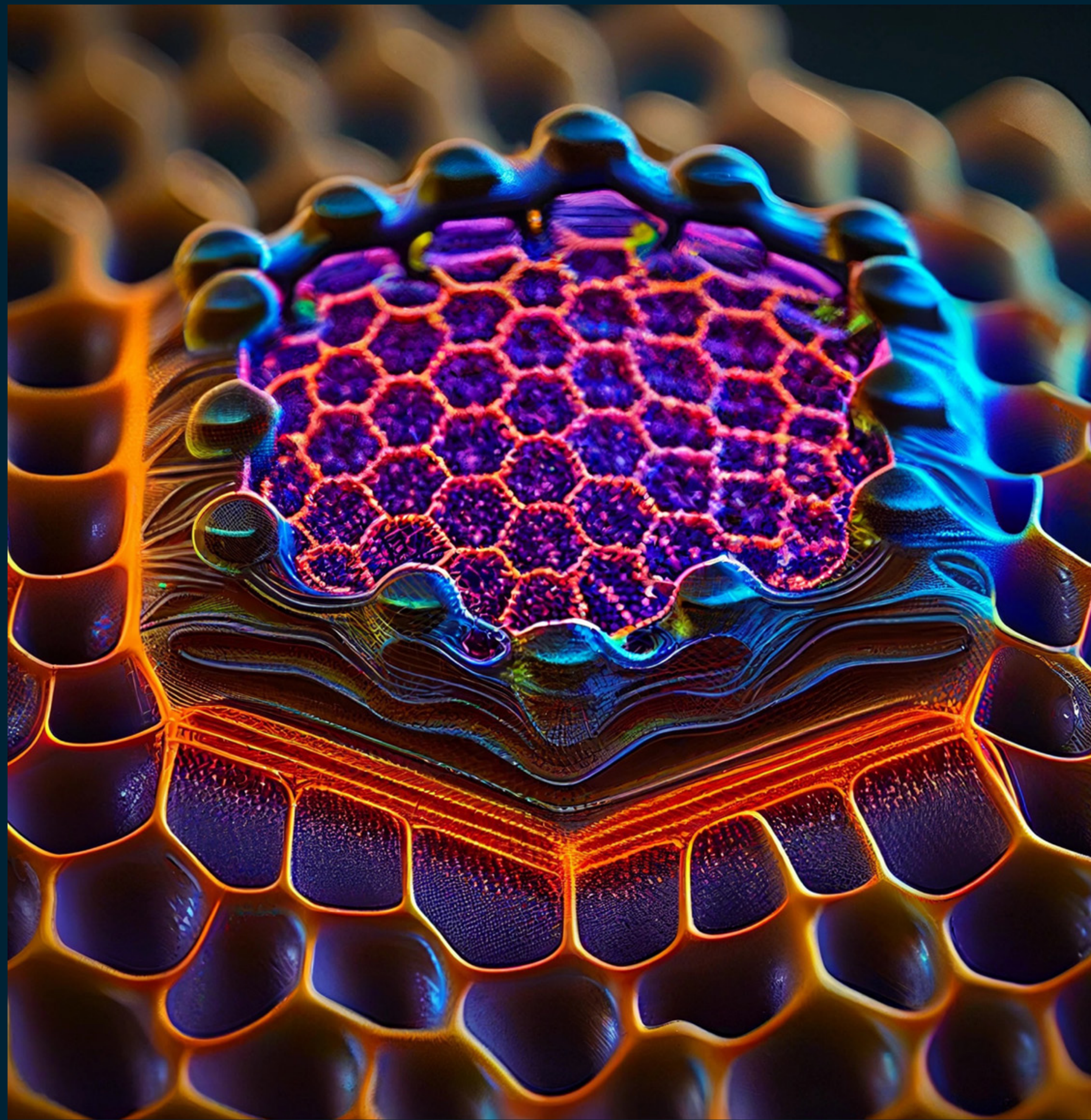
Flexible Electronics

PROTOTYPE
NFC DEVICES - 2018

Fabrication and characterisation of Near-Field Communication (NFC) devices based on highly flexible, carbon-based antennas composed of stacked graphene multilayers.



Read more about Graphene Flagship outputs on our website.



Artistic impression of the surface of a graphene microphone membrane.
Credit: Midjourney and Peter Steeneken

Impact of new structures created by the Graphene Flagship

The nature of the Graphene Flagship, namely its duration and size, has facilitated the development of several new structures which have been integral to the success of the project, and testaments to its success.

The majority of these structures were established to foster further commercialisation of graphene and 2DM – from health and safety to regulatory bodies – and have or will have a wider impact than on just the partners and Associated Members of the Graphene Flagship. In addition to the structures dedicated to the more scientific and technical side of the project, the creation of cross-cutting Work Packages such as Management, Innovation, Industrialisation and Dissemination ensured that the project and its outputs reached a global audience.

> When the [high number of publications and patent applications filed are] combined with future collaborations at a European level in areas such as standards, standardised manufacturing and quality control methods, and in health and safety, the innovation impact should be significant. Industry engagement in the Graphene Flagship is, however, essential if such impact is to be achieved here in Europe."

FET Flagships – Interim evaluation – Final report

HEALTH AND ENVIRONMENT

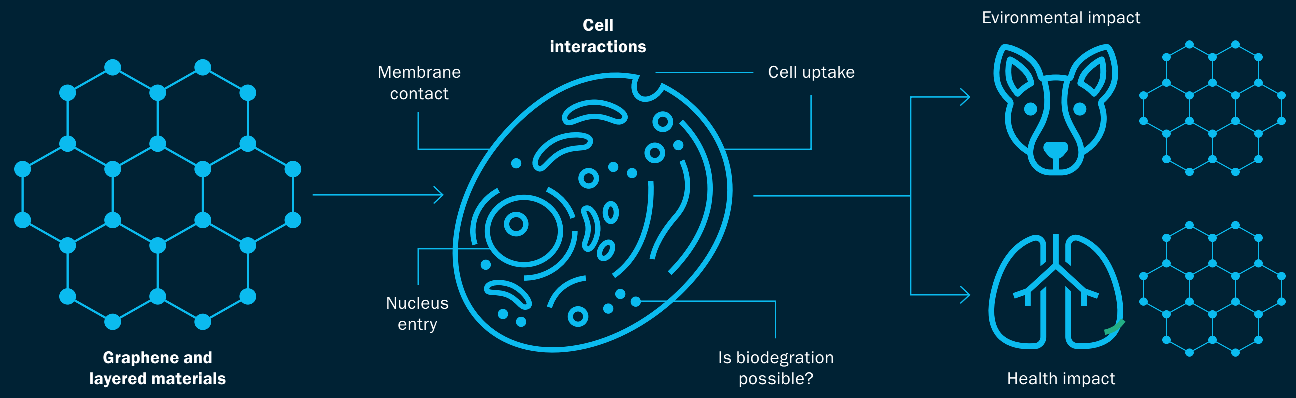
Safety assessment is an essential requirement that cannot be dissociated from the development of new technologies. The increasing exploitation of graphene-based materials necessitates a comprehensive evaluation of the potential impact of these materials on human health and the environment. Therefore, the Graphene Flagship has invested considerable efforts in evaluating their potential impact, both through a dedicated work package and, additionally in Core 3, an industry-led spearhead project. The work of Work Package Health and Environment has evolved from evaluating the impact of graphene oxide and few-layer graphene using in vitro and in vivo models, to studies on the assessment of the life cycle of GRM (graphene and related materials) and their (bio) degradability, toxicity studies on other layered materials and the impact of composites containing graphene that underwent a process of degradation.

Most recently, researchers evaluated the applicability of the Organization for Economic Cooperation and Development (OECD) guidelines to GRM in view of the European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation and future commercialisation of graphene materials. The culmination of this work is a detailed safety assessment of graphene and layered materials and its effects on human health and the environment.[6]

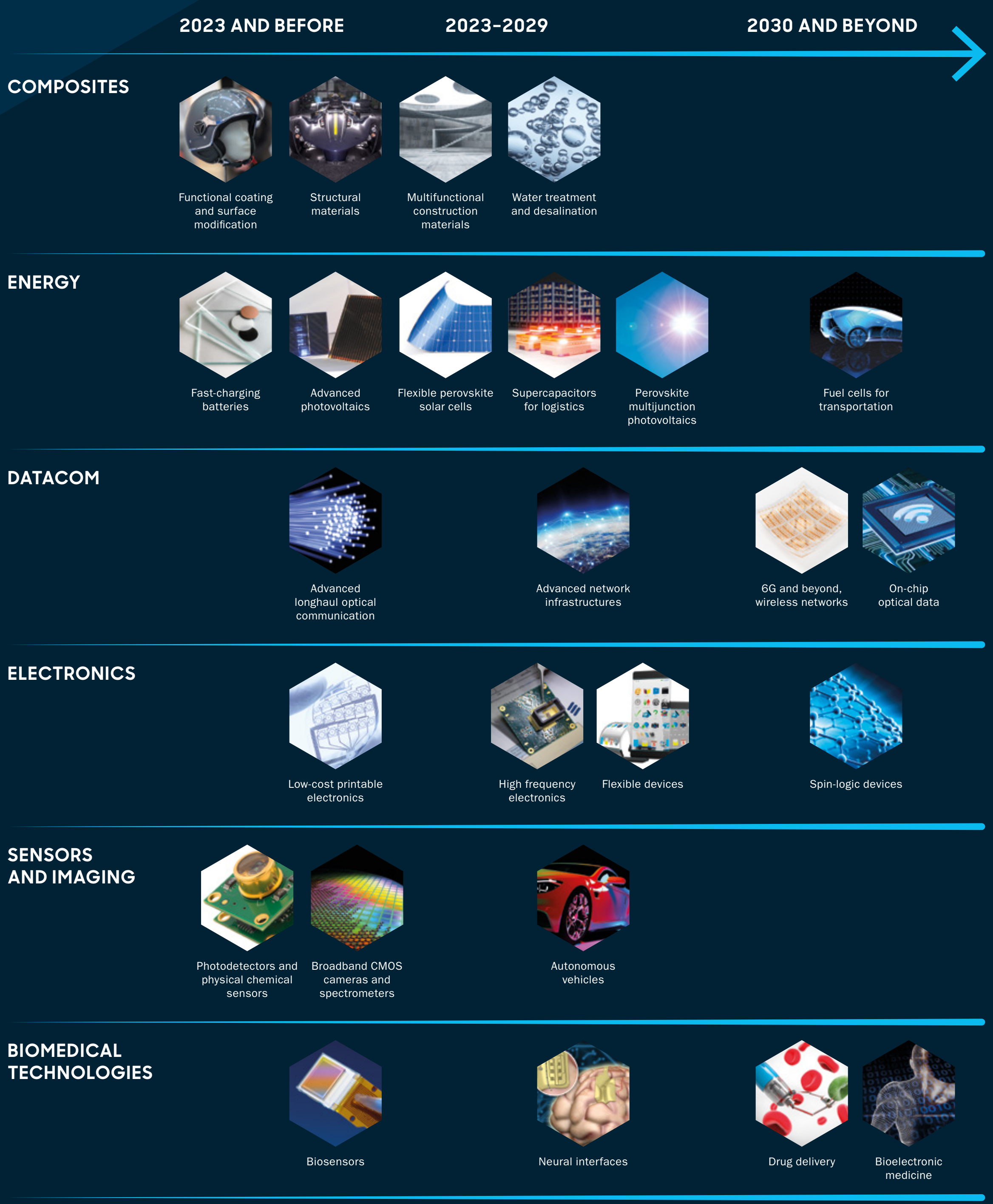
The spearhead (SH) project launched in Core 3, SafeGraph, aims to complement the outputs of the Health and Environment Work Package by developing a regulatory strategy and market authorisation pathway which, coupled to an occupational, consumer and environmental risk assessment will support the projects to reach the market, paving the way for future products. The comprehensive evaluation of the impact of graphene and layered materials conducted within the Graphene Flagship is fundamental to the current and future commercial applications of these materials.

[6] https://pubs.acs.org/doi/10.1021/acsnano.8b04758

Division 6 structure.



Environmental and health impact of graphene and layered materials.



Technology and Innovation Roadmap.

STANDARDISATION, VALIDATION AND ROADMAPPING

From the launch of the Graphene Flagship, the partners involved in the Industrialisation Work Package have played an important role in guiding the project towards market needs via innovation roadmaps and their innovation interface investigation concept. Furthermore, it has worked to establish a coherent industrial workflow towards GRM-based innovation involving key requirements for the adoption of new materials in industry: trust, confidence, reliability of material properties, via validation and standardisation.

The Technology and Innovation Roadmaps (TIR) have proven to be a remarkably accurate resource to determine the most promising markets and applications for GRM and have been used to reveal the best path forward. At the same time, the Graphene Flagship Validation Service has provided confidence in graphene and related materials to enable a quicker transition of graphene products to market using authorised national measurement institutes and facilities world renowned for their excellence, independence, integrity and impartiality. Furthermore, the Graphene Flagship Standardisation Committee (GFSC) works with both the IEC and ISO in a formal and informal capacity and has ensured a strong European voice in both bodies. In the IEC, 50% of all graphene projects are being led by European scientists. Within that, the GFSC is leading 70%, giving the Graphene Flagship a strong voice in graphene standardisation.

Business Developer distribution through Europe.

The Samples and Materials Database (SMDB) is a tool curated for the Graphene Flagship community, to help partners exchange samples and materials, and to gather information on their use. In 2021 a new SMDB was developed as a standalone application that has the potential to be used as a template for other emerging materials, outside of the scope of the Graphene Flagship, or even graphene as a material. At the close of the Core 3 project, the SMDB has over 50 samples/materials from partners, which are available on request.

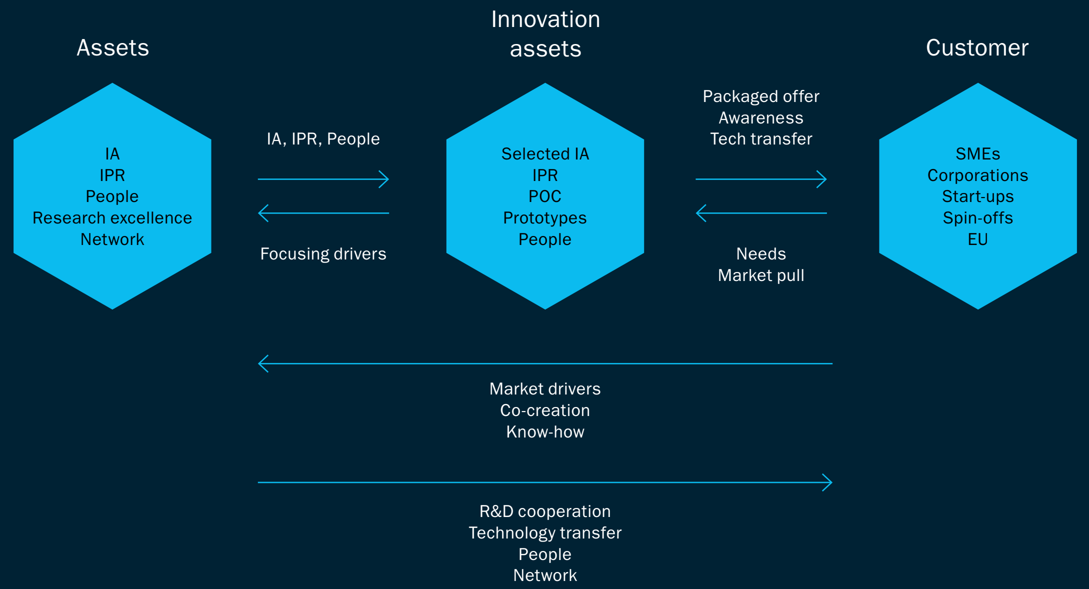
BUSINESS DEVELOPERS AND COMMERCIALISATION

The Innovation Work Package has transformed its work from small, strategy and governance focused efforts to actively driving the Graphene Flagship's commercialisation efforts on an operational level. The formation of the business development function, creation of the Spearhead Projects and active collaboration with other work packages and external stakeholders have had a profound effect on the results and success of the project.

Understanding and developing value chains and an ecosystem in Europe requires constant interaction between research and industry and research needs a lot of promotional activities and dissemination to be noticed by industry. Dedicated efforts and resources for business development and dissemination have been essential in creating impact within the Graphene Flagship. The Business Developers (BDs) have played a key role in helping to launch spin-off companies and to attract private investment, which has reached a total of nearly € 170 million across 20 spin-offs. Work Package Innovation also helped to select the six Core 2 and 11 Core 3 Spearhead Projects, significantly increasing industrial participation in the Graphene Flagship and growing the volume of high technology readiness level (TRL) development to 12% of the project's budget in Core 2 and up to 30% in Core 3.

During Core 2, eight business developers were hired to help bridge the gap between the laboratory and the marketplace. Each business developer served a specific application area to help to identify industry needs and how graphene and related materials could address them. The business developers were the key players in creating a network connecting Graphene Flagship research efforts to industry. BDs act as bridges between the research within the Graphene Flagship and respective industries which can benefit from the project's results. Their tasks range from scouting the customers and end users for our technologies to being messengers from industry when it comes to industry trends, needs and roadmaps. They arrange workshops and help teams to create business models. One important decision was to share the BDs function with prominent and active hubs of graphene research as hosting partners (see figure above).

BDs were heavily involved in shaping some of the main decisions taken in the Graphene Flagship, such as the spearhead proposal evaluations, support to spin-off creation and the connection between academics and potentially interested companies. In Core 3 the main impact has come from working with SH projects and start-up support and creation as well as from technology transfer work. Cooperation has also continued with the 2D-EPL, which is of high impact within and outside the Graphene Flagship. Outreach activities and cooperation with industry have greatly boosted the quest for moving GRM from the laboratory to the factory floor, and are further described in the next section: Societal and economic impact.



Innovation activities help to bridge the gap between industry and research.

BUSINESS DEVELOPER TASKS

A

Technology push: Support, commercially package and promote promising research results created by Graphene Flagship partners.

B

Market pull: Engage industry to start working with graphene-based materials and technology. Initiate research collaboration between industry and Graphene Flagship partners on specific projects.

C

Represent a business domain: Act as the key person with business understanding and contacts within a specific domain.

Essential to the BDs' success was a focus on an application domain and more specifically on certain industries and business lines. The technical work packages and projects as well as spearheads also needed to integrate BDs in their efforts; proactive and positive collaboration between BDs and WPs was elemental.

Bridging between industry and research is essential, as reducing the technological risk is a prerequisite for many industry stakeholders before market risk can be taken. The Business Developer role and industry-led spearhead projects have proved to be very valuable in this aspect.

The mechanism of Innovation support, including the BDs, within the Graphene Flagship has been successful in many ways and can be described via the following summary:

1. A more hands-on, bottom-up approach was appreciated and accepted by the technical work packages and researchers.
2. Workshops that brought together industry end-users and Graphene Flagship stakeholders provided a lot of added value in focussing and guiding the research efforts of the project.
3. Continual and consistent promotion and participation in different conferences showcasing project results in selected application areas as a common, unified effort worked well (compared to a more fragmented, research area approach).
4. It takes a long time to build trust and fruitful collaborations with external stakeholders.

INDUSTRY LED INITIATIVES: SPEARHEAD PROJECTS

The spearhead initiative was introduced in 2017 with the second core project. The Spearheads (SH) are market-motivated, industry-led targeted sub-projects that aim at creating prototypes (technology readiness level 6 or above) in areas where graphene-related technologies have an edge over competing approaches. In the third core project, the spearhead program expanded to comprise about 30% of the Graphene Flagship's budget, with 11 spearhead projects starting in 2020, out of 46 proposals submitted. The main criteria to be selected as a SH project included:

- A consortium led by industry or a research institute focusing on technology transfer.
- A project motivated by market opportunities created and directly addressable by SH partners, such as topics where graphene and related materials (GRM) have a clear competitive advantage and where the market size/value is sufficient to warrant a substantial effort.
- A topic where European industry could be expected to take the prototype or demonstrator further to the market, or issue licensing.

Communications

5G

The Graphene Flagship 5G project focused on creating graphene-enabled fibre communications that are quicker and more reliable thanks to the photonic and electronic properties of graphene.

"Our devices can transmit data at up to 56 gigabits per second, more than five times quicker than the best ethernet cables available today."

Marco Romagnoli
Wafer-Scale System Integration Leader

RFID

The Graphene Flagship RFID project focused on producing a sensing platform, based on layered materials, able to monitor a wide range of physical parameters – to change the way we collect, monitor and read data.

"We developed a low cost, flexible, easy to integrate and wireless sensing platform, able to detect parameters not previously available on a RFID."

Cinzia Casiraghi
RFID Leader

Wearables

WEARGRAPH

The Graphene Flagship's Weargraph project focused on designing and fabricating graphene-based energy devices to power battery-free wireless wearables.

"Using this technology, the system can be integrated into clothes to power electronic devices. For example, using a sensor to control a smart fabric cooling system for workwear."

Xinliang Feng
Functional Foams and Coatings Leader

CHEMSENS

The Graphene Flagship's CHEMsens project has developed a graphene-based sensor to detect biological data on the human skin.

"We have already fabricated an electronic plaster composed of PET-based plastics endowed with four independent devices, which can be operated separately. Our prototypes will be ready by April 2020."

Paolo Samorì
CHEMsens Leader

Energy

SOLAR FARM

The Graphene Flagship's Solar Farm initiative has so far increased the power conversion efficiency of its solar cells by almost 20%, as well as achieving the large-scale manufacture of solar cells – over 1 square metre in size – results that are difficult to achieve using other technologies.

"The project aims to cut the cost of solar MWh by 80%, reaching limits of around €20/MWh."

Aldo di Carlo
Solar Farm Leader

BATTERIES

The Graphene Flagship's Batteries project has successfully upscaled silicon-graphene materials, in preparation for mass-production – achieving production quantities of over 100 grams of silicon-graphene composite per week.

"For the high-energy cell, we expect to outperform state-of-the-art benchmark cells by 20% in capacity and 15% in energy, with a lifetime target of 300 full cycles. These batteries should fully charge in six minutes."

Christoph Stangl
Batteries Leader

Spearheads cross the finish line.

The SH projects proved to be perhaps the most effective tool for advancing our goal to bring graphene out of the lab and into the market. As the SHs in Core 3 were company-led initiatives with well-defined, application-oriented objectives, they provided focus, framework and visibility for project research efforts. As the Graphene Flagship moved from mastering materials and developing components towards system integration, the understanding of the industry value chains and business needs became crucial in delivering the true economic impact of the results created during the years. Moreover, the SHs brought in many new industrial partners, growing the consortium, and allowing for further collaboration.

During Core 3, the cooperation models with industry stakeholders evolved from technology push to market pull, as long-term collaboration gained momentum. This kind of success may not have been possible without the Graphene Flagship, as the project had already yielded quantifiable results which were better positioned for transfer to industry. Multi-stakeholder collaborations are built on trust and trust takes time and constant interaction to form. Bridging the gap between research efforts and industrial utilisation happens by starting small demonstrative cases and building the trust gradually as illustrated below.

The next phase is then to go from market pull to co-creation and aiming for longer term partnerships and maximising the benefits from top research for industrial R&D work (see illustration below). The SHs have been a very effective tool towards this goal.

Spearheads – Where Innovation meets Industry

The Graphene Flagship Spearhead Projects are industry-led initiatives working to increase the technology readiness level (TRL) of graphene-based technologies. These projects collaborate closely with the rest of the project to maximise the impact of the Graphene Flagship in the innovation ecosystem and the European economy.

GRAPHIL

GRAPHIL is aimed at developing a new generation of water filters employing a polymeric membrane enriched with graphene. The composite material obtained should enhance filters' capabilities to remove emerging chemical contaminants from water.

G+BOARD

G+BOARD is producing an integrated copper-free automotive dashboard for vehicles, consisting of a glovebox and steering wheel. The dashboard features conductive patterns, sensors and devices based on multi-functional graphene or reduced graphene oxide.

CIRCUITBREAKERS

CircuitBreakers aims to demonstrate a first-of-its-kind, maintenance-free low-voltage air circuit-breakers by replacing grease lubrication in the drive mechanism with self-lubricating metal–graphene composites, either in the form of coatings or as sintered parts.

METROGRAPH

METROGRAPH advanced technologies will contribute to the improvement of internet networks, as well as make them more sustainable. Thanks to graphene-enabled optical and wide-bandwidth communications, people will have better access to information for education, work, healthcare and more.

GRAPES

By exploiting 2D materials, the GRAPES team aims to boost the performance and stability of perovskite cells to a new record level and fabricate cost-effective, stable photovoltaic panels based on GRM-PSK/Si tandem technology.

AUTOVISION

The Autovision Spearhead Project is aimed at enabling semi-autonomous cars to operate under adverse ambient conditions. It is strongly focused on scaling up the manufacturing of graphene-based infrared image sensors for advanced driver systems.

GBIRCAM

The GBIRCAM Spearhead Project revolves around developing an image sensor and camera system for the simultaneous detection of visible, short-wave infrared and mid-wave infrared wavelengths.

AEOGRAFT

The AEROGrAFT Spearhead Project aims to build a sustainable, innovative air filtration system for passenger aircraft. The filtration system is made of lightweight filter materials based on graphene foams, which possess unique mechanical and electrical characteristics.

GICE

The GICE Spearhead Project exists to advance graphene-based ice protection and ice sensing technologies to high technology readiness levels. It aims to produce three demonstrators for specific applications, tailored to the needs of industrial partners Airbus and Sonaca.

GREENBAT

The GrEEnBAT Spearhead Project seeks to scale up the fabrication of innovative silicon-graphene composite electrodes for lithium-ion batteries. This project has the aim of fully developing functional battery modules for electric vehicles.

SAFEGRAPH

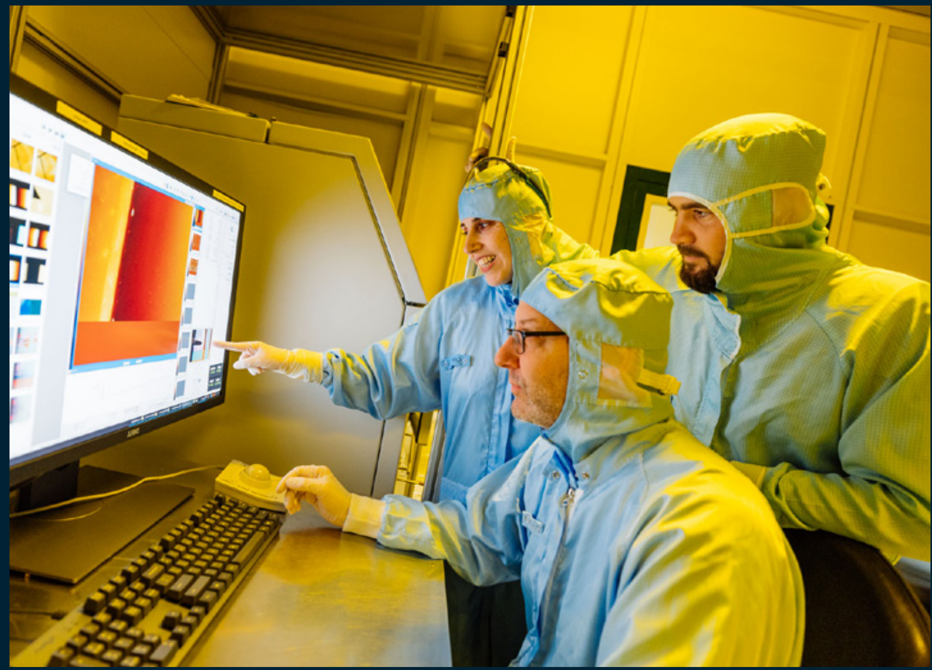
SafeGraph delivers a set of guidelines to support other Spearhead Projects and the Graphene Flagship to achieve essential regulatory compliance for their new products. This will accelerate the path to market, saving our partners time and money prior to commercialisation.

The 2D-EPL provides multi project wafer runs where universities, research institutes and companies can include their designs as dies on joint graphene-integrated wafers. The completed devices are delivered as diced chips, wafer parts or wafers.

2D EXPERIMENTAL PILOT LINE

The 2D Experimental Pilot Line (2D-EPL), a € 20 million project launched in October 2020 to integrate 2D materials into silicon wafers, is the culmination of many of the Graphene Flagship's efforts to bring graphene and related materials (GRM) out of the lab and into commercial applications. This project is an example of the innovative community created by the Graphene Flagship, as it brought together partners from the Core 2 phase with external industrial suppliers to address commercialisation challenges of achieving reliable fabrication processes for high-volume production and establish a European ecosystem for prototype production of GRM based electronics, photonics and sensors. The 2D-EPL covers the entire value chain from tool producers to chemical and material providers and pilot lines, to secure progress in GRM integration and to be able to offer prototyping services to academics, SMEs and companies which can benefit from the progress of GRM integration with silicon achieved within the 2D-EPL consortium.

The goal of the 2D-EPL is to advance the production of electronic, optoelectronic and photonic devices and electronic sensors based on graphene and layered materials beyond the laboratory scale towards industrialisation. As such, it builds an important bridge to facilitate the industrialisation of many of the technologies developed in the Graphene Flagship's Work Packages and Spearhead Projects, as well as by other European and global customers pursuing the commercialisation of graphene and layered material-based electronic technologies. The 2D-EPL will continue one year after the close of Core 3, ensuring that the infrastructure created by the Graphene Flagship remains relevant.



The 2D-EPL addresses the challenges of establishing reliable fabrication processes for high-volume production of graphene and related materials-based electronics, photonics and sensors.

The Graphene Flagship Management and Dissemination teams at Graphene Week 2023.

One other key success factor of the Graphene Flagship is the excellent coordination."

Evaluation study of the European framework programmes for research and innovation for excellent science – Horizon 2020

10 000+
Attendees to Graphene Flagship events

4 000+
Oral/poster presentations

75
Attendees from 75 countries

30%
Attendance from women

MANAGEMENT AND DISSEMINATION

The effective management of the Graphene Flagship and successful dissemination of its outputs have been key factors in the project's success, as reported in the H2020 ex-post evaluation.[7]

From the start, Work Package Management has ensured that the consortium had the tools it needed for growth and collaboration. It has developed infrastructure to help the partners share data, report their work efficiently and receive project updates. Furthermore, the Management team has updated the Graphene Flagship's governance structure to keep up with the growth of the project as it has increased in size and complexity. There have been a total of 232 different partners in the Graphene Flagship over the past ten years, including some in competitive market positions. Management has been instrumental in finding pathways to collaboration, even when relations have been challenging.

Work Package Dissemination complements this work by ensuring visibility and accessibility of results, community building through events and fostering of diversity. Over the first ten years of the Graphene Flagship, more than 10,000 individuals have attended an event organised by the Dissemination team.

In the beginning, WP Dissemination's goal was to help people understand what graphene is, why it is unique and how it can be applied to critical applications that touch all our lives. As the Graphene Flagship has become more established and graphene has become widely known, their mission has shifted to sharing the project's broader commercialisation message, success stories and exciting GRM applications.

It is incredible to see how well the project is administered, coordinating even a large group of academic institutions can be a challenge, but adding industrial partners successfully into the mix is remarkable."

Margrethe Vestager, European Commission Executive Vice President

[7] European Commission, Directorate-General for Research and Innovation, Budraitis, M., Pranckevičius, P., Dėlkutė, R. et al., Evaluation study of the European framework programmes for research and innovation for excellent science – Horizon 2020 – Annexes, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2777/353383

Graphene Flagship Director Jari Kinaret walks European Commission project officer Wide Hogenhout through the production process of graphene from graphite at Mobile World Congress 2019. Credit: Alexandra Csuport

INTERFACES WITH REGULATORY BODIES, EUROPEAN COMMISSION AND EU MEMBER STATES

Throughout the first ten years of the Graphene Flagship, many different points of connection have been made with various stakeholders, both nationally and within the EU. In particular, a good working relationship has been maintained with the European Commission throughout the project, decreasing the need for bureaucracy and shortening the line of communication. For a project as large as the Graphene Flagship, having access to project officers and other Commission staff has been vital.

The alignment work done by the European Science Foundation (ESF) has ensured a strong connection to EU Member States via the interface with FLAG-ERA. This has allowed the Graphene Flagship community to grow outside of the confines of the core consortium, increasing collaboration and strengthening the European Research Area.

In 2020, a Graphene Flagship Working Group for liaising with the European Chemical Agency and the regulation for Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH/ECHA) Working Group was created to coordinate the communication between the Graphene Flagship and different stakeholders such as ECHA, the European Union Observatory on Nanomaterials (EUON) and the Graphene Reach Registration Consortium (GRRC).

The Working Group aimed to enhance cooperation with ECHA and EUON and to find ways to share knowledge in the field of toxicity and safety of graphene and other 2D materials. In particular, the Graphene Flagship WPs for Biomedical Technologies and Health and Environment were invited to write an article about graphene and why it is different from carbon nanotubes that was published on the EUON website.[8]

As the graphene market grows and more industries incorporate it into their processes and products, it is clear that REACH registration will soon be, if not already, a key issue for EU companies manufacturing and importing graphene. As such, part of the Working Group's tasks was also to liaise with the Graphene REACH Registration Consortium (GRRC), a consortium of companies managing the REACH registration of graphene. To facilitate progress on this topic, the Working Group organised a webinar to inform companies in the Graphene Flagship about graphene registration and to point out its relevance in the long-term perspective.

European Commission project officer Emilie Klecha learns about a graphene-enhanced rocket at Graphene Week 2019. Credit: Vesa Laitinen

[8] Bianco, A., Prato, M., Kostarelos, K., What does "graphene" really look like and why is it not "carbon nanotubes", European Union Observatory for Nanomaterials Nanopinion, 2022, https://euon.echa.europa.eu/nanopinion/-/blogs/what-does-graphene-really-look-like-and-why-is-it-not-carbon-nanotubes-

Societal and economic impact

The scientific impact of the Graphene Flagship, as well as its impact upon the broader 2DM community, value chains and innovation ecosystems, to name a few, have been detailed above. In this section, we provide an overview of the Graphene Flagship's societal and economic impacts, outputs which may often be more difficult to convey in the reporting of traditional research projects. However, the Graphene Flagship's ten-year lifetime gives us a unique opportunity to observe real and impactful changes outside of the lab and the fab.

DIVERSITY INITIATIVES

The Graphene Flagship has worked to increase awareness of challenges impacting underrepresented groups in science and specifically within the Graphene Flagship ecosystem and to provide support for these groups. The diversity initiative began in 2015 with the first Women in Graphene event, initially as an event during our annual Graphene Week conference with talks sharing women's personal journeys and how they overcame gender challenges in their careers. By 2017, Career Development days were added to the initiative, helping to teach women valuable skills for promoting their career. In 2020 the initiative was broadened to Diversity in Graphene with the aim of encouraging inclusion in the Graphene Flagship and providing support for all underrepresented groups. Finally in 2021, the initiative launched a one-on-one mentoring programme to provide more personalised support within the Graphene Flagship community. Throughout Core 3, 66 mentees were supported by this programme. This initiative has helped to raise awareness in our community and foster a general feeling of inclusion and acceptance at our events and in our management. We have seen the number of women in leadership increase, particularly in the newer projects like the spearheads and the 2D Experimental Pilot Line, where women make up close to 50% of the leadership roles. In addition, nearly one-third of attendees to Graphene Flagship events are now female.

A networking session at a Women in Graphene Career Day event in Manchester, UK. Credit: Graphene Flagship

> Flagships are not only moving towards delivering on the general objectives, but are also now essential to Europe's future prosperity and well-being."
>
> FET Flagship – Interim evaluation – Final report

A poster session at Graphene Study 2017.
Credit: Oscar AB

CAREER GROWTH

The scale of the Graphene Flagship has also allowed for a unique perspective on career growth related to scientific research. Over the past decade, we have been able to observe the evolution of young, early career researchers into senior research staff, the movement of key Graphene Flagship researchers into important roles across European research institutes, the transition of researchers from academia to industry, and the growth of established SMEs.

The importance of fostering the new generation of researchers has been seen continually during the project. From the organisation of Graphene Study – the Graphene Flagship's winter and summer school – to career coaching and mentorship programmes, and an emphasis on poster sessions at the Graphene Week conferences, early career researchers have maintained a strong presence in the Graphene Flagship's activities over the past ten years.

More than 500 students and early career researchers attended Graphene Study events during the first ten years of the Graphene Flagship. The final edition of Graphene Study in Core 3, which over the years has given students the chance to work closely with senior researchers and leaders in the field, saw two invited speakers who themselves had attended the same event as students, a testament to the power of career development opportunities.

Career development in the Graphene Flagship has not just been reserved for students, however. Even more senior researchers have seen their positions evolve and accelerate due to the project. Xinliang Feng (TU Dresden), leader of the Functional Foams and Coatings WP, who joined the project at the beginning of our ramp-up phase, was appointed Max Planck Director at the Institute of Microstructure Physics in Halle, Germany, during Core 3. Vincenzo Palermo, deputy leader of the G+BOARD Spearhead project, was one of the nine scientists who wrote the initial proposal for the Graphene Flagship and later became the project's Vice-Director. He has now been appointed Director at the Institute for Organic Synthesis and Photoreactivity, a centre at the Italian National Research Council during Core 3.

> The funding scheme of the Graphene Flagship, including EC and Member State investment, has allowed the funding of researchers, from PhD position to their post-doctoral phase and even beyond. The Graphene Flagship has furthermore been able to keep the interest of top-researchers and key industry players for a long period of time. This is one of the unique and successful features of the FET Flagship scheme that has led to the success of the Graphene Flagship initiative in being able to shorten the time-frame of basic research to applications in ten years, as compared to the usual 20 or more years."
>
> Evaluation study of the European framework programmes for research and innovation for excellent science – Horizon 2020

The Graphene Flagship has also seen the movement of academics into industry. In many cases, these moves are from established project partners to spin-offs, ensuring that the initiative is keeping its promise to bring graphene closer to commercialisation. In several examples, these spin-offs have gone on to lead Core 3 Spearhead projects, further showing how the Graphene Flagship has gone from lower TRL to higher TRL over its lifetime.

A decade of growth

Early career researcher

"I attended Graphene Study three times, and I always enjoyed the experience and learned a lot. Graphene Study is a great event for networking with people working in the same field. I would advise Graphene Study participants to use the opportunity not only to learn about the science and technology, but also to form connections with the (future) experts in the field."

Miika Soikkeli, VTT
current WP Leader in the 2D-EPL

"I attended Graphene Study 2015 in Kaprun (Austria). During that week I learned a lot about mesoscopic transport, spin transport and spin orbit coupling. I also presented a poster with my results on high quality CVD graphene, which led to a fruitful collaboration with the group of Bernard Plaçais of the Ecole Normale Supérieure (France)."

Luca Banszerus
Former Graphene Flagship PhD student who returned to Graphene Study as an invited speaker

Another former Graphene Study attendee, **Meganne Christian**, is a researcher at Graphene Flagship partner the National Research Council (CNR), Institute for Microelectronics and Microsystems (IMM), Italy. Since 2014 she has been involved in the Graphene Flagship's work packages for Composites and Functional Foams and Coatings. During this time, she has taken part in two parabolic flight campaigns, in 2017 and 2021, to test graphene coatings in loop heat pipes destined for use as thermal management systems in satellites. In 2022, she was inducted into the 17-person class of European Space Agency (ESA) astronauts.

Meganne Christian
Member of the European Space Agency astronaut group

Stjin Goossens presented his research at the Graphene Flagship Mobile World Congerss exhibition in 2016.

Senior researcher

"It was November 2010, when I was chairing a meeting of GOSPEL, the first project on graphene that I ever coordinated, launched by the European Science Foundation. There, a Finnish professor introduced himself asking me to join eight other partners to write a proposal on a new type of ambitious EU project, never heard of or attempted before. This professor was Jari Kinaret, who eventually became the Director of the Graphene Flagship; we went on to work together for eleven years, and this of course had a very strong influence on my career."

Vincenzo Palermo
Director ISOF-CNR

"I was lucky to be involved in the Graphene Flagship from the very beginning, before 2010. Back then I was a group leader in Mainz, and I started collaborating with other European colleagues to define the key topics and directions for this one-of-a-kind initiative. My personal career grew alongside the Graphene Flagship. During these past years, I have learnt a lot with my colleagues and friends in the project, understanding more about graphene and layered materials, from physics and fundamentals to the applications and innovation. Besides, I have met many new good friends!"

Xinliang Feng
Director at the Max Planck Institute of Microstructure Physics

Academia to industry

Vittorio Pellegrini, BeDimensional, Leader of WP Energy Storage: Pellegrini has been involved in the Graphene Flagship throughout the project, first as the director of the Graphene Labs at the Italian Institute of Technology (IIT) and then at Graphene Flagship and IIT spin-off BeDimensional, which he co-founded in 2016. While at IIT, Pellegrini chaired the Graphene Flagship Executive Board, and at both IIT and BeDimensional he has been WP Leader. Meanwhile, the company has attracted millions of Euros in investments to further grow their business dedicated to the development, production and commercialisation of composites, functional paints and lubricants with graphene and related materials.

Vittorio Pellegrini
CEO BeDimensional

Stijn Goossens, Qurv, Leader of SH AUTOVISION: Goossens began working on the electronic properties of graphene at TU Delft in 2009 when there was no large-scale graphene available, and researchers were still exfoliating graphite with scotch tape. With a goal to push graphene towards applications, he joined Graphene Flagship Partner ICFO, leading an incubation project on graphene-based and wide-spectrum pixel technology. In 2020, Qurv was spun out from ICFO, and Goossens brought the company into the Graphene Flagship to continue his work in the industry lead Spearhead AUTOVISION.

Stijn Goosens
Co-Founder and CTO Qurv

INDUSTRIAL OUTREACH

Industry and business outreach aims to attract companies that may benefit from disruptive graphene and related materials technologies. The Graphene Flagship has seen its industrial outreach activities grow in parallel with the evolution of research activities from fundamental to more applied. In addition, the COVID-19 pandemic, increased connectivity, new travel policies and focus on the digital world have played an important role in shaping this activity.

Starting with multiple successful editions of Mobile World Congress (MWC 2016, 2017, 2018, 2019) and diversification into different applications areas, such as biomedical (MEDICA 2017), composites (Composites Europe 2017, JEC World 2023), energy (Enlit Europe 2022) and aerospace (ILA Berlin 2022), tradeshow attendance has created unique opportunities for partners to look for collaborators and investors. In addition, these activities also increased the visibility of the project among policy makers (Tallinn Digital Summit 2017, ICT 2018, European Research and Innovation Days 2019) and the general public ("Graphopolis" for school children on display at the Youth Mobile Exhibition 2017 and 2018, Graphene Pavilion at Graphene Week 2022 in BMW Welt Munich). The Graphene Marketplace concept has also successfully promoted graphene applications among industrial partners (Airbus, Leonardo, TetraPak, Electrolux) and strengthened the project's connection to industry. In some cases, these Marketplace events led to concrete actions between Graphene Flagship stakeholders that may not otherwise have occurred. When the Graphene Flagship first started attending trade shows, much of the time was spent answering the question 'what is graphene'. In 2023, the question is no longer 'what' but 'what kind of graphene should I use', illustrating the successful dissemination of results generated by the project.

More targeted approaches to industry outreach have been consistently organised by the Innovation Work Package through events connecting the research of the Graphene Flagship to the wider innovation ecosystem, with a focus on the commercialisation of applications containing 2D materials. This type of outreach began as early as 2014 with the Graphene Connect series, set up simply to connect industry to academia, as at the time there was less familiarity with graphene and other 2D materials. Graphene Connect events continued until the end of Core 2 when they were replaced by Innovation Workshops which have provided opportunities to hear about successful implementation of graphene from both start-ups and larger corporations. The Graphene Flagship Spearhead projects have often featured and presented their views on challenges and opportunities with graphene commercialisation. The Graphene Innovation Forum, organised as part of the Graphene Week conferences, allowed a wider audience to learn about the impact of 2DM on business and innovation. This event has also served as a key moment for networking within and outside of the Graphene Flagship.

Out of the total € 5.9 billion contributed by graphene to the world GDP between 2014 and 2030, € 3.8 billion will be in the EU27.

For every Euro of GDP contributed by the Graphene Flagship in the EU27 directly, an additional € 1.70 will be supported in the EU27 based on inter-industry and inter-country linkages.

The Graphene Flagship will support 38,400 jobs in the EU27 between 2014 and 2030.

For every job created by the Graphene Flagship directly, an additional 2.15 jobs will be created in the EU27 based on inter-industry and inter-country linkages.

60% of the total impact of graphene in the EU27 will be from the electronics and equipment sector.

ECONOMIC IMPACT ASSESSMENT

Assessing the economic impact of publicly funded research is not as straightforward as analysing key performance indicators such as publications, patents or products, with no agreement in studies of standard economic returns for research and development (R&D) activities.[9] Considering the length of the Graphene Flagship, its large budget and hundreds of partners, an economic impact assessment was undertaken to attempt to answer this question. Of course, it will take years for the full impact of the work done by the Graphene Flagship to be realised.

The report, commissioned by the Graphene Flagship and completed by the WifOR Institute in 2023, aimed to estimate the economic impact of the Graphene Flagship in Europe and globally since its inception, including its market share and projection up to 2030. The study quantifies the economic value in terms of the gross value added (GVA), i.e., contribution to Gross Domestic Product (GDP), and the jobs supported by the R&D activities stemming from the Graphene Flagship from 2014 and forecasted until 2030. The main data for this study was the invested budget of the Graphene Flagship, including partners of the FP7 ramp-up phase, the Core projects, 2D-EPL project and project funding by member states, i.e., via FLAG-ERA, together with estimated market share values.

> By investing around € 1.4 billion into Graphene's European R&D and business activities, the funding entities will have contributed € 5.9 billion to the world GDP and supported 81,400 jobs around the world between 2014 and 2030 – of which 65 and 47 percent occurred in the EU27, respectively. Thus, the Graphene Flagship has already successfully contributed towards supporting the European graphene market, which is growing at an annual rate of 30 percent."
>
> WifOR Institute

[9] European Commission, Directorate-General for Research and Innovation, The economic rationale for public R&I funding and its impact, Publications Office, 2017, https://data.europa.eu/doi/10.2777/047015

[10] Albu, N., Juneja M., Economic footprint and R&D footprint for Graphene Flagship, WifOR Institute, 2023, https://www.wifor.com/en/download/economic-footprint-and-rd-footprintfor-graphene-flagship/?wpdm-dl=340676&refresh=6515dfb0c29cb1695932336

Future progress within the Graphene Flagship framework

Lessons Learned

In large, multi-disciplinary projects, it is crucial to have long-term vision and cooperation. The exceptional duration of the Graphene Flagship has been pivotal in creating the successful project results and impact.

Creating networks and trusted partnerships enables co-creation and innovation.

Understanding and developing value chains and an ecosystem in Europe needs constant interaction between research and industry.

There must be a focus on application domains and further focus on certain industries and business lines in order to work out the value chain and ecosystem.

Bridging between industry and research is essential, as reducing the technological risk is a prerequisite for many industry stakeholders before market risk can be taken.

INDUSTRIAL OUTREACH

The future for graphene and 2D materials in Europe looks bright as the seeds sown over the past decade are growing, and still more are being planted. As the Graphene Flagship initiative sails on into Horizon Europe with a dozen new projects leading the way, the next big steps are engaging with independent, industry-led initiatives such as the 2D Materials Industry & Innovation Consortium (2DMIC).

2DMIC is set to boost the European 2DM industry's competitiveness and economic growth, and support implementation of 2DM technology by EU industrial sectors for the benefit of EU economy and society. The aim is to establish a business-driven association to push an industrial framework of 2DM in Europe and bring together large industrial companies, SMEs, start-ups and investors to boost innovation with a focus on high TRL industrial R&D. This will enable European companies to accelerate their deployment in the EU market and have a direct impact in the growth of the field. Graphene Flagship partners have been engaged in this association from its inception, and it will be a key stakeholder as 2D material-enabled technologies continue to enter the market.

The planning by the European Commission for a Public Private Partnership on innovative materials further confirms the importance of the research and development that has taken place over the last ten years. This significant investment in the industrialisation of 2D materials will take graphene even further out of the lab and into established and emerging markets in Europe.

At the same time that these ambitious, industry-focused initiatives are launching, the projects which will continue under the umbrella of the Horizon Europe Coordination and Support Action, GrapheneEU, will benefit from the robust infrastructure for research, innovation and collaboration created by the Graphene Flagship.

Conclusions

The "Evaluation study of the European framework programmes for research and innovation for excellent science" published by the European Commission in 2023 included a case study on the Graphene Flagship with positive results. The study contained policy recommendations stemming from the project, including the suggestion of continued long-term research funding for projects such as the Flagships, allowing for flexibility in long-term research, and risk reduction. While the Graphene Flagship's form in Horizon Europe differs from Horizon 2020, the framework developed over the ten years of the project will have a lasting impact on 2D materials research that will continue within and outside of the Graphene Flagship initiative. The structures created provide a blueprint for how to conduct research over a long period of time while reducing the risks that may otherwise slow down or derail innovation.

In terms of pure numbers, the Graphene Flagship has had an incredible impact on science in its first decade. The project's impact is easily seen in the products, prototypes and spin-offs described in this report. In our assessment, the Graphene Flagship has had a major effect on collaboration in the 2D materials community – from academics to industry – as it has helped to shape this emerging ecosystem in Europe. The time, the networks, the infrastructure and the innovation of the Graphene Flagship has indeed proven that the project has had a good return on investment for Europe, an investment that will continue to grow for years to come.

> The Graphene Flagship has proven to be effective in delivering excellent science and innovation. It has furthermore led to the creation of lasting eco-systems proven to function well and intended to continue beyond H2020 and Horizon Europe (Graphene Flagship, 2022)."

Evaluation study of the European framework programmes for research and innovation for excellent science – Horizon 2020

[11] European Commission, Directorate-General for Research and Innovation, Budraitis, M., Pranckevičius, P., Dėlkutė, R. et al., Evaluation study of the European framework programmes for research and innovation for excellent science – Horizon 2020 – Phase 1 final study report, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2777/967813

Summary

The Graphene Flagship was funded to ensure that Europe would maintain its lead in graphene research and innovation following the scientific breakthrough of graphene's isolation at the University of Manchester. The European Commission launched the unprecedented long-term and large-scale Flagship research initiatives to tackle major challenges in science and technology, bringing positive changes that benefit society and the economy and advance European leadership in technology and industry. A decade on, we are proud to say that the Graphene Flagship has delivered on its promise. The clearly achieved objectives within scientific excellence, as well as societal and economic impact are detailed inside these pages.

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